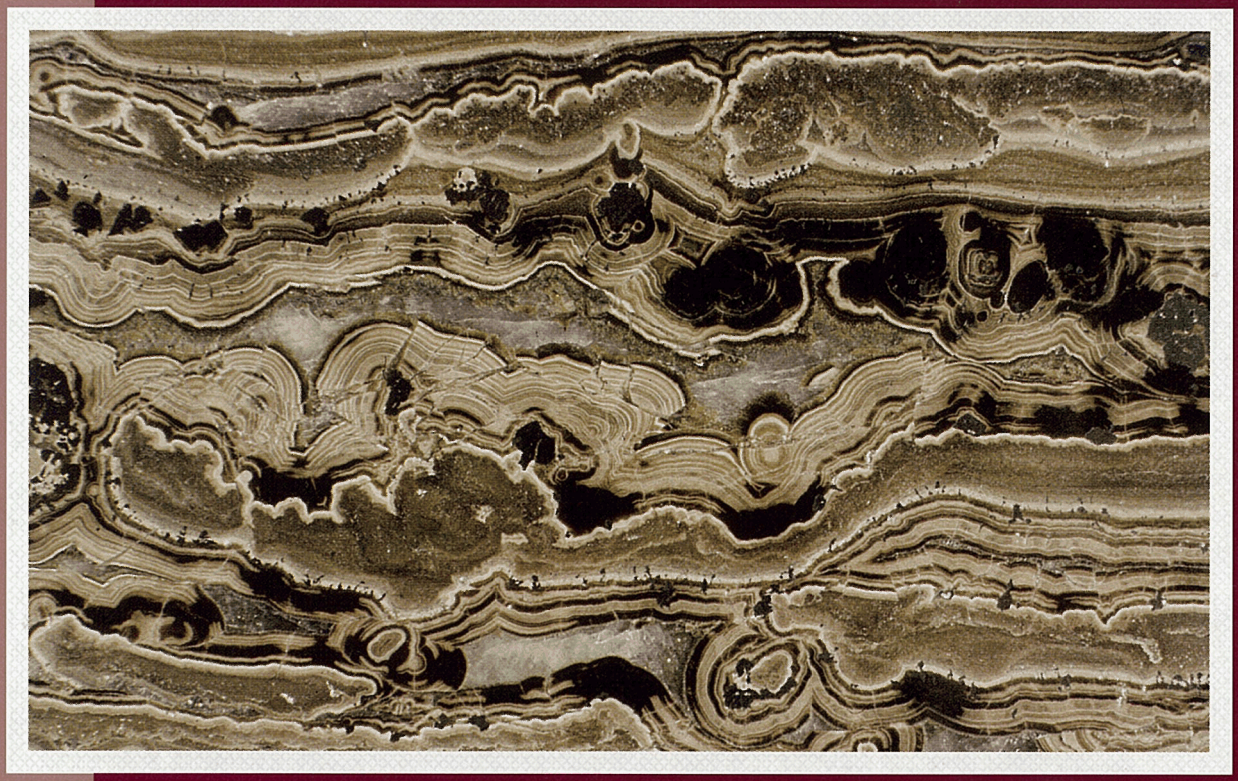
MINERAL RESOURCES BULLETIN 15

GOVERNMENT OF WESTERN AUSTRALIA

LEAD, ZINC AND SILVER DEPOSITS OF WESTERN AUSTRALIA

by K. M. Ferguson



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

DEPARTMENT OF MINERALS AND ENERGY

LEAD, ZINC AND SILVER DEPOSITS OF WESTERN AUSTRALIA

FRONTISPIECE

Sulfur and copper staining in creek draining the Sulphur Springs deposit, Pilbara Craton

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by
K. M. Ferguson

Perth 1999

MINISTER FOR MINES
The Hon. Norman Moore, MLC

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Cover photograph:

Cadjebut zinc ore showing infill structures in variably colour-banded sphalerite and late calcite. Photograph courtesy of Peter Muhling (BHP)

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Lead, zinc and silver deposits of Western Australia

by

K. M. Ferguson

Summary

This Bulletin is the result of a complete updating and rewriting of The Geological Survey of Western Australia Mineral Resources Bulletin No. 9 — The Lead Zinc and Silver Deposits of Western Australia (Blockley, 1971) — and incorporates the large number of changes that have occurred in the understanding of the mineralizing processes associated with lead, zinc and silver deposits. Recent advances in the mining and extraction of these metals are documented, together with an account of exploration and major discoveries in Western Australia over the past 25 years.

World and Western Australian exploration, treatment and production, economic aspects and uses, are summarized in Chapter 2. Chapter 3 reviews the geochemistry and mineralogy of the three metals, including the effects of primary and weathering processes.

The occurrence of potentially economic concentrations of lead, zinc and silver is set within the geotectonic framework of the State and grouped under the four major deposit types, which reflect the mode of formation and, to some extent, the age of mineralization. The four types are volcanic-associated massive-sulfide deposits, sediment-hosted clastic deposits, sediment-hosted carbonate deposits, and hydrothermal vein-type deposits. Classification has been facilitated by the greatly increased knowledge of the genetic aspects of lead, zinc and silver deposits and improved understanding of the Western Australian occurrences and their settings. These aspects are summarized in Chapters 4 and 5.

In Chapters 6, 7 and 8 the Western Australian occurrences are grouped under their broad genetic associations and within the relevant tectonic units. For each unit the geological framework, mineralization and exploration history are reviewed. Deposits, prospects and occurrences are then described in terms of location, setting, main regolith and primary geological and mineralogical features, with surface and drillhole geochemistry. Exploration history is detailed and reserves, mining, and production information are included where available. References are listed for each occurrence. This Bulletin also contains detailed contributions from the mining industry on important and recently discovered deposits. Where appropriate the potential of a tectonic unit for further discoveries of economic lead, zinc or silver mineralization is also assessed.

In Chapter 9 the overall potential of the State is reviewed, along with possible further exploration strategies and potentially valuable research and innovations.

KEYWORDS: Economic geology, mineral deposits, mineral exploration, mineralization, regional geology, base metals, lead, zinc, silver, resources, exploration history, mineral potential

Chapter 1

Introduction

Object and scope

This Bulletin was instigated as a result of a recommendation of the Geological Survey Liaison Committee to update the original Mineral Resources Bulletin for this commodity group (Blockley, 1971). Over the past 25 years, there has been greatly increased understanding of the geological processes affecting economic concentration of lead, zinc and silver, and as a result there has been a growth in the number and variety of important discoveries within the State.

The past two decades have seen the establishment of an energetic and sophisticated mineral exploration sector in the State. This has been fuelled by commodity booms for base metals, gold and diamonds, by the increasingly comprehensive regional geological mapping and resource studies carried out by the Geological Survey of Western Australia (GSWA), and by the rise of resource-targeted academic research in the tertiary institutions and at the Commonwealth Scientific Industrial and Research Organisation (CSIRO).

For these reasons this new Bulletin presents a commodity study with the aim of providing a comprehensive summary of both technical and economic results of exploration to date. A critical evaluation of the potential for the variety of lead–zinc–silver deposit types, within the State's geological framework, provides a springboard for more effective exploration in the future.

This revised Bulletin follows the objectives of the original in aiming to 'summarize all the available information on base metal deposits in Western Australia which have been worked, or are potentially workable, for some combination of the metals lead, zinc and silver'. This definition adequately covers all mines, abandoned mines, established deposits and many of the prospects outlined by exploration. However, minor prospects and occurrences cannot be ignored in defining the regional framework of mineralizing processes and related productivity.

In the original Bulletin (Blockley, 1971), speculative discussion on the origin of ore deposits was kept to a minimum, mainly due to the lack of detailed studies of the significant deposits and prospects known at that time. This is no longer so, and a realistic attempt can now be made to place the various deposits and prospects within a clearly defined metallogenic framework, allowing more informed speculation on prospectivity within the various tectonic units of the State.

The earlier Bulletin dealt with those mineral deposits 'which contain significant quantities of galena and/or sphalerite in their primary ore' and was not concerned with 'deposits of other metals in which lead and zinc are present in uneconomic amounts, nor with the many gold and copper mines in the State which have yielded silver as a by-product'. The more inclusive approach of this revised edition, however, recognizes that ore-forming processes often ignore the artificial separation of their products. This is particularly so in the association of lead and zinc with copper, both in volcanogenic and in sedimentary deposit types. This was recognized in the last Mineral Resources Bulletin on copper (Marston, 1979), which subdivided deposits by genetic type within the State's tectonic framework and, while concentrating on those in which copper was the dominant economic mineral, allowed significant overlap with the previous lead, zinc and silver Bulletin.

It is clear, for example, that the sedimentary base-metal deposits of the Paterson Orogen, and the volcanogenic deposits of the Archaean cratons, show differing combinations of copper, lead and zinc, depending on varying lithostratigraphic, tectonic and chemical controls, both within the regions and also within individual deposits. These related occurrences are therefore all included in this Bulletin, with lesser attention given only to those which either contain only copper in significant quantities or are demonstrably genetically unrelated to processes which have the potential for producing significant lead and/or zinc accumulations. Lead and zinc in gold deposits, however, are less clearly from one end of a spectrum which might yield economic accumulations for both types, particularly in the Archaean greenstone belts, and are therefore not considered in detail.

Given the above considerations, the major deposits and prospects select themselves. The relatively minor prospects and occurrences that are included in the database, and mentioned in the text, are selected on the basis of signs of old workings, the possible significance of geological setting, and the presence of sample material that has not necessarily been affected by surface enrichment and carries lead or zinc at concentrations of 1% or greater.

Relatively detailed descriptions of mines in the areas of historical production of lead–zinc–silver were included in the previous Bulletin. These were based on field examinations and included extensive references to earlier GSWA reports. No mines have been visited during the preparation of this revised Bulletin and descriptions of

such workings are not repeated in any detail unless relevant to genetic considerations. Production information has largely been tabulated. The reader is referred to the first Bulletin for the more detailed material.

Sources

The information compiled in this Bulletin has been summarized from a wide variety of relevant GSWA publications, including the most recent Mineral Resource Bulletins on lead, zinc and silver (Blockley, 1971), and copper (Marston, 1979), and the GSWA Bulletins dealing with the geology and mineralization of the tectonic units in which lead, zinc and silver deposits are preferentially located.

A second major source of information is the large archive of company mineral-exploration reports available in the Open File system at the GSWA. The computer-based WAMEX system enables this very extensive database (approximately 20 000 reports for 9000 mining tenements or tenement groups) to be accessed, searched and evaluated relatively quickly in a comprehensive manner. A broad variety of prospects and occurrences has been identified in the evaluation of open-file reports and an important overview of exploration strategies, both technical and metallogenic, has been obtained.

Confidential company information for important mines, deposits and prospects, which are currently being developed or explored, has been sought directly from the relevant companies. Contributions from some of these companies have been incorporated directly into the Bulletin, with company source and author indicated (e.g. sections on Whim Creek, The Sholl Belt, Panorama, Koongie Park, and Admiral Bay). These contributions refer to areas of high potential and new projects. They demonstrate innovative and successful exploration programs and highlight new geographical or conceptual target areas for which very little, or nothing, has been published to date.

Resource-targeted academic research has become increasingly valuable over the last twenty years in Western Australia through the efforts of the tertiary institutions, particularly the Key Centre for Strategic Mineral Deposit Research at the Geology Department of the University of Western Australia, and the School of Applied Geology at Curtin University. Information from various published regional and detailed studies, including geoscientific publications of GSWA, have been incorporated in this Bulletin.

Note

This Bulletin, because of its wide scope and size, has taken a significant period of time to assemble and produce. While every effort has been made to continuously update geological and mineral potential information, there have been numerous revisions to stratigraphy and terrane relationships (following recent regional mapping programs), and it was decided not to include many of these that would have further delayed publication. Revisions that have been included, for example in the Nabberu Province, are those that particularly affect the estimation of potential for lead, zinc and silver in these areas. In other areas, and particularly in those covered by the external contributions, stratigraphy and mineral occurrence nomenclature may not exactly coincide with recent GSWA publications, or those currently in press.

Layout

Following this introductory section of the Bulletin there are three sections of general information about the commodity group. The first briefly outlines the economic history of the group, including the history of recovery and usage of the metals and the methods of treatment and refining. Information on world production is followed by a history of exploration and production in Western Australia. The second details the abundance, mineralogy, chemical features and behaviour of the three metals while the third outlines a genetic classification of the deposit types found, or which may be found, in the State.

There then follows a description of the Western Australian geological setting, with particular reference to the main tectonic units which host lead–zinc–silver deposits and an outline of their distribution within these units.

In the previous Bulletin the known deposits, prospects and occurrences in the State were grouped for description by their geographical presence in gold or mineral fields or by land division. That procedure has been abandoned for this publication in favour of a grouping under deposit types. This has been facilitated by the greatly increased knowledge of the genetic aspects of lead–zinc–silver deposits and by the comparably improved levels of study and understanding of the Western Australian occurrences.

Four main deposit types are represented in the State: volcanogenic massive-sulfide deposits, clastic sediment-hosted deposits, carbonate sediment-hosted deposits and hydrothermal vein-type deposits.

The chapters that deal with each deposit type include an introductory section on the geology and distribution of that type within the State, and are then subdivided under the tectonic units which host these deposits. They may then be further grouped where geologically related deposits occur in a geographically defined district; for example, the Kooline group.

Information recorded for deposits and occurrences includes the following:

- name(s) and location;
- regional geological controls;
- ore-deposit geology, including lithological, stratigraphic and structural controls, and data on mineralogy, paragenesis, alteration styles;
- comments on genesis;

- exploration history (including current mining tenements and WAMEX cross reference), resources and production.

Finally, for each tectonic unit, current exploration and prospectivity is reviewed.

A final chapter deals with exploration trends in relation to target-deposit types, tectonic units, methods and research and concludes with a review of overall potential for further lead–zinc–silver discoveries in Western Australia.

Terminology and abbreviations

Abbreviations used in this Bulletin are defined below:

Mt	million tonnes (mega tonnes)
Ma	million years (mega anna) — date
m.y.	million years — time span
Ga	billion years (giga anna) — date
BMR	Bureau of Mineral Resources (*now* AGSO: Australian Geological Survey Organisation
GSWA	Geological Survey Division of the Western Australian Department of Minerals and Energy
CSIRO	Commonwealth Scientific and Industrial Research Organisation

In descriptions of exploration and other work on various projects company tenure is usually indicated thus: Billiton (1978–89). Dates indicated thus: (1992 on) indicate that the company is still active in the project and that WAMEX reports are therefore confidential.

Company names

AAR	Australian Anglo American Resources
Aberfoyle	Aberfoyle Exploration Pty Ltd
Academus	Academus Minerals Pty Ltd
Agnew *or* Garrick Agnew	Agnew Clough Ltd, Agnew Clough Pty Ltd, Garrick Agnew Pty Ltd
Alcoa	Alcoa of Australia Ltd
Allied Mins	Allied Minerals NL
Amad	Amad NL.
Amax	Amax Exploration Australia Inc.
Amoco	Amoco Minerals Australia Co.
Anaconda	Anaconda Australia Inc.
Aquitaine	Aquitaine Australia Minerals Pty Ltd
Arboyne	Arboyne NL
Arimco	Arimco NL, *now* Australian Resources and Mining Co. NL
Asarco	Asarco Australia Ltd
Ashling	Ashling Resources NL
Ashburton	Ashburton Mining Co. Pty Ltd
Anglo American, *or* Aust Anglo, *or* Australian Anglo Mines Ltd Anglo Australian Resources, *or* AAR	Australian Anglo American Services Pty Ltd Anglo Australian Resources NL
Anglo Westralian	Anglo Westralian Pty Ltd
Associated Mins	Associated Minerals Pty Ltd
Auridiam	Auridiam Consolidated NL *or* Auridiam NL
ACM *also* Acmin and Acmex	Australian Consolidated Minerals Ltd *and* Australian Consolidated Minerals Exploration Pty Ltd
Auselec *or* Seltrust	Australian Selection (Proprietary) Ltd
Aust Min Ventures *or* Aus Mins	Australian Mineral Ventures
Australian Hanna	Australian Hanna Ltd
Australian Inland	Australian Inland Exploration Company Ltd
Australian Ores and Minerals	Australian Ores and Minerals Ltd
Aztec	Aztec Mining Company Ltd *and* Aztec Exploration Ltd
Barrack	Barrack Mines Ltd *and* Barrack Exploration Pty Ltd
Barrier	Barrier Exploration NL *and* Barrier Pacific Resources Ltd
Billiton	Billiton Australia Pty Ltd
BHP	The Broken Hill Proprietary Co. Ltd *and* BHP Minerals Pty Ltd
BP *or* BP Minerals	BP Minerals Australia Pty Ltd
Burmine	Burmine Ltd
Callina	Callina NL *and* Callina Creek Mining and Exploration Pty Ltd
CEC	Carpentaria Exploration Company Pty Ltd (Mount Isa Mines Ltd)
Carr Boyd	Carr Boyd Minerals Ltd
Centenary Mining	Centenary International Mining Ltd
Century *or* Century Mining	Century Metals and Mining NL
Chevron	Chevron Exploration Corporation

Clackline	Clackline Ltd
Cominco	Cominco Exploration Pty Ltd
Command	Command Minerals NL
Conwest	Conwest (Aust) NL
CRA	CRAE Conzinc Riotinto of Australia Pty Ltd *and* CRA Exploration Pty Ltd
CSR	CSR Ltd
Cyprus Gold *or* Cyprus	Cyprus Gold Australia Corporation *and* Cyprus Minerals Australia Co.
Dalrymple	Dalrymple Resources NL *and* Dalrymple Exploration Services Pty Ltd
Dampier	Dampier Mining Company Pty Ltd
Delta	Delta Gold Exploration Pty Ltd
Dominion	Dominion Resources Pty Ltd
Duval	Duval Mining (Australia) Ltd
Eastmet	Eastmet Minerals NL
EZ	Electrolytic Zinc Co. of Australasia Ltd
Elmina	Elmina NL
Endeavour	Endeavour Oil Co. NL *and* Endeavour Resources Ltd
Esso	Esso Australia Ltd *and* Esso Exploration and Production Australia Inc.
Geopeko	Geopeko *and* Peko Wallsend Ltd
Geotechnics	Geotechnics Australia Pty Ltd
Giralia	Giralia Resources NL
Golden Deeps	Golden Deeps Ltd
Goldmines	Gold Mines of Australia Ltd *and* Gold Mines of WA Ltd
Great Boulder	Great Boulder Mines Ltd
Griffin	Griffin Coal Mining Company Pty Ltd
Group Explorations	Group Explorations Pty Ltd
Hamersley Exploration	Hamersley Exploration Pty Ltd
Hancock and Wright	Hancock and Wright Prospecting Pty Ltd
Hanna	*see* Australian Hanna
Hawkstone	Hawkstone Investments Ltd
Haoma	Haoma North West NL
Herald Res	Herald Resources Ltd
Homestake	Homestake Australia Ltd
Inco	International Nickel Australia Ltd
Indian Ocean Res	Indian Ocean Resources Ltd
Jays Exploration	Jays Exploration Pty Ltd
Jennings Mining	Jennings Mining Ltd
Jilbadgi Gold	Jilbadgi Gold Mining Co. NL
Jododex	Jododex Australia Pty Ltd
Kennecott *or* Kennco	Kennco Exploration (Australia) Pty Ltd
Kalgoorlie Southern Goldmines	Kalgoorlie Southern Gold Mines NL
Kia Ora Gold	Kia Ora Gold Corporation NL
Leopold Minerals	Leopold Minerals NL
MC Mining	MC Mining NL
Meekal	Meekal Pty Ltd
Metals Ex	Metals Exploration Ltd
Metana	Metana Minerals NL
Mines Admin	Mines Administration
Mines Ex	Mines Exploration Pty Ltd
Miralga Mining	Miralga Mining NL
Moder	Moder EM and HF
Moonbeam	Moonbeam Nominees Pty Ltd
Mount Martin	Mount Martin Gold Mines NL
Mount Newman	Mount Newman Mining Company Pty Ltd
MIM	Mount Isa Mines Exploration Pty Ltd, *see* CEC
Narla	Narla Minerals NL
Newmont	Newmont Pty Ltd
Newmex	Newmex Exploration Ltd
NGM	NGM Pty Ltd
Nord	Nord Australex Nominees Pty Ltd
Norseman Gold	Norseman Gold Mines NL
N Flinders *or* North Flinders	North Flinders Mines Ltd
Orion	Orion Resources NL
Otter	Otter Exploration NL
Outokumpu	Outokumpu Exploration Australia Pty Ltd
Pancon *or* Pancontinental	Pancontinental Resources (Exploration) Pty Ltd
Pegmin	Pegmin Ltd
Peko	Peko-Wallsend Ltd *and* Peko Exploration Ltd
Pennzoil	Pennzoil of Australia Pty Ltd
PMI	Pickands Mather and Co. International
Pioneer	Pioneer Minerals Australia Ltd *and* Pioneer Resources NL
Placer	Placer Prospecting Pty Ltd *and* Placer Exploration Ltd
Planet	Planet Resources Group NL
Polaris Pacific	Polaris Pacific NL

Poseidon	Poseidon Ltd *and* Poseidon Exploration Ltd
Preussag	Preussag Australia Pty Ltd
Project Mining	Project Mining Corporation Ltd
Regional Resources	Regional Resources NL
RGC *or* Renison	Renison Ltd *was* Consolidated Gold Fields Australia Ltd
Richenda	Richenda Minerals NL
Roebuck	Roebuck Resources NL
RT Min Corp	RT Mining Corporation Pty Ltd
Samantha	Samantha Exploration NL
Samin	Samin Australia Pty Ltd
Sanidine	Sanidine NL
Seltrust	Seltrust Mining Corporation Pty Ltd *also see* Auselec
Serem	Serem (Australia) Pty Ltd
Sipa	Sipa Resources Ltd
Southwest Goldmines	Southwest Gold Mines NL
Sovereign Res	Sovereign Resources Pty Ltd
Stratin	Stratin Minerals Pty Ltd
Stratem	Strategic Minerals Corporation NL
Texasgulf	Texasgulf Australia Ltd
Troy Resources	Troy Resources NL
Tycho	Tycho Mining
UCABS	UCABS Pty Ltd
Unimin	Union Miniere Development and Mining Corporation Ltd
Union Oil	Union Oil Development Corporation
UAL *or* Uranerz	Uranerz Australia Pty Ltd
Utah	Utah Development Co. Ltd
WA Metals	West Australian Metals NL
Walgardy	Walgardy Pty Ltd
West Australian Metals	West Australian Metals NL
WC Holdings	West Coast Holdings NL
Westfield *or* Westfield Mins	Westfield Minerals (WA) NL
WMC	Western Mining Corporation Ltd
Whim Creek	Whim Creek Consolidated NL

Chapter 2

Economic history

Background and uses

Lead and zinc are two of the more common of the base metals; they are neither noble (gold, silver and platinum) nor ferrous (iron and manganese). Silver is a noble metal but is commonly associated with lead and zinc in nature. Lead and zinc also share an association with copper, another common base metal.

Lead, zinc and silver are among the oldest metals known to, and used by, man and are important in the history of mankind and the development of modern industrial society. Lead, particularly, with its softness, malleability and resistance to corrosion, was used in Roman and earlier times in plumbing, sewerage and in structural cladding. The early use of zinc, from about 2000 BC, was primarily in the manufacture of alloys such as brass (copper–zinc alloy). Silver acquired early value and use in coinage, jewellery, and other ornamental applications.

Lead has a wide range of uses but its current main use (>60%) is in lead storage batteries (for aircraft, motor vehicles etc.). Other uses include tetra-ethyl lead as an additive in petrol (declining use), red-lead coating for construction steel, coatings in electrical and telecommunication cables, radiation shielding, lead foil, lead shot, solder, paints, dyes, explosives, insecticides, type metal for printing (declining use), sound proofing, and rubber products.

Zinc is used mainly (>45%) as a coating to protect iron and steel from oxidation (galvanizing) but is also used in the manufacture of brass (>20%), in die casting (15%), in car bodies, grills and trim, in fences, household appliances and fittings, dry cell batteries, cosmetics, plastics, rubber products, soaps, paints and inks.

Silver is used in photographic film and developing paper, silverware, jewellery, industrial refrigerators, coinage, batteries, electronic solder in aircraft, and in mirrors.

World production

Among the nonferrous metals zinc and lead are third and fourth in terms of world demand. World zinc production in 1994 was 6 825 000 tonnes (t), lead production was 2 700 000 t and silver was 13 847 t.

China was the world's leading producer of zinc in 1994 with 1 017 000 t, followed by Japan, Germany, the US and Australia. In the 18th and 19th centuries most of the world's zinc production was centred in Europe. The position of the US, the dominant producer between 1901 and 1970, has declined recently due both to the closure of many smelters for environmental and technical reasons, and to the post-World War II rise of smelting and production in Australia, Canada, Japan and China.

Australia was the leading producer of lead in 1994 with 486 000 t, followed by China, US and Peru.

Mexico, the US and Peru dominate world production of silver followed by Kazakhstan, Canada and Russia.

Historically, in world production, lead and zinc have followed parallel rising trends with dips during the post-World War I slumps of the 1920s and 1930s, and following World War II in the latter part of the 1940s. Silver, because of its intrinsic value in currency and jewellery, has followed a more level trend (Figs 1, 2, and 3).

Recent trends have seen a peaking of world consumption of lead and zinc in 1989, partly due to the world recession and, in the case of lead, partly due to environmental concerns. With production remaining steady, in excess of demand, prices have experienced downward pressure. Demand for silver has also been affected by recession, leading to falling prices since 1989. The steady rise in world silver production in the 1980s came to an end in 1992 in response to the falling price and to a build-up of stocks.

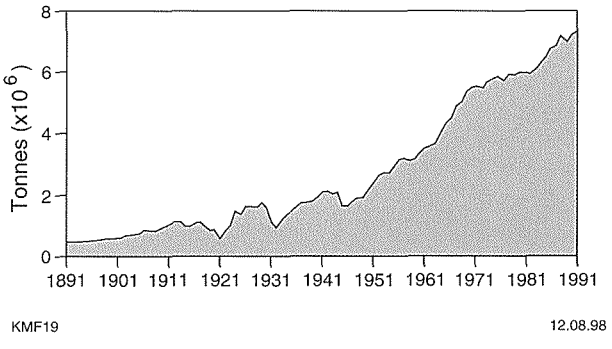

Figure 1. Historical world zinc mine production

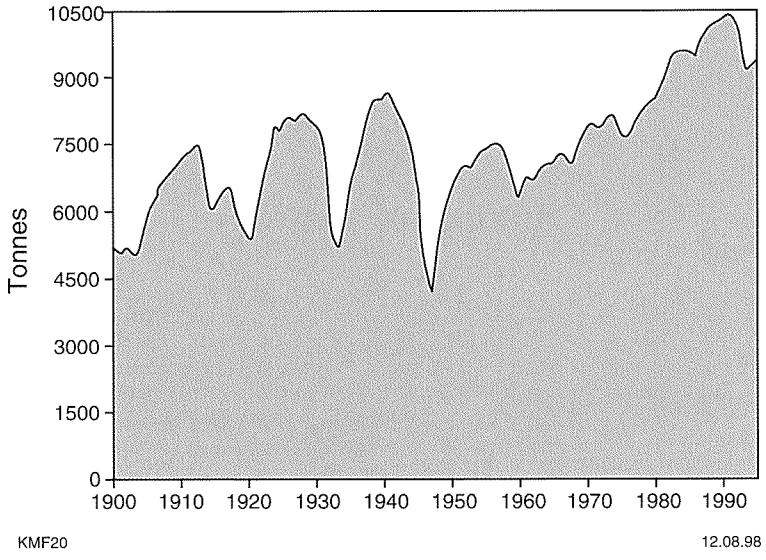

Figure 2. Historical world silver mine production (excluding Communist areas)

World resources of zinc are presently at about 1500 Mt and reserves at 140 Mt. About 37 Mt of the reserves are in North America while Australia accounts for some 17 Mt. Western Australia has resources of 4.87 Mt.

World resources of lead are presently at about 1500 Mt and reserves at 68 Mt. Australia has the highest national reserves of lead at 19 Mt while Canada and the US together have 12 Mt. Western Australia has resources of 2.64 Mt.

World reserves of silver are presently at 280 000 t with Mexico and Peru collectively holding 62 000 t. Australian resources stand at about 24 000 t of which Western Australia holds 3133 t.

Western Australia: history of exploration and production

Figures 4 and 5 summarize lead–zinc–silver production in Western Australia since 1840. Blockley (1971; table 1) summarized the annual lead and zinc production for Western Australia from 1850 to 1968, and Table 1 lists the annual production from 1968 to 1996.

Lead was first discovered in Western Australia in the Darling Ranges at the Mundijong prospect in 1846, but the first production came from the Geraldine mine in the Northampton area, on the Murchison River, in 1850. This deposit, in the bed of the river, was discovered in 1848 during exploration by A. C. Gregory's party and was the first mine to be opened in the State. Further lead and copper deposits were then discovered in the Northampton area and mined between the 1850s and 1880s during a 'boom' period which came to an end in the late 19th century with the discovery of gold elsewhere in the State and declining base-metal prices.

Blockley (1971) reports that from 1850 to 1899, a total of 34 140.2 t of lead ore grading between 65 and 70% Pb was exported from the Northampton field. During the same period, 696.9 t of smelted lead was exported from the Geraldine mine.

In this early period, prior to 1900, exploration was a direct process based mainly on the recognition of outcropping ore, particularly in greatly enriched secondary accumulations. Often discoveries were made in the process of more general, geographical and rural exploration or as a by-product of the search for gold and silver. Lead and silver grades were commonly very high, as at Northampton, leading quickly to relatively simple mining and processing.

A second major period of lead mining, between 1910 and 1930, was driven by another rise in metal prices related to the First World War. This again came largely from the Northampton field with the biggest producers being the Baddera mine, the Narra Tarra mine and the Surprise mine. During this period there was some contribution from the Braeside group of mines, discovered in the eastern Pilbara around the turn of this century. The Uaroo and Narlara deposits, in the Gascoyne and Lennard River areas, were also discovered at this time. Overall, there was little exploration in this period, with mines discovered by the early 1900s providing the bulk of the production. However, in the eastern states some initiatives were undertaken which would be important in the future. Detailed mapping and reinterpretation of the Broken Hill lode in the late 1930s led to the recognition of sedimentary ore deposits and signalled the development, in the 1940s and 1950s, of genetic concepts beyond the simplistic 'ascending solutions' (Legge and Haslam, 1990). Also, geophysical surveys began to be used in the 1930s and the Commonwealth government-sponsored Aerial Geological and Geophysical Survey of Northern Australia (AGGSNA) carried out some valuable pioneering work.

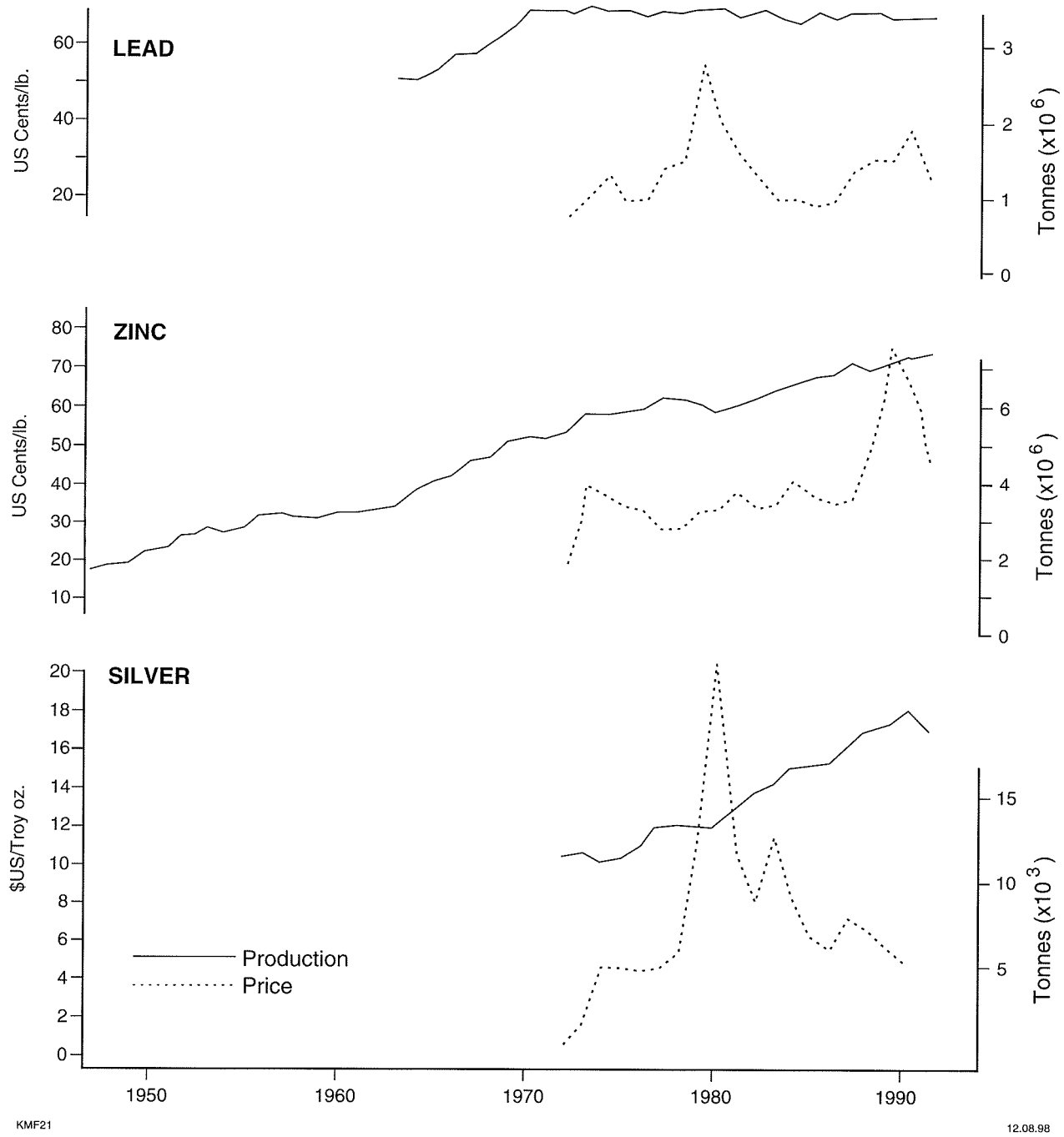

Figure 3. Recent world production (and prices) of lead, zinc and silver

Prices again rose in the late 1940s to late 1960s following the stagnation of the war years. This period saw the last phase of production from the Northampton field. Most mines were worked out and closed by the end of the 1960s but sporadic production continued until 1973 at Mary Springs, Wheal Ellen, and Nooka.

A combination of the development of more sophisticated concepts of ore genesis, particularly for sedimentary ores and volcanogenic ores, and the development of new exploration techniques, saw a rejuvenation of mineral exploration in Australia from 1945, and particularly between 1960 and 1972. The GSWA and the new Bureau of Mineral Resources began promoting regional mapping, and aeromagnetic and metallogenic studies. Following successes in Canada and Sweden electromagnetic (EM) surveys began to be used in the 1960s to detect the sulfide bodies associated with lead–zinc mineralization. Also in the 1960s, the development of rapid chemical analyses by atomic absorption spectrometry revolutionized regional geochemical studies by providing cheap, accurate and quick analysis of base metals.

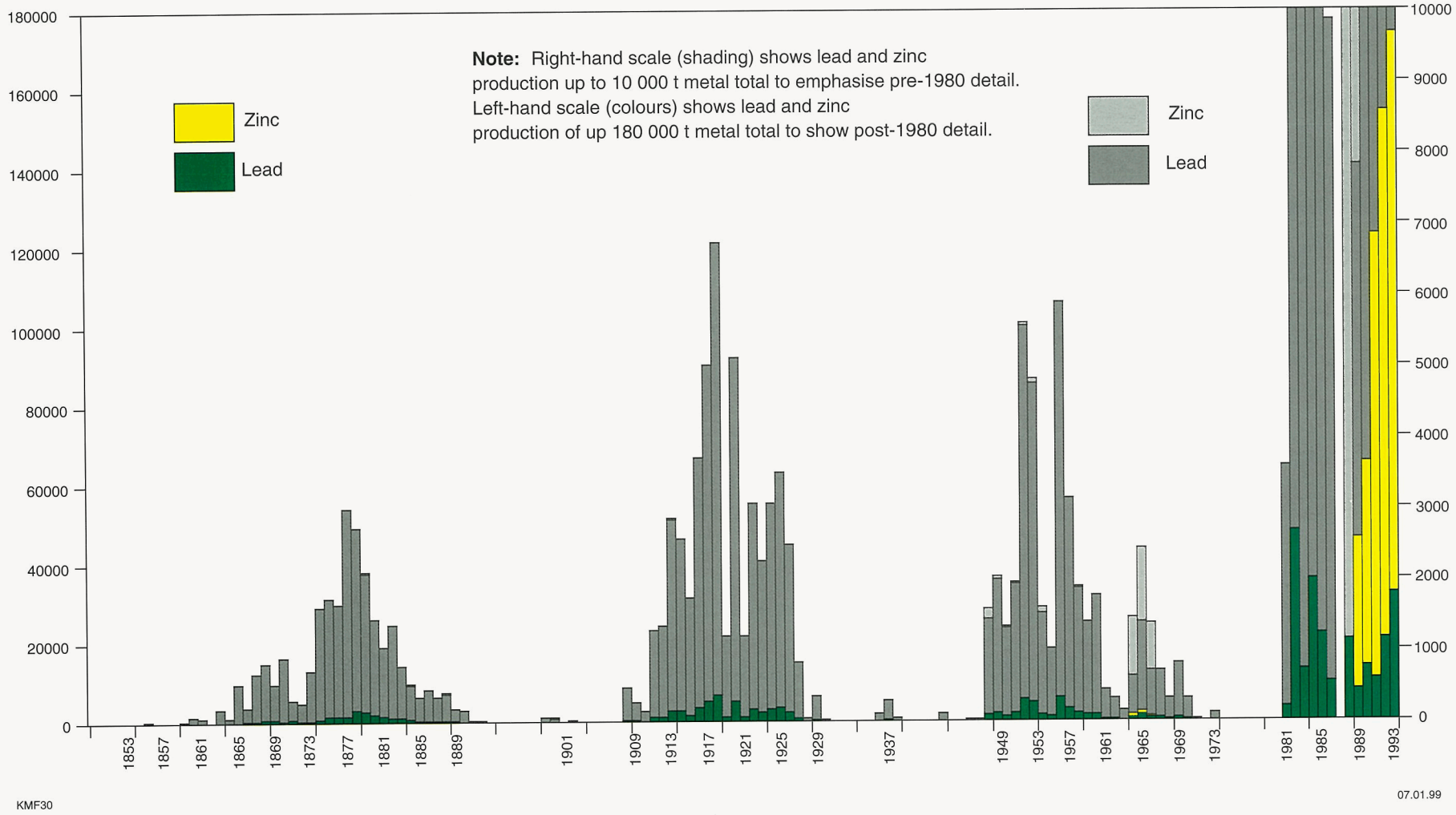

Figure 4. Lead–zinc production in Western Australia

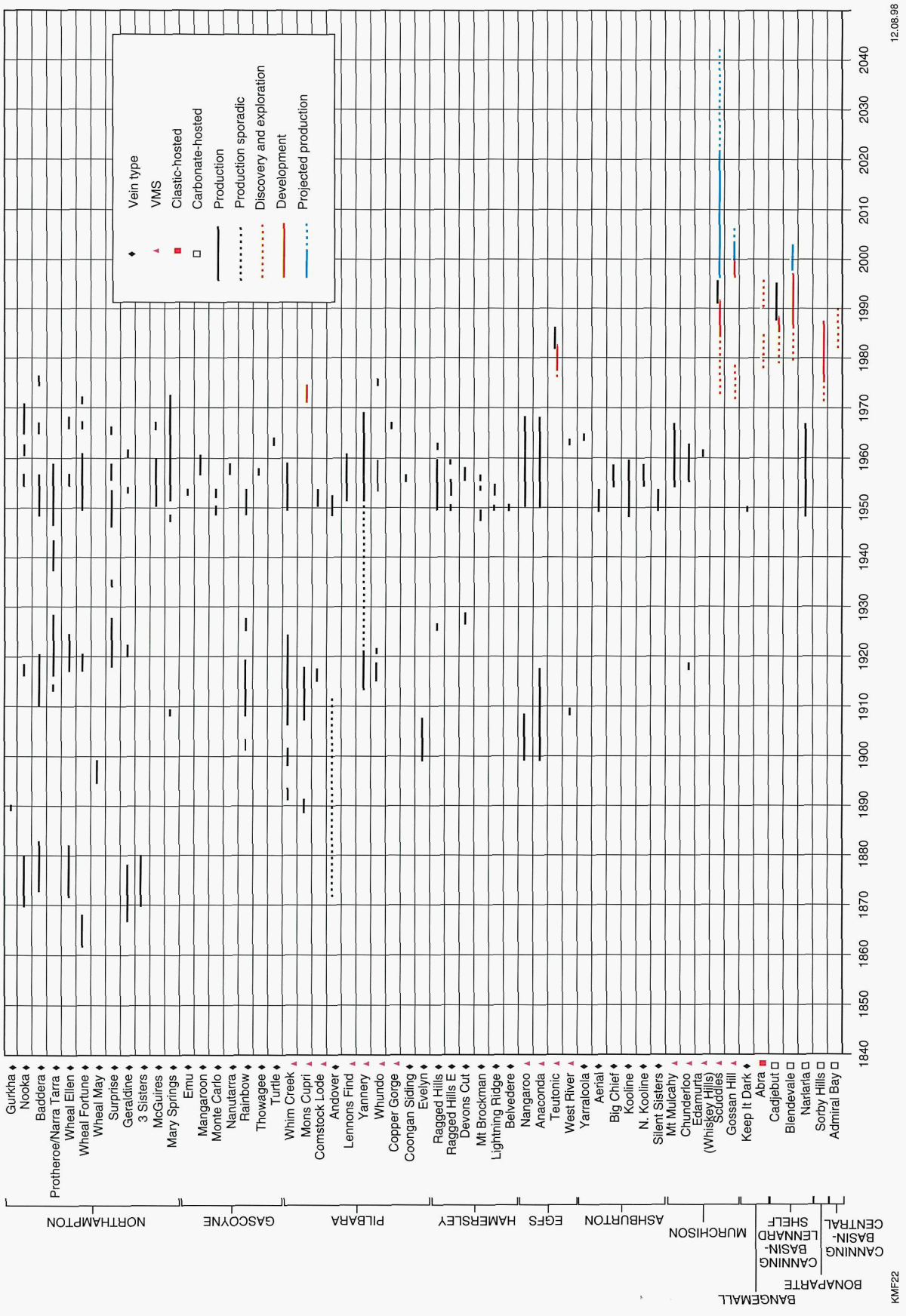

Figure 5. Historical and present development and mining of lead–zinc–silver in Western Australia

Table 1. Annual production of lead and zinc 1968–1996

Year	Ore and concentrate Pb (t)	Lead metal (t)	Ore and concentrate Zn (t)	Zinc (t)
1968	424.31	315.99	–	–
1969	1 122.05	818.96	–	–
1970	483.99	306.20	–	–
1971	41.05	21.53	–	–
1973	149.12	101.74	–	–
1981	–	–	10 129.00	3 613
1982	–	–	101 787.00	48 018
1983	–	–	26 455.00	13 158
1984	–	–	70 431.00	35 640
1985	–	–	51 977.00	21 936
1986	–	–	23 969.00	9 886
1988	–	–	36 800.00	20 250
1989	11 211.00	7 846.00	72 786.00	38 064
1990	19 014.00	13 606.00	104 866.00	51 704
1991	14 543.00	10 698.00	249 655.00	112 015
1992	26 431.00	20 964.00	295 159.00	141 385
1993	39 791.00	32 276.00	283 267.00	141 096
1994	25 402.00	20 287.00	253 512.00	123 621
1995	19 675.00	15 642.00	250 298.00	126 336
1996	22 364.00	17 085.00	213 064.00	104 230

The Narlarla mine, which began operating in this period (1948 to 1966), was the State's first recorded producer of zinc. Earlier, zinc was seldom recovered from mines, such as those in the Northampton area, where it was present. This was due to lack of demand and poor extraction methods. Narlarla produced 2866.1 t of metal.

Silver has been extracted predominantly as a secondary by-product of lead–zinc, copper, and gold ores in Western Australia. Only at the Uaroo mine has it been mined for a period in its own right. Silver grades were low in the Northampton lead–zinc ores with only 212 297.57 g produced. The lead mines of the Gascoyne Complex and Ashburton Basin, however, produced 2 118 453.3 g of silver between 1901 and 1967 and the Ragged Hills mine in the Braeside field produced 873 802.71 g in the 1950s. The Narlarla mine produced 1 162 412.4 g.

Recognition of the potential for Mississippi Valley-type, epigenetic, carbonate-hosted lead–zinc mineralization in the Canning and Bonaparte Basins followed regional mapping by the BMR and GSWA (Matheson and Guppy, 1949; Playford and Lowry, 1966) the drilling of oil exploration wells giving stratigraphic control, discoveries of galena, and studies of the known Narlarla deposit. While engaged in petroleum exploration, Aquitaine, in 1970, drilled oxide and sulfide outcrops to discover the Sorby Hills deposit. A number of companies explored the Lennard Shelf of the Canning Basin in the early 1970s but it took a major concerted effort from 1978 over a large tenement area by Shell/BHP before significant mineralization was discovered at Blendevale, and subsequently Cadjebut, in the Pillara area. This led to the opening of the Cadjebut mine in 1987. From 1989 to the end of 1992, 71 199 t of ore concentrate have yielded 53 112.08 t of zinc and 53 433.57 t of lead.

Modern exploration specifically targeted at volcanogenic copper–zinc–lead mineralization in Australia began in 1963–64 around Whundo–Yannery mines in the west Pilbara by Westfield Minerals (I 3227*). Drilling by Texas Gulf at Mons Cupri intersected massive sulfides essentially similar to Canadian volcanogenic deposits. Big Stubby in the east Pilbara was first evaluated in 1968 and drilled in 1971 (*see* under Duffer Creek *in* Blockley, 1971). Other previously known related prospects in the Pilbara, such as Lennons Find, were properly evaluated at this stage.

The potential for volcanic-associated massive-sulfide (VMS) deposits in the Murchison Province of the Yilgarn, through association with Canadian deposits, led to the discoveries by Aztec of the Gossan Hill Cu–Zn and the Scuddles Zn–Cu deposits in 1971 and 1979 respectively. Detailed mapping and surface sampling of favourable lithologies, alteration styles and gossans led to the recognition of the potential of a specific unit. Further concentrated sampling, EM surveys and deep geochemical drilling located deposits with no direct surface expression. Mining finally commenced at Golden Grove in 1990, and in the six years of operation until the end of 1996, 903 245 t of concentrate have yielded 370 870.21 t of zinc and 105 390 kg of silver.

These discoveries further stimulated a very active phase of VMS exploration in the Yilgarn from 1971 which, with other lead–zinc exploration, was increasingly dominated by big base-metal producers using systematic, sequential, scientific exploration based on high-quality geological mapping and geophysical surveys. The GSWA played a major part with coordinated regional mapping covering the whole state during the 1970s and early 1980s, and more specific mapping and metallogenic studies in the Pilbara, Murchison, and Eastern Goldfields.

The Teutonic Bore volcanogenic zinc deposit was discovered by CEC and Australian Selection (I 4029) in 1974–76 in the Eastern Yilgarn (again, following a conceptual model) and a modern era of mining was ushered in with the commencement of openpit mining in 1981. Mining was completed in 1984 but stockpiled ore continued to be treated until 1986. A total of 284 748 t of ore were treated for 132 251 t of zinc and 149 307 kg of silver.

From 1974, exploration has been affected by indifferent base-metal prices, although a brief resurgence peaked in 1980 following a period of high profits for oil companies with mineral subsidiaries. From the mid-1970s, there has been an emphasis on exploration for volcanogenic targets in the Archaean, clastic-hosted deposits in the Proterozoic and carbonate-hosted deposits in the Palaeozoic, all of which have potential for large tonnage and moderate to high grades of lead and/or zinc. The parameters of these target types are better known and a high degree of technical, academic and field expertise characterizes much exploration. The semi-regional studies carried out by the GSWA are complemented by university-based detailed studies of particular deposits and

* I3227 is the I number for a project group of open-file exploration reports in the DME's WAMEX database. The number identifies the appropriate microfiche in the Geological Survey library. Appendix 1 lists the I numbers referred to in this Bulletin.

geologically critical areas. Increasingly accurate geochronological studies, from a number of sources, are also contributing to the establishment of metallogenic patterns.

Problems still remain with the elucidation of the complex and varied effects of deep weathering in the Western Australian terrain. This affects both geochemical and geophysical exploration. Thick conductive overburden limits the effectiveness of electromagnetic systems and geochemical surveys must be carefully controlled.

The unusual physical and chemical nature of the surface mineralization was highlighted, however, when successful exploration revealed further volcanogenic mineralization in the greenstones of the Pilbara Craton in the Panorama project area. It had been thought that sufficient attention had been given to this area in relation to this type of target.

Westfield Minerals commenced modern exploration for clastic-hosted copper, lead, and zinc mineralization in the Bangemall and Asburton basins in 1965 (I 3227, 4641). In the Bangemall Basin the Abra deposit was intersected in the early 1980s, following a program of conceptually based exploration looking at the right combination of stratigraphy and structure, and drilling a geophysical target beneath 260 m of cover. The Abra discovery, in particular, highlights the importance of geophysical methods in base-metal exploration to generate drill targets in prospective environments *(see* **Chapter 9, Geophysics**).Clastic-hosted mineralization has also been located in the Yeneena Basin, at Nifty and Maroochydore, and in the Glengarry Basin at Magellan.

The Ordovician carbonate-hosted lead–zinc–silver mineralization at Admiral Bay in the Canning Basin was discovered in the early 1980s in a petroleum well and subsequently intersected by CRA beneath 1280 m of cover.

The recent upsurge of lead and zinc mining in Western Australia defies the downward international trend of the late 1980s and early 90s. This is in part because the two mines responsible, Cadjebut and Scuddles, were planned when projections were still relatively optimistic (Townsend, in prep.).

Relatively recently developed exploration techniques with applicability to base metals include the use of satellite imagery to define stratigraphic and structural features, and also to help recognize zones of alteration of the kinds typically related to various types of mineralization.

Research at both CSIRO and the Geochemistry Research Centre (Mann et al., 1993) may also prove useful in the remote detection of ore zones at depth by sensitive measurements of soil gas and groundwater.

Beneficiation of ores

Blockley (1971) summarizes the treatment of lead and zinc ores to that time noting that, due to the limited size of the deposits, methods of concentration of the ores had reached little refinement. Crushing plants with gravity concentrators were located close to the mines and separation of complex ores was achieved only where they were rich enough to be hand sorted.

The early use of mine-based smelters in the Northampton area failed owing both to the lack of sufficient ore and the shortage of natural fuel. A later attempt, in Fremantle, to smelt lead ores in combination with gold ores from Kalgoorlie also failed, but the smelters were subsequently used to successfully treat lead ores alone in the period 1915 to 1923.

Following the closure of the Fremantle smelter, at a time of low lead prices after the First World War, all lead, zinc and silver ore mined in the State was shipped interstate or overseas for treatment.

Ore from the Teutonic Bore mine was concentrated on site in a flotation plant. In this process the ore from the mine is crushed and finely ground. The sulfide minerals are then separated from the waste material in an agitated mixture of water and chemicals that causes the sulfide to adhere to bubbles which float to the surface. Lead–copper and zinc can be floated off separately in this process. These are then skimmed off and dried. This produces a concentrate of about 50% metal, also containing silver. The concentrate from Teutonic Bore was sent to EZ's Risdon refinery in Tasmania where zinc was produced by the electrolytic process. In this process the roasted concentrate is leached with sulfuric acid to form zinc sulfate solution. This is then purified of other contained metals and piped to electrolytic cells where the zinc is deposited on aluminium cathodes. It is then melted and cast into slabs. Lead bullion, containing silver, is separated in this process.

At Golden Grove–Scuddles (Murchison Zinc Co. Pty. Ltd.) copper, zinc and silver concentrates are produced by flotation at the mine site and exported through Geraldton. The zinc concentrate typically contains about 51% Zn, while the copper concentrate contains about 20% Cu, 2000 g/t Ag and 11.5 g/t Au.

At Cadjebut (Western Metals Ltd.) lead and zinc concentrates are produced by flotation and exported through Wyndham to be smelted in Korea and Holland. The lead concentrate averages about 75 to 80% Pb and the zinc concentrate averages about 60% Zn.

Chapter 3

Geochemistry and mineralogy

Properties and abundances

Lead

Lead, atomic weight 207.19 and atomic number 82, can be bivalent or tetravalent. There are four stable isotopes, Pb^{204}, Pb^{206}, Pb^{207} and Pb^{208}, and four short-lived isotopes, Pb^{210}, Pb^{211}, Pb^{212} and Pb^{214}. All but Pb^{204} are the product of radioactive decay of uranium or thorium.

In the Earth's crust bivalent lead is more common than the tetravalent form. The ionic radius of Pb^{2+} is between 1.18 and 1.32 angstrom (Å). Because of its similar size lead has a pronounced tendency to replace potassium in silicate minerals, and may also replace strontium, barium and even calcium or sodium. Lead is thus a common constituent of potassium feldspars and micas and to a lesser extent of plagioclase, amphiboles and pyroxenes. These lithophile characteristics contrast with a more chalcophile affinity for sulfur reflected in the common occurrence of lead as the sulfide galena (PbS). Lead, however, tends to be excluded from early-forming potassium minerals and is enriched in late-forming potassium feldspars whose lead contents average 100 ppm in pegmatites and may be as high as 1300 ppm.

Lead is the most abundant of the heavy elements (atomic number >60) in the crust, with an estimated mean of 12.5 ppm due partially to relatively high cosmic abundance. Lead has also been concentrated in the crust as a product of the long-term radioactive decay of uranium and thorium, both elements that are highly enriched in the crust. This process is estimated to have produced one-third of the present crustal lead content (Wampler, 1972). Finally, the close association of lead with potassium in potassium feldspars and micas means that it is progressively concentrated in more felsic melts, and therefore in the upper crust, during magmatic differentiation.

This is reflected in the distribution of lead within the common igneous rock types in the crust. Partial melting of ultramafics, for example, produces basalt which is enriched in lead (compared with the source material) by a factor of 20. Because of the close chemical relationship with potassium, lead levels increase through the sequence oceanic tholeiitic basalt, tholeiitic basalt, alkali olivine basalt, from an average of 0.8 to 4.3 ppm Pb (Wedepohl, 1974a). This potassium-related trend continues, more or less evenly, through andesite (5.8 ppm Pb) and alkalic intrusives to granitic intrusives (23 ppm Pb). Rhyolite contains about 24 ppm Pb.

Lead in detrital sediments is contained predominantly in feldspars and mica. Some lead, liberated during weathering, is adsorbed onto clay minerals and ferric iron oxides. Sand and sandstone average about 10 ppm Pb whereas shale and clay contains about 23 ppm Pb. The efficiency of sulfide precipitation of lead commonly leads to enrichment in some black shales formed in reducing conditions (20–100 ppm Pb). The lead may be in pyrite or galena, or within organic residues. Carbonate sediments are low in lead (about 5 ppm), this mainly in the silt/clay fraction.

The lead content of metamorphic rocks depends mainly on the nature of the original rock. The highest contents are in potassium-rich mica schists and gneiss and are similar to those of granitic rocks.

Zinc

The geochemistry of zinc, atomic weight 65.37 and atomic number 30, is largely dictated by its single, bivalent oxidation state.

It can be considered both lithophile and chalcophile, being commonly incorporated in the structures of silicate minerals, but also showing a marked affinity for sulfur at ore-level concentrations. In silicate minerals, and oxides, zinc substitutes for ferrous iron and magnesium by favouring tetracoordinated positions. Fe^{2+} and Zn^{2+} have the same ionic radius (0.74°Å). Zinc is commonly found in high concentrations in magnetite in basaltic–gabbroic rocks (1000–4000 ppm), and in granitic rocks predominantly contained in biotite at about the same concentration range (Wedepohl, 1974b). In terms of crustal abundance these associations are much more important than that of zinc with sulfide in ore deposits. The predominant zinc sulfide, sphalerite, is found in some igneous rocks, notably in basalt and gabbro, but in general zinc is only a minor constituent of early pyrrhotite–pentlandite-dominated sulfidic differentiates from magmas, preferably concentrated in the residual melts and late hydrothermal phases together with lead and copper. The affinity of zinc for the sulfide phase is lower than that of iron, nickel, cobalt and copper.

The estimated mean crustal abundance of zinc is about 70 ppm. Concentration in the latter phases of magmatic crystal differentiation leads to a predominance in the upper crust. Occurring largely as a trace element in common minerals, zinc averages between 40 and 80 ppm in

ultramafic rocks, and 80 to 100 ppm in gabbro, basalt, alkalic rocks, diorite and andesite. In granitic rocks, where the zinc content is largely in biotites, levels are higher in the darker varieties, but the average is around 50 ppm with most in the range 20 to 90 ppm Zn. For rhyolite, liparite and obsidian the average is twice as high.

Zinc is deposited in the sedimentary environment primarily as a result of the chemical weathering of magmatic and metamorphic rocks. It is accumulated in a detrital, iron-rich fraction and is most abundant in shales and greywackes (about 100 ppm) in proportion to their iron content. In bituminous 'black' shales, however, zinc is fixed from sea water by degraded organic material, by sulfides and by phosphates within the reducing environment. Levels of up to 5000 ppm of zinc, in the form of sphalerite, are present in the Upper Permian 'Kupferschiefer' in Europe. About 200 ppm is a more likely concentration for zinc in black shales formed in less unique conditions. Pelagic clay has zinc in the range 130 to 150 ppm with some zinc in association with manganese nodules in the clays. Limestone contains some 20 ppm Zn, about half of this within silt and clay residues. Quartz sandstones and arkose contain about 30 ppm Zn.

Metamorphic rocks contain zinc more or less in proportion to their original rock types. Mica schist and gneiss average about 65 ppm Zn.

Silver

Silver, atomic weight 107.88 and atomic number 47, is predominantly univalent in compounds and as an ion.

Silver is most closely associated with the other elements of the subgroup IB, copper and gold, and is a major constituent of several relatively rare minerals associated largely with ore deposits. Many of these are sulfides demonstrating silver's strong chalcophile affinity. This affinity is also seen in the variable to high content of silver in the sulfides of other elements, most notably argentiferous galena, sphalerite and pyrite. Silver also forms antimonides, arsenides, tellurides and sulfosalts and is found as the native element, or in solid solution with gold, copper, tellurium or antimony. In rock-forming minerals, silver is a trace constituent and has no obvious relationship with any other elements in the common silicates.

The estimated mean abundance of silver in the crust is roughly 0.1–0.2 ppm, placing it about seventy-second in the abundance list of elements. The distribution of silver in igneous rocks, with levels ranging from 30–40 ppb in granites to 50–190 ppb in basalt and gabbro, probably reflects no chemical affinity other than the chalcophile association with sulfides, which are more abundant in the mafic rocks.

These associations also explain the high levels of silver (≤10 ppm) in black shale, which contains carbonaceous matter and fine-grained pyrite. Silver levels in ordinary shale, sandstone, limestone and evaporites are low (50–300 ppb). Silver of probable syngenetic origin, and at the level of low-grade ore, is found in the Permian 'Kupferschiefer' of Germany and Poland where it is intimately associated with copper sulfides, galena and sphalerite.

In metamorphic rocks silver appears to be concentrated in copper or iron sulfides and in ferromagnesian minerals. It is also evident in late-stage veins and other features of the latter part of the metamorphic and granitization process. Its chalcophile nature will presumably determine an association in metamorphic processes with sulfur, arsenic, antimony, gold, lead, zinc, copper and cadmium.

Primary ore-forming (concentration) processes

The details of the formation of the various types of deposit of lead, zinc and silver will be looked at in the following chapter under deposit classification. However, it is appropriate here, within the general discussion of the geochemical properties and affinities of these metals, to summarize the concentration processes that play a part in the formation of deposits.

It can be observed that lead, zinc and silver, through their lithophile and/or chalcophile affinities, become concentrated during the processes of magmatic differentiation into the more acidic phases of the magma and finally into the late melts and volatile phases. The partitioning of lead and zinc from silicate melts of granitic composition into the vapour phase has been shown to be aided by the presence of chloride in the latter. The metals may then be further concentrated, in the case of intrusive igneous rocks by hydrothermal and autometasomatic processes, and deposited as sulfides in vein systems in appropriate structural and lithological sites in the magmatic halo. The lead, zinc and silver will tend to be deposited in an outer zone, separate from an inner zone of pyrite and copper sulfides.

This may be the only situation in which the direct magmatic source of the metals can be unequivocally assigned. In intermediate to felsic extrusive belts, the formation of copper–zinc and copper–zinc–lead hydrothermal/exhalative massive-sulfide deposits may reflect a direct magmatic source. Alternatively, these deposits may reflect the leaching of metals from the volcanic pile by hydrothermal fluids which are either essentially sea water being convected above the volcanic heat source, or a combination of meteoric water and magmatic, pre-enriched hydrothermal fluids. Magmatic vapours, hot brines and connate waters cannot always be easily distinguished.

The leaching of lead, zinc and silver from the volcanic sequences which host this type of deposit in sufficient quantities to lead to the formation of ore deposits depends on the chemical and physical properties of the fluids. At the probable temperature range of 100° to 250°C, the presence of chloride has once again been shown to facilitate the process. Lead and zinc readily form chloride and bisulfide complexes in hydrothermal solutions when

they are released from their host silicate minerals or are present in the form of sulfides. Silver is, in all probability, largely mobilized in similar complexes.

Similar processes are likely to control the leaching of lead, zinc and silver from sedimentary sequences, by hot brines of whatever provenance.

In the volcanic-associated situation, the location of ore deposition would be controlled by the position of the convective heat source in relation to structures which would facilitate the upward flow of the metalliferous solutions to the sea floor.

In the sedimentary situation, basin geometry and structure would be important in focusing the fluids, either to the surface in the case of sedimentary exhalative deposits, or to favourable host lithologies and chemical environments within the pile.

Mobility of lead–zinc–silver in the supergene zone

In this section, the role of weathering and transport in both the concentration and dispersion of lead, zinc and silver within the supergene zone is examined. In contrast to the previous section this is dealt with particularly in relation to the variety of supergene and regolith environments found in Western Australia. A number of studies of specific environments and known base-metal prospects and deposits have been carried out over the past 15 years. These provide a guide to the processes and are an essential aid to geochemical exploration for these deposit types.

Regolith in Western Australia is often thick and variable reflecting the processes of deep weathering, residual accumulation, erosion and sedimentation. This environment can result in the enrichment of base metals at the surface, particularly in the formation of gossans over sulfide accumulations, or in their dispersion and/or concealment. Most studies so far have dealt with regolith concentration and dispersion patterns in the Archaean cratons in relation to gold and base metals. Butt et al. (1993), in summarizing trends for the Eastern Goldfields, indicated that lateritic weathering under warm humid conditions has led to a progressive weathering of sulfides during which mobile elements like zinc and copper are leached. Mobile elements include S, Na, Cs, Ca, Mg, Sr, Mn, Co, Ni, Cu, and Zn. Less mobile elements, often retained in secondary minerals, include Si, Al, Fe, Ba, Cr, Ti, V, As, Sb, Sc, Ga, Mn, Cu, and Ni. Subsequent weathering under warm, semi-arid conditions leads to a continuing leaching of base metals with minor precipitation in the middle to lower saprolite.

Davy (1980) has pointed out that copper, although mobilized by weathering, is retained in the near-surface environment, and that whereas it may migrate some distance laterally, it is readily precipitated by carbonate-bearing waters in near-neutral solutions. In aerated water at pH 8 the solubility of copper is only 6.4 ppm. Lead is not very soluble in neutral water, though more so than copper. Zinc, however, is very mobile.

Gossans

Gossans are a surface expression of weathered sulfides. They form over base-metal deposits and occurrences in the oxidized (supergene) zone in response to a number of factors, including present and past climatic regimes, geomorphology, type of mineralization and nature of the host rocks. They are complex and variable in detail but the essential constituents are iron oxides and quartz. Lead, silver and zinc may be enriched or depleted depending on local geochemical and climatic factors. Particularly important are pH and the degree of maturity of the gossan. Chalcophile elements which may resist leaching and provide useful pathfinders are Pb, As, Sn, Sb, Bi, Se, Te and platinum-group metals. Iron oxides may retain some relics of the original sulfide textures although the minerals and metals are no longer present.

Nickel (1983, 1984) has studied the gossan profile of the Teutonic Bore volcanogenic massive-sulfide deposit in the Eastern Yilgarn, thus providing a rough guide to some of the effects of weathering on base-metal ore deposits in the Yilgarn Craton. In the lower supergene zone, immediately above the primary ore zone, metals including lead, zinc and silver have become enriched through the dissolution of sulfides. The released iron is taken up in goethite which, together with quartz, forms a spongy network in which secondary ore minerals including native metals, oxides, halides, sulfates, carbonates and silicates are deposited in an irregular manner. In the upper part of the supergene zone most of the secondary ore minerals have been depleted due to the leaching effect of downward-percolating meteoric water. The chalcophile elements, including lead, zinc and silver, thus tend to be depleted towards the surface at the expense of siderophile elements but become concentrated in the lower supergene zone. Tin, however, is resistant to weathering and is preserved at the surface. Chalcophile elements remaining at the surface are mostly in chemical combination with goethite but some primary sulfides are also preserved as inclusions in detrital quartz.

In the Duketon area, at the Mason Hill and Tuff Hill VMS prospects, Bell (1980) found Zn:Pb ratios of between 8:1 and 15:1 in the primary ore converted to between 1:1 and 1:30 in gossans. This reflects the tendency of lead to be more resistant to leaching, along with arsenic, tin, antimony, bismuth, selenium and tellurium.

Gossan Hill, in the Murchison Terrane of the northwest Yilgarn, is a massive gossan within a partially stripped weathered zone up to 90 m deep. Copper and zinc, while still anomalous in the gossan, are severely depleted from levels of up to 7% in primary mineralization to maxima of 1890 ppm and 870 ppm respectively at the surface (Smith et al., 1980).

At Mons Cupri, in the west Pilbara Craton, Smith (1980) described some enrichment of copper, lead and silver in the gossans while zinc is depleted. This is within a partly stripped, deeply weathered profile. At the nearby Whim Creek copper–zinc–lead–silver deposit an abundance of secondary ore minerals indicates a relatively

immature gossan (Nickel, 1982). Secondary carbonates are abundant suggesting a buffering effect on low pH by carbonates and silicates. Copper and lead are enriched in the gossan, as at Mons Cupri, whereas zinc is more or less unchanged.

At Sulphur Springs, in the east-central Pilbara, Pickard and Barley (1994) described a variety of gossans that have undergone almost complete leaching. Quartz and iron oxides are dominant and grain size is too fine for the recognition of boxwork textures other than those of pyrite. Both target and pathfinder elements are leached relative to the mineralized body but are still geochemically anomalous showing, particularly, high lead indicating a well-developed, mature weathering profile. Arsenic, silver, bismuth and barium are the most diagnostic pathfinders in the gossans.

The Proterozoic Ilmars VMS prospect, in the Halls Creek Orogen also shows enriched lead (up to about 10×) and maintained levels of copper in gossan material. Zinc is depleted from levels of up to 4% in primary mineralization to 0.85% in gossan. By contrast, for the gossan associated with carbonate-hosted sulfides in the Lennard Shelf, at Chedda Cliffs, Fletcher (1980) shows relative enrichment of copper, lead and particularly zinc over primary mineralization.

With increasing maturity the typical gossan may lose all but the most stable elements such as iron, silicon and aluminium in the surface zone.

Silver can be concentrated in lateritized detritus in the weathering halo of gold and silver deposits. The concentration is partly detrital and partly the result of solution and reprecipitation processes and may also occur in silver and gold placer deposits.

Butt (1995) has pointed out that not all base-metal sulfide deposits produce gossans. Carbonate-hosted deposits with iron-poor sulfides or deposits with disseminated sulfides, for example, may not form gossans. He lists typical element suites for gossan identification, in particular mineralization target types and host rocks. For VMS in felsic volcanics, Cu, Pb, Ag, Au, As, Sb, Bi, Se, Hg, Sn, and Ba are positive indicators. For clastic-hosted mineralization, Pb, Zn, Ag, Cu, As, Hg, and Sb are positive indicators, and Mn, Ba, Co, and Ni are negative. For carbonate-hosted mineralization Pb, Zn, and Cd are positive.

Weathering and transport (dispersion) processes

Lead is relatively resistant to weathering processes. The potassium feldspars and micas, in which lead most commonly occurs in igneous and metamorphic rocks but to some extent in sedimentary rocks, are not readily broken down during weathering. Only biotite is less resistant. Under the normal oxidizing conditions of weathering, lead may be carried in relatively low concentrations (due to its low solubility) in sulfate. In more neutral or alkaline water the lead ion may become hydrolized and co-precipitated with hydroxides of more abundant elements, or adsorbed onto clay minerals. Transport would thus be limited. In conditions of lateritization lead is sometimes readily depleted but accumulates again in zones of ferruginous concretions. This behaviour accounts for the low levels of lead in seawaters (0.03 ppb).

The solubility of zinc, released from its host rocks by weathering processes, is controlled by the availabilty of the few anions which produce relatively insoluble zinc compounds; i.e. sulfide, phosphate, and carbonate. Precipitation can, however, be limited by complexing. Zinc sulfate and chloride have high solubility but reduzate sediments precipitate zinc as sulfide, and zinc from sulfate can be adsorbed onto clay minerals, iron oxides and organic substances. The effectiveness of these processes, and therefore the restricted mobility of zinc following rock weathering, is indicated by the low concentration of zinc in surface water (about 10 ppb). Seawater averages about 2 to 5 ppb zinc.

During weathering of rocks silver is brought into solution as sulfate, or as chloride and sulfide complexes, or as colloids. The silver may then be precipitated in hydrolyzate sediments, such as shale and clay, as sulfide, chloride or sulfate. Silver may remain in suspension on clay particles in natural waters but much of it will be desorbed in seawater by the presence of sodium and magnesium ions. Silver chloride may precipitate on plant fossils or clay galls in sandstone.

In the types of regolith common in Western Australia, particularly in the Archaean cratons, lead, copper and zinc leached from weathered mineralized rock are commonly dispersed into the laterite horizon, in duricrust, pisoliths and nodules, forming an anomalous dispersion halo. Buried residual laterite and ferruginous saprolite may also contain geochemical haloes. In environments such as the Kalgoorlie area, where laterites are patchy, calcareous soil and ferruginous granules and mottles may accumulate remobilized lead–zinc–silver (Anand and Smith, 1993).

Of the deposits and prospects described above in relation to gossan geochemistry, the Ilmars copper–zinc–lead prospect in the east Kimberley shows clearly defined geochemical dispersion in the close pattern of ephemeral streams that are present in the area, with anomalies between three to five times background for all three metals.

The related VMS deposits at Gossan Hill and Scuddles both have multi-element secondary geochemical dispersion haloes in Tertiary pisolitic laterite (Smith and Perdrix, 1983). At Gossan Hill the gossan is exposed on the crest of a hill and dispersion is radially away from the crest. Individual pisolites and the concretion skins contain fragments of gossan, but the goethite of the concretion skins also contains anomalous copper, zinc and arsenic, indicating hydromorphic dispersion. The Scuddles gossan pinches out in weathered bedrock about 40 m below the laterite/weathered bedrock interface. The pisolite dispersion anomaly is expressed in terms of the indicator elements bismuth, tin, molybdenum, antimony and arsenic, but not directly in lead, zinc or copper,

presumably because of leaching (particularly of zinc and copper) in the weathered zone.

Mineralogy

Table 2 gives a list of the various lead, zinc, silver and copper minerals associated with base-metal deposits in Western Australia that carry significant grades of lead and/or zinc. Those most commonly found in the primary ore are galena and sphalerite, and in the oxidized zone cerussite, anglesite, pyromorphite, smithsonite and hydrozincite. In base-metal deposits with significant grades of copper, chalcopyrite, cubanite, digenite and bornite are found in the primary zone; bornite, digenite, chalcocite and covellite are common in the secondary zone; and azurite, brochantite, chalcanthite, chrysocolla, native copper, cuprite, malachite and tenorite are found in the oxidized zone.

Pyrite and pyrrhotite are commonly represented in lead–zinc base-metal sulfide bodies with marcasite in the supergene zone.

Table 2. Lead, zinc, silver and copper minerals

Lead minerals		*Zinc minerals*		*Silver minerals*		*Copper minerals*	
Anglesite	$PbSO_4$	Adamite	$Zn_2(AsO_4)(OH)$	Argentite	Ag_2S	Antlerite	$Cu_3(SO_4)(OH)_4$
Bayldonite	$PbCu_3(AsO_4)_2(OH)_2$	Descloizite	$PbZn(OH)VO_4$	Chlorargyrite	AgCl	Atacamite	$Cu_2(OH)_3Cl$
Beudantite	$PbSO_4,FeAsO_4$	Franklinite	$(Zn,Mn)Fe_2O_4$	Native silver	Ag	Azurite	$Cu_3(CO_3)(CO_2)_2(OH)_2$
Bindheimite	$2HPbSbO_4.3H_2O$	Gahnite	$ZnAl_2O_4$			Bornite	Cu_3FeS_4
Boulangerite	Pb_5Sb_4	Hemimorphite	$Zn_2SiO_4.H_2O$			Brochantite	$Cu_4(SO_4)(OH)_6$
Bournonite	$Pb_2Cu_2Sb_2S_6$	Hydrozincite	$Zn_5(OH)_6$			Chalcanthite	$CuSO_4.5H_2O$
Caledonite	$Pb_5Cu_2(CO_3)(SO_4)_6$	Smithsonite	$ZnCO_3$			Chalcocite	Cu_2S
Carmintite	$Pb_3Fe_{10}(AsO_4)_{12}$	Sphalerite	ZnS			Chalcopyrite	$CuFeS_2$
Cerussite	$PbCO_3$	Zincite	ZnO			Chrysocolla	$CuSiO_3.2H_2O$
Crocoite	$PbCrO_4$					Native copper	Cu
Descloizite	$PbZn(OH)VO_4$					Covellite	CuS
Diabolite	$2Pb(OH)_2.CuCl_2$					Cubanite	$CuFe_2S_3$
Galena	PbS					Cuprite	Cu_2O
Hildagoite	$PbAl_3AsO_4SO_4(OH)_4$					Digenite	Cu_9S_3
Jamesonite	$Pb_4FeSb_6S_{14}$					Enargite	Cu_3AsS_4
Jordanite	Pb_9As_4					Lavendulane	$(Ca,Na)_2Cu_5(AsO_4)Cl.4\text{-}5H_2O$
Kasolite	$Pb(UO_2)(SiO_4).H_2O$					Malachite	$Cu_2(CO_3)(OH)_2$
Linarite	$PbCu(SO_4)_3(OH)_6$					Olivenite	$Cu_2(AsO_4)(OH)$
Massicot	PbO					Pseudomalachite	$Cu_5(PO_2)2(OH)_4.H_2O$
Mimeite	$Pb_5Cl(AsO_4)_3$					Rosasite	$(Cu,Zn)_2(CO_3)(OH)_2$
Mottramite	$2PbCu(OH)VO_3.H_2O$					Tennantite	$Cu_{12}As_4S_{13}$
Perite	$PbBeO_2Cl$					Tenorite	CuO
Plattnerite	PbO_2					Tetrahedrite	$Cu_{12}Sb_4S_{13}$
Plumbojarosite	$PbFe_3+6(OH)12[SO_4]_4$						
Pyromorphite	$Pb_5Cl(PO_4)_3$						
Wulfenite	$PbMoO_4$						

Chapter 4

Classification of lead, zinc and silver deposits

As the understanding of the geology of ore deposits has been transformed in the past few decades, so has an almost paradoxical reticence come into the classification of the various types of deposits that are recognized. This has expressed itself in a reluctance to genetically label deposit types, in preference to a descriptive approach without any explicit genetic implication.

This process reflects the changes in thinking that have accompanied the increased sophistication of the magmatic, volcanological, sedimentological, geochemical and structural models that have been applied to ore deposits. Ore types which were once thought to be distinct are now seen to be related; and vice versa.

This has most affected those base-metal deposits that are at least stratabound, and commonly stratiform, and which occur in sedimentary and/or volcanic sequences. The process, however, has not bypassed those hydrothermal vein deposits for which a relationship to specific igneous intrusions, volcanic centres, regional metamorphic events and/or regional, deep-seated structural features has still not been clearly established.

At the present state of the development of genetic ideas, this Bulletin approaches the genetic options within three descriptive groups, which encompass most deposits that have lead, zinc and silver as major species. These groupings give importance to the dominant morphology–host-rock relationship, but also incorporate other structural, and even geographic associations where appropriate. They are:

Hydrothermal vein-type

Volcanic-associated massive sulfides

Sediment-hosted massive sulfides
- Clastic-hosted
- Carbonate-hosted

Within these seemingly simple associations complexities abound. Even the separation of sedimentary and volcanic types is complicated by the large number of massive-sulfide deposits that occur in rocks of mixed sedimentary and volcanic association. Both contain mineralization of syngenetic origin, assumed to have formed as the result of the exhalation of ore fluids on the sea floor, and have stratiform zones with bedded sulfides and transgressive feeder zones associated with brecciation and veining. Within the sediment-hosted group those hosted by carbonate sediments are conventionally separated off as Mississippi Valley type, being stratabound and epigenetic. But 'Irish-type' deposits, also in carbonate host rocks, are partly stratiform, may be closer to syn-diagenetic in origin, and have many similarities to clastic-hosted deposits.

Workers such as Sawkins (1989a) give emphasis to the plate-tectonic setting of ore deposits as an aid to genetic concepts and to classification. Titley (1993) relates the temporal distribution of ore deposit types to the global tectonic Wilson Cycle and to similar earlier cycles.

A complete understanding of ore genesis must resolve the questions of metal source, nature of ore fluids, geochemical and mechanical aspects of transport and concentration within the lithologic/tectonic framework, timing of mineralization in relation to the formation of the host rock and the relative importance of regional and local controls. Only in this context can the prospectivity of tectono-stratigraphic units, magmatic associations, mineral belts and individual occurrences be realistically assessed.

Hydrothermal vein-type deposits

A vein-type ore deposit can be defined as 'a deposit of ore filling a fissure or fissures in rock' Haynes (1993). The term hydrothermal implies that the vein-filling material, including the ore and gangue, has been deposited from hot aqueous solutions, whether or not these are associated with magmatic processes. In general the deposits would be considered epigenetic but might be late-syngenetic, as in the breccia feeder zones beneath exhalative deposits.

The aqueous solutions would most commonly derive from connate or deeply penetrating groundwater, metamorphic water or magmatic water, and many are probably combinations of these. The difficulties of differentiating the source of aqueous solutions, for a given deposit, from their isotopic composition means that inferences as to source are usually made from a number of deposit features, including geological setting, paragenetic sequences, fluid inclusions and alteration styles. In attempting to classify vein-type deposits the source of the solutions alone, therefore, has limited value. Pressure and temperature conditions of formation are similarly limited. A combination of these features, along

with ore and gangue mineralogy, host-rock associations and tectonic setting, is required to derive a workable scheme.

Vein-type deposits that contain significant quantities of lead, zinc and silver (± Cu, Au, Sb, Bi, As, Ga, Ge, In) occur in two broad associations. The first association is with acid magmatism in the inner-arc areas of continental margin subduction zones (Sawkins, 1989a) and occurs in rocks of all geological ages. The magmatic rocks typically have compositions in the diorite to granodiorite range, or the volcanic equivalent, though a spatial relationship to intrusive or volcanic centres is variable and sometimes not obvious.

These vein-type deposits may be associated with related skarn-type deposits, but occur only in non-carbonate host rocks. They are commonly polymetallic and/or zoned. Where these deposits are zoned, silver is concentrated in the distal veins. The principal ore minerals are galena, sphalerite and chalcopyrite. Where these deposits are closer to a subvolcanic association, rather than a plutonic association, they may form breccia pipes and show a close association with VMS deposits.

Beaudoin and Sangster (1992) carried out comparative studies of a number of districts that contain this mineralization type and cast some doubt on the common association of the mineralization and veins with a magmatic source. They defined a specific class of lead–zinc–silver deposits associated with Precambrian to Mesozoic clastic metasedimentary terranes which is distinct from veins with other dominant metal associations such as cobalt, uranium, barium, fluorine or gold, and from epithermal veins in volcanic terranes. Table 3 summarizes the main features defined by Beaudoin and Sangster (1992), who highlighted the monotonous nature of the host sediments, the low incidence of volcanics in the sequences and the non-genetic association with intrusives of gabbroic to granitic composition. Mineralization, at temperatures between 250° and 300°C, is the result of mixing of deep-seated hydrothermal fluid with higher level crustal fluids of meteoric origin. The metals derive from the crustal country rocks. The veins form late in the development of the orogen and are associated with extensional collapse. The vein-fault complexes are associated with deep crustal breaks at terrane boundaries.

Most of the Proterozoic vein-type lead–zinc–silver deposits and occurrences in Western Australia (e.g. the Northampton Complex and Capricorn Orogen groups) are probably of this association.

A second association, dominated by gold but with subsidiary copper, lead and zinc (± As, Sb, Hg, Te, W), is most commonly seen in the Archaean greenstone belts of Australia, Canada, and Africa. Much work has been done

Table 3. Descriptive model for silver–lead–zinc veins (after **Beaudoin and Sangster, 1992**)

Feature	*Summary*
Metal ratios	
Pb/(Pb + Zn)	0.51 to 0.72
(Ag×100)/((Ag×100) + Pb)	0.22 to 0.63
Mineralogy	
Sulfides	Galena and sphalerite
Gangue	Siderite, quartz, dolomite, and calcite
Alteration	Local sericitization, silicification, pyritization
Host rocks	
Sedimentary	Precambrian to Mesozoic fine- to medium-grained clastic basins with minor volcanic rocks
Plutonic	Granite, granodiorite (most common), monzonite, syenite, I and S type; collision to post-collision
Metamorphism	Mainly greenschist, up to granulite
Age of mineralization	Precambrian to Eocene
Maximum size of vein structure	Length, 15 km; depth, 2300 m; thickness, 15 m
Depth of mineralization	0 to 10 km; probable average, 6 km
Tectonic setting	In faults conjugate or secondary to crustal shear zones which often are terrane boundaries; late tectonic in orogen history, after compression, during or after crustal extension
Fluid inclusion	Temperature; 250–300°C; salinity, 0–26 wt % NaCl equivalent; CO_2 abundant but not universal, minor CH_4, N_2
S	Highly variable $\delta^{34}S$, correlated with local country rocks
C	Variable $\delta^{13}C$ between -14 and 0; C probably leached from local country rocks; homogeneous $\delta^{13}C$ between -8 and -5; C probably deep seated from mantle CO_2 degassing
Pb	Linear or scattered arrays, one to four groups of deposits; upper crustal to orogen Pb, lower crustal and upper mantle components present locally

in recent years on the genesis of deposits of this association. Some models have included preconcentration of gold in chemical sediments within the greenstones, with subsequent metamorphic remobilization and related plutonism generating enriched vein systems (Hutchison, 1993). Others suggest derivation from broad plumbing systems of metamorphic fluids focused through deep-seated, crustal-scale shear zones. Groves et al. (1992) have suggested a version of the latter which recognizes the related nature of gold-dominated vein-type deposits from sub-greenschist through to lower granulite facies. This broad range of crustal depths combined with recent lead and strontium isotope evidence has ruled out derivation of ore fluids solely from greenstone host rock, magmatic or granulite/metamorphic sources. Giant plumbing systems and a deep, subgreenstone belt and/or a mantle-derived source are invoked.

Most vein-type deposits of this kind in the Western Australian Archaean are associated with only low quantities of lead and zinc and variable levels of silver. The zinc–lead-rich Black Flag gold deposit (Bennett, 1989) is an exception to this association.

Volcanic-associated massive-sulfide deposits

Volcanic-associated massive-sulfide deposits (VMS) can be defined as base-metal sulfide deposits which occur in a host sequence dominated by submarine volcanic rocks. This follows the convention adopted by Franklin et al. (1981) and Large (1992). VMS deposits can be divided into two broad groups: the 'Cyprus type', formed at spreading centres with high Cu:Zn ratios, and the 'Kuroko type', formed in island-arc and continental margin, subduction-related settings and containing Cu with significant amounts of Pb, Zn, Ag and Ba. The discussion below refers largely to the 'Kuroko type'.

The deposits are predominantly stratiform, forming lenses of variable extent, commonly with associated underlying transgressive stringer or breccia zones. They are associated with bi- or polymodal sequences of submarine calc-alkaline volcanics, including lavas and epiclastics, and commonly occur at what appears to be a hiatus in the volcanic activity, marked by the presence of tuff and chert layers. This hiatus typically marks the end of a long period of predominantly rhyolitic volcanic activity, and is followed by less uniform felsic and mafic accumulations.

The deposits are generally considered to have formed by the exhalation of metal-rich brines on the seafloor in relatively deep-water conditions, reflecting the operation of hydrothermal systems within the volcanic pile. Metal sulfides are deposited at or near the seafloor where hydrothermal solutions are cooled rapidly by contact with seawater, or more slowly by contact with connate water. Recognition and examination, in the 1970s, of present mound-chimney sulfide deposits on the East Pacific Rise have led to better understanding of the processes involved (Lydon, 1988). Conical deposits are formed in proximity to the mound chimney, whereas more-distal deposits are sheet or blanket-like either fed from below, accumulated by gravity in depressions, forming as a result of coalescing of mounds, or by stratabound replacement of favourable sedimentary horizons adjacent to feeder pipes or faults. Further important details from modern settings have been reported by Binns (1993) for the eastern Manus Basin, northeast of Papua New Guinea. These will be discussed in **Chapter 9** in relation to establishing clearer guidelines to prospectivity in Archaean greenstones terranes, particularly in the eastern Yilgarn.

VMS deposits are typically zoned in their ore mineralogy, chemistry and alteration styles both horizontally and vertically. This reflects distance from the source of fluids, both on a local and regional scale, and decreasing temperature. The typical sequence upward and outward is Fe to Fe–Cu to Cu–Pb–Zn to Pb–Zn–Ba. Thus the feeder or stringer zones are typically rich in pyrite and chalcopyrite with pyrrhotite and magnetite, whereas upper and more distal zones contain pyrite, sphalerite, galena and chalcopyrite with barite as a common gangue mineral. Put simply, alteration of the host rocks by the mineralizing fluids creates an inner chloritic core around the stockwork or stringer zone, into which Fe and Mg are introduced while Ca, Si, Na and K are depleted, reflecting destruction of original feldspar. In the outer zone, sericitization is accompanied by an increase in K. In lenticular orebodies, chloritization may extend as a blanket of alteration in the footwall. In the hangingwall, alteration is less intense, with weakly developed sericite, chlorite and quartz.

The source of the mineralizing fluids that create these deposits has been the subject of considerable debate over the past decade or so. The present concensus is that they are derived principally from seawater, which has been circulated through the volcanic pile driven by either localized, subvolcanic, magmatic heat, or a more regional plutonic heat source. The heated fluids leach their ore components from the volcanic-dominated substrate. However, Sawkins (1989a) and Stanton (1990), among others, have argued that a significant proportion of the metal content of VMS deposits derives directly from the magmatic heat source. The fact that the largest, most metal-rich deposits are associated with highly fractionated volcanic suites, that particular ore compositional types relate to particular volcanic types, and that deposits commonly cluster at one or two stratigraphic levels in a district, suggest the release of metalliferous volatiles at a specific stage of magmatic evolution. Large (1992) suggested that a combination of sources is most likely, with the less readily leached metals, such as copper, deriving from the higher temperature magmatic source. This would partially account for the tendency for proximal deposits to be copper rich while more distal deposits are lead–zinc rich and copper poor.

It is also possible that some VMS deposits are not formed directly by magma-driven fluid convection, but by the tectonic release of deeply buried, hot pore fluids from capped aquifers in rapidly deepening basins. Deep burial and low levels of saturation would promote efficient leaching of ore components, and tectonic release along fracture systems would provide large volumes of mineralizing fluid at, or near the surface over a short

period of time, forming either surface exhalative deposits or replacement-style deposits in near-surface aquifers. This model is closely related to the sedimentary–exhalative model, discussed below in relation to Mount Isa-type deposits and even Irish-type carbonate-hosted deposits.

VMS deposits display a great variety of forms in detail owing to the variability of genetic factors. The nature of the ore fluid in terms of its chemistry and temperature, the composition of the volcanic pile (as source and host) and the depth and configuration of the seafloor all affect the physical and chemical aspects of the deposit. These will be discussed later in relation to specific deposits but the most important can be summed up as follows (summarized *from* Large, 1992):

Salinity of fluids: It seems possible (Solomon et al., 1990) that highly saline fluids on venting form a dense brine which migrates downslope to form a distal brine pool giving laminated sulfide layers and only minor footwall alteration. If venting occurs in an area of low seafloor topography, brine pools could form from lower salinity fluids. Mound-type, and coalescing mound-type, deposits form from fluids of a salinity that makes them slightly less dense than seawater. In these proximal deposits footwall alteration is intense.

Temperature of fluids: High-temperature fluids will carry copper to the surface whereas lower temperature fluids will produce lead–zinc-dominant surface deposits with copper only in the stockwork zone.

Permeability of footwall volcanics: High permeabilty will lead to focused discharge creating mounds. Low permeabilty will tend to produce a surface sulfide sheet and stratabound stockwork.

Reducing conditions: Low ore fluid levels of fO_2 and a_{H_2S}, believed to prevail in most Archaean sea-floor hydrothermal systems and to reflect low fO_2 in Archaean oceans, are considered to be responsible for the presence of pyrrhotite and magnetite in the lower massive and footwall stringer parts of some Archaean VMS deposits, and the general absence of barite.

Depth of seawater: In shallow seawater, rising hydrothermal fluids boil before reaching the surface. This is thought to give rise to footwall brecciation and precipitation of sulfides to give extensive stockwork systems. Depths of 1000 to 1500 m are required to prevent boiling and concentrate sulfide deposition at the surface with little stockwork development.

Nature of host volcanic suite: Fox (1979) has noted that VMS deposits associated with tholeiitic volcanics are Zn–Cu types with abundant iron sulfides. Those associated with calc-alkaline suites are Pb–Zn–Cu types, iron poor and sphalerite rich.

A useful method of subdividing VMS deposits, based on their metal content rather than specific to genetic implications, is by their Copper and Zinc Ratios (Huston and Large, 1987; Large, 1992). The Copper Ratio, 100 Cu/(Cu+Zn), and the Zinc Ratio, 100 Zn/(Zn+Pb) together highlight three deposit types: Cu deposits (Cu ratio>60, Zn ratio>60), Zn–Cu deposits (Cu ratio<60, Zn ratio>90), Zn–Pb–Cu deposits (Cu ratio<60, Zn ratio=60–90). This method can also be used to separate various lenses within a deposit.

VMS deposits of the 'Kuroko type' are distributed throughout geological time. It is now widely accepted that Archaean greenstone belts contain analogues of the continental margin backarc and intra-arc basins, and that Archaean VMS deposits are in many ways similar to the more easily studied Palaeozoic deposits.

Titley (1993) has related the temporal distribution of stratabound Phanerozoic and Proterozoic metal-sulfide ore deposits, including VMS, to the Phanerozoic Wilson Cycle of global tectonic processes, and to Wilson-like cycles in the Proterozoic. VMS deposits form in '...times of compression of continental margins linked with extension along ocean ridges, concordant with ocean ridge hydrothermal activity and seafloor volcanism...'. In the Wilson Cycle these correspond with times of opening and fragmentation and maximum sea depths. For Atlantic, African and Western Hemisphere examples these coincide with VMS peaks at about 500 and 100 Ma, and a Proterozoic peak between 1700 and 2000 Ma.

Most Western Australian VMS deposits and occurrences are associated with Archaean greenstone belts in the Yilgarn and Pilbara Cratons. Some deposits and prospects are also present in the Early Proterozoic Halls Creek Orogen.

Sediment-hosted massive-sulfide deposits

The complexities in the subdivision of sediment-hosted massive-sulfide deposits are partially due to the variety of sediment-hosted ores in terms of factors such as type of host, form of ore, metal content, basinal/structural/plate-tectonic setting, source of metals and fluids, and timing of mineralization. Recent reviews of these deposits can be found in Gustafson and Williams (1981) and Edwards and Atkinson (1986),

Initially, a subdivision can be made in terms of two broad host-rock types, separating those predominantly in clastic sequences from those predominantly associated with carbonates. Further subdivision can be made in relation to a few commonly accepted end members thought to form coherent groups in relation to a number of features. These are:

Clastic-hosted:	lead–zinc type
	Broken Hill type
	copper type
Carbonate-hosted:	Mississippi Valley type
	Irish type

Clastic-hosted: lead–zinc type

These deposits are usually stratiform, essentially syngenetic, and occur predominantly in reduced marine shales or siltstones, sometimes associated with carbonates but only rarely with volcanics. They are commonly in rift basins or grabens associated with intracratonic rifting, or more advanced continental separation. Thick sequences of sedimentary rocks (5–15 km) indicate long-lived subsidence in association with contemporaneous extensional faulting. The sedimentary rocks are generally

characteristic of deep water but, where carbonates and cherts are present, may be shallower.

In these extensional, basin-margin situations secondary sub-basins also develop. Where such features can be observed, sulfide deposits are commonly located near basin-marginal faults. Where mineralizing fluids exhale onto the sea floor they may collect in protected depressions or small third-order basins downslope from the conduit.

Maynard (*in* Force et al., 1991) describes a second tectonic setting for shale-hosted mineralization; a continental margin distinguished by a closing ocean. In this setting, however, barite deposits form in the absence of significant lead and zinc. It is speculated that this absence is related to lower temperatures of between 100° and 200°C, at which sphalerite is less soluble. This type is roughly comparable with the 'flysch basin' type of Morganti (1980). He points to the presence of an alteration or feeder pipe either beneath or adjacent to the mineralization as a common feature of this style of deposit.

Galena and sphalerite are the predominant ore minerals in clastic-hosted lead–zinc deposits, along with pyrite and pyrrhotite. Lead and zinc occur in roughly equal proportions unless zinc is dominant. Silver is commonly also present in economic proportions but copper and gold tend to be absent. Barite may be an important gangue mineral in the upper parts of some deposits.

There is a general concensus that clastic-hosted deposits are the product of the introduction of deep-sourced hydrothermal fluids at or near the sea bed. The fluids are considered to represent connate waters buried with the rapidly accumulating sediments and then periodically expelled during basin compaction. The association of deposits with basin marginal faults or rifts is significant. The metallic elements are considered to have been extracted from the rock-forming silicates by the highly saline formation water at depth under the influence of the geothermal gradient or possibly, in some cases, a magmatic heat source.

The likelihood that at least some of these deposits have formed as the result of the exhalation of dense brines on the sea floor has led to them being characterized in some schemes as sedimentary–exhalative (Sedex) deposits. Gustafson and Williams (1981) have pointed out that, if anoxic conditions did not apply at the sea floor, rapid burial would be essential to prevent the sulfides being destroyed by oxidation. The rapid sedimentation in actively subsiding rift grabens would provide this. More tranquil, shale-dominated sedimentation in deeper water, however, would allow the slower accumulation and delicate banding seen in many deposits. The common location of mineralization in the form of multiple-stacked lenses near bounding faults suggests a periodic basin dewatering, possibly related to earthquake activity in the subsiding sediment column.

In practice many deposits show evidence of discordant, brecciated subfloor feeder zones beneath, or marginal to stratiform zones. Mineral zoning is common both laterally and vertically away from the feeder zones. In detail this may be complex and relate to a number of variables. Copper, if present, is generally found within or adjacent to the feeder zone and is the product of precipitation during boiling of the fluids as they approach the surface, whereas Zn:Pb ratios tend to increase towards the distal parts of stratiform zones. Barite and oxidized iron may occur beyond the lead–zinc zone and manganese may form an enriched zone around the deposit.

The footwall sediments, overlying the feeder zone, are commonly altered, with silicification and, in places, chloritization being evident.

Solomon and Groves (1994), and Parr and Plimer (1993) have argued that a Broken Hill-type deposit may be separated from other clastic-hosted (or Sedex) deposits. The Broken Hill type, they suggest, is more specifically found in an intracratonic setting, than in the continental margin or epicontinental re-entrant settings attributed to Sedex deposits (Goodfellow and Lydon, 1993). It is unique also in the association with evaporites, significant bimodal volcanism and granite sills and in having generally undergone multiple deformation and high temperature–low pressure metamorphism.

The type includes, in Australia, the Menninnie Dam prospect in the Gawler Craton and the Pegmont and Cannington deposits in the Eastern Fold Belt of the Mount Isa Inlier.

Most clastic-hosted lead–zinc deposits are of Middle Proterozoic age. Broken Hill, Mount Isa and McArthur River are the major examples in Australia. Titley (1993) finds that mineralization of this type, in contrast to VMS, forms in periods of rifting and continental fragmentation at the beginning of the Wilson Cycle and related Proterozoic cycles. Such periods of relatively shallow ocean occurred in the Mesoproterozoic (between 1.6 and 1.0 Ga), in the Lower Cambrian, and from the Devonian to the Permian.

Clastic-hosted: copper type

This Bulletin is less concerned with sediment-hosted sulfides dominated by copper. They are of interest only in the sense that they may form a continuum with some lead–zinc deposits or that their presence may indicate the predominance of conditions not favourable to lead–zinc ores. Their general features are therefore summarized only briefly.

Sediment-hosted copper deposits may be stratabound and stratiform but, in contrast to analogous lead–zinc deposits, tend to be disseminated rather than massive. They are found in more varied, more permeable, shallower water sediments (up to about 30% are in arenite); and have a distinctive mineralogy with relatively minor sphalerite and galena. They also tend to be related to a redox contrast between red-bed deposits and marine shales containing abundant organic matter.

Mineral zonation follows the outward and upward trend: chalcocite–bornite–chalcopyrite–pyrite. Any lead–zinc occurs above, or beyond chalcocite in reduced

shales associated with syngenetic pyrite. Cobalt is a significant component of the Zambian and Zairean copper deposits.

Copper deposits such as those of the Zambian copper belt were long thought to reflect transport of copper in surface waters to near-shore depositional palaeo-environments which become progressively anoxic (Garlick, 1961). More recent studies have tended toward emphasizing hydrothermal/late-diagenetic processes. A comprehensive review of genetic theories in the light of the most recent data (Sweeney et al., 1991) confirmed that the origin of the deposits is still controversial but concluded that metal-rich fluids within the sediments were expelled during burial and trapped during early diagenesis of the host strata in a process involving bacterial fixation of seawater sulfate. Unrug (1988), however, argues a late-diagenetic origin for the mineralization with metals derived from compactional dewatering of a downfaulted wedge of overlying volcaniclastic pelites 5 km thick. Copper was fixed in the host strata by early diagenetic primary pyrite.

Maynard (*in* Force et al., 1991), in a comparison of the Kupferschiefer, the African Copperbelt and White Pine, also suggests that a strong argument can be put for a late diagenetic origin. The necessary ingredients in each case are a continental rift setting, availability of basic volcanics or their clastic derivatives, an episode of red-bed formation to prime the source beds to provide metals, then deposition of a suitable pyrite-rich host rock. Deep brines mobilized by further rifting then leach metals from the footwall red beds and deposit them in the pyrite-rich host. Some sulfur may also be introduced in the brines.

An epigenetic deformational control model has been proposed for the stratabound copper bodies at Mount Isa (Perkins, 1984, 1990). The copper orebodies are enclosed in brecciated silica dolomite and are close to syngenetic stratiform lead–zinc–silver mineralization. Zones of dolomite, silica and chalcopyrite are considered to be formed in a hydrothermal alteration system during a post-lithification regional deformation event, at least 150 m.y. after the stratiform mineralization. The dominant spatial control on the copper alteration–mineralization event was a tectonized contact zone with basement greenschist (Swager, 1985).

Stratiform copper deposits occur in environments typical of the early stages of rifting in stable continental or continental-margin settings. Sawkins (1989a) has pointed out that basaltic volcanism is usually present within or nearby these rift/basinal settings. Titley (1993) suggested that whereas stratiform copper deposits are essentially continental and VMS deposits essentially oceanic, the stratiform lead–zinc association is transitional between the two, in ocean-linked basins or continental-margin rifts. Within Wilson-type cycles the copper deposits, in similar fashion to the lead–zinc types, group in the latter parts of periods of continental stasis, when rifting and fragmentation is beginning to occur and sea levels are shallow. Thus they are found in the middle to late Proterozoic and are particularly well represented in the Permo-Carboniferous.

Carbonate-hosted: Mississippi Valley type (MVT)

As their name implies these deposits occur in carbonate rocks, principally limestones and dolomites, and are essentially epigenetic. They commonly form near the margins of basins or on arches within, or between, basins. They tend to occur in districts distributed over hundreds of square kilometres, implying large-scale rather than local controls on the mineralizing process. Many are associated with prominent erosional surfaces indicative of extensive karstification. Faulting, brecciation and dolomitization are also strongly associated, implying that the creation of zones of high permeability is a major factor in the formation of deposits.

Most MVT deposits have a relatively simple mineralogy, containing sphalerite and galena, with zinc generally dominant, accompanied by pyrite and/or marcasite. Barite and fluorite are common in some districts. Chalcopyrite and other copper species may be present while nickel and cobalt occur in some lead-dominant deposits.

It is generally accepted that MVT deposits are epigenetic, with sulfides having been deposited in pre-existing pore spaces from highly saline brines at temperatures between 80° and 200°C. These have migrated upwards from deeper parts of the basin. Sulfur is derived from seawater sulfate or from evaporites and metals from crustal material, most probably basin sediments.

The brines associated with MVT deposits have marked similarities with oilfield brines. Sawkins (1989a) used this information, along with other evidence, to suggest that the major basin dewatering required to create large districts of related MVT mineralization is driven by collisional events at continental margins. These are considered to have the potential to cause fluid migration of hundreds of kilometres into continental interiors, where most MVT deposits occur.

MVT deposits in platform or shallow-shelf settings occur in rocks ranging from Proterozoic (1.1 Ga) to Permian (0.2 Ga) age with about 80% in the Cambro-Ordovician or Carboniferous. Titley (1993) recognized MVT deposits characterizing times of compressional tectonics, continental assembly, and stasis within the Wilson Cycle.

Carbonate-hosted: Irish type

This subtype is based on the deposits in central Ireland discovered since the 1960s. The deposits, in their mixture of syngenetic and epigenetic features, suggest a transition between Mississippi Valley-type, carbonate-hosted, and clastic-hosted lead–zinc deposits. Recent summaries of the main features of these deposits can be found in Edwards and Atkinson (1986) and Sawkins (1989a).

The mineralization and its hosts are of early Carboniferous age. The sediments are transitional from continental to marine with limestone and micritic limestone overlying shallow water or littoral clastics. Mineralization

varies in style from finely laminated stratiform sulfides, sometimes in stacked lenses, to cross-cutting, vein, breccia or fault-related zones. The cross-cutting mineralization appears to represent feeder zones beneath the stratiform lenses. Features suggesting hydrothermal chimneys and mounds have been interpreted.

Sphalerite and galena are the economically important minerals. Silver is associated with sulfosalts intergrown with galena. Argentiferous tetrahedrite, pyrargyrite, argentian boulangerite and jordanite are also found. Pyrite is also common. Metal zoning in the orebodies seems to reflect faulting trends.

It seems clear that faulting has controlled ingress of mineralizing hydrothermal fluids into the basin-marginal carbonates with both exhalative and subfeeder ore styles forming. The fluids are probably the result of basin dewatering, as in the clastic-hosted lead–zinc model, a process that may have been driven by Hercynian arc–continent collision to the south of Ireland (Duane and de Wit, 1988).

Chapter 5

Geological setting of Western Australia

It is the intention of this chapter to give a brief outline of the present understanding of the geotectonic framework of the State. This is designed to provide a context to the distribution of lead–zinc–silver mineralization and to the variety of metallogenic processes involved. Metallogeny within specific tectonic units will be discussed at greater length, in relation to particular deposit types, in succeeding sections.

This summary is derived primarily from GSWA Memoir 3 (1990) but is updated where necessary from the more recent publications cited.

Archaean and Proterozoic evolution

Myers (1990a) proposed that the Precambrian in Western Australia represented a long and dynamic history involving repeated aggregation and dispersal of crustal fragments between 2.7 and 0.6 Ga. This contrasts with the views of earlier workers that Archaean and Proterozoic orogenic belts were essentially ensialic, formed within the supercontinent of Gondwana.

The Archaean comprises two major segments, the Yilgarn and Pilbara Cratons which, although they are both made up predominantly of granite–greenstone terranes, developed separately and are geologically distinct. They have remained as coherent units since about 2.5 to 2.4 Ga (Myers and Hickman, 1990).

The granite–greenstone terrane of the Pilbara Craton reflects two extensive periods of mafic and felsic volcanism with associated subvolcanic intrusion and development of granitic to granodioritic plutons (3.6–3.3 Ga and 3.0–2.8 Ga). Barley and Groves (1990) have suggested that within this framework a number of separate geotectonic domains developed. That these are now separated by north-northeasterly trending strike-slip faults suggests correlations with the tectonic evolution of younger orogens. A craton was established by 2.9–2.8 Ga and, following a period of erosion, rift-related flood basalts were deposited in an extensive blanket over the sialic basement (2.8–2.7 Ga). Subsequently, between 2.5 and 2.4 Ga, banded iron-formation with associated dolomite, shale and felsic volcanics were laid down in a large depression or shelf on the southern part of the craton.

The oldest components of the Yilgarn Craton are the western and northwestern gneiss complexes (3.7–3.0 Ga), consisting predominantly of granite–gneiss with some metasedimentary rocks. The rest of the Yilgarn consists of granite–greenstone terrane, which can be broadly subdivided into a regional high-grade portion in the southwest with mainly greenschist facies in the remainder. The high-grade portion is a poorly known composite region of deep crustal exposure with granulite- to upper amphibolite-grade metamorphic rocks intruded by granites (2.65 Ga) that are little deformed and low grade. Some low-grade volcanics are approximately contemporaneous with these granites (e.g. the Saddleback Greenstone Belt).

The greenschist facies portion can be further subdivided. In the northwest, the Murchison Terrane contains a regionally extensive greenstone sequence (Watkins and Hickman, 1990), with a dominant period of volcanism between 3.0 and 2.9 Ga. This sequence appears to have formed as a single large coherent volcanic–plutonic unit which has been folded into large-scale dome and basin structures and metamorphosed to greenschist–amphibolite facies. The eastern part of the greenschist granite–greenstone terrane is dominated by regional-scale, deep-seated northwesterly to north-northwesterly trending structures which separate differing structural domains. These form a collage of different tectono-stratigraphic environments which may represent a continental margin arc and back-arc basin assemblage related to west-dipping subduction (Barley et al., 1992a). Volcanic assemblages are predominantly in the range 2.72–2.69 Ga.

The Capricorn Orogen, a major zone of sedimentary deposition, plutonic intrusion, deformation and metamorphism, was created by the collision between the Pilbara and Yilgarn Cratons at about 1.8 Ga (Blockley and Myers, 1990; Myers and Barley, 1992; Tyler and Thorne, 1990). Thrusting of granite–greenstones onto the southeast Pilbara Craton led to uplift and erosion with transport to the west into a developing foreland basin (Ashburton Basin). South of this, in the Gascoyne Complex, southward thrusting occurred along large ductile zones in Archaean granitic basement and Palaeoproterozoic cover. Major granite batholiths, related to the Pilbara–Yilgarn suture, intruded this zone. To the east, in the Nabberu Province, gabbros, ultramafic and mafic volcanics and greywackes, of possible island-arc or back-arc provenance, were thrust south to interleave with shelf clastics and banded iron-formation on the northern margin of the Yilgarn. Later, Mesoproterozoic sedimentation along the axis of the collision produced the sandstones and shales of the Bangemall Group with abundant dolerite sills.

The western and southern margins of the Pilbara and Yilgarn Cratons and the Capricorn Orogen are formed by the Pinjarra and Albany–Fraser Orogens. The Pinjarra Orogen is poorly known due to limited exposure and is confined to a few small windows in the Perth Basin. Repeated orogenic activity occurred throughout the Proterozoic. Most of the exposures are of high-grade gneiss and granite with ages in the range 1.10–0.55 Ga. The Albany–Fraser Orogen represents a zone of continental collision between the Yilgarn Craton and an obscured craton to the east and southeast. It is made up of components of Palaeo- and Mesoproterozoic granitic gneiss, clastic sediments, gabbro and granite in huge thrust sheets transported to the northwest onto the Yilgarn platform. Granulite-facies metamorphism and granite emplacement accompanied continued oblique collision and crustal thickening between 1.3 and 1.0 Ga.

The Paterson Orogen truncates the northeast margin of the Yilgarn and Pilbara Cratons and Capricorn and Albany–Fraser Orogens and represents the accretion of a belt of rocks onto the West Australian plate in the Neoproterozoic. Palaeo- to Mesoproterozoic orthogneiss, metasedimentary and metavolcanic rocks, mafic and ultramafic intrusives and unconformably overlying late Proterozoic sediments have been thrust to the southwest in detached folds in a collision event at about 0.7 to 0.6 Ga. The Paterson Orogen extends beneath Phanerozoic cover to the southeast from the Rudall area and is exposed again in the Musgrave Complex in Central Australia.

The roughly contemporaneous Kimberley Basin sedimentary rocks (1.75 Ga) and the deformed and metamorphosed sedimentary and volcanic rocks and intrusive granites of the Hooper and Lamboo Complexes (1.8 Ga) seem to have formed at some distance from each other. Their present juxtaposition is the result of the southward movement of the Kimberley Basin sequence, originally formed on stable sialic crust. The basin sediments and underlying granite were first involved in northward-directed thrusts and faults in the Leopold Orogen followed by southward transport and deformation of the basin sequence over the sediments, volcanics and granites of the orogen. To the east, in the Halls Creek Orogen, the movements were mostly transcurrent and sinistral along steep faults, lateral to the thrusting in the west.

Phanerozoic evolution

The Phanerozoic geotectonic history of Western Australia can be divided into Gondwana and Post-Gondwana phases (Cockbain and Hocking, 1990).

Basin development in the Gondwana phase was intraplate, intracratonic, and began with tholeiitic volcanism and subsequent subsidence and marine sedimentation in the Bonaparte and Ord Basins. The Canning Basin was initiated in the Ordovician, again as an intracratonic sag, with a period of marine sedimentation ending in the Late Ordovician. In the Silurian, intracratonic fracture basins were initiated in the area of the currently defined Carnarvon and Northern Perth Basins, with near-shore sedimentation. Marine conditions returned to the Canning and Bonaparte Basins. Following a brief period of uplift, shallow-marine and fluvial conditions returned to all the previously initiated basins. Faulting and associated graben development related to the Alice Springs Orogeny led to the formation of the Fitzroy Trough in the Canning Basin and also affected the Bonaparte and Ord Basins. Shallow-marine conditions led to the development of reef complexes in the Canning and Bonaparte Basins, in a tropical climate. This ended in the Early Carboniferous with a general hiatus.

The next phase of sedimentation, beginning in the late Carboniferous, was the most widespread in Gondwana affecting and extending all the Western Australian Phanerozoic basins except those on the south coast. Deposition took place under marine and continental glacial and post-glacial conditions. Towards the end of the Gondwana phase, renewed faulting and graben development occurred in the Triassic and Early Jurassic along the present west and northwest coastline. Mixed marine and onshore sedimentation, within the current Western Australian coastline, occurred only in the Canning Basin and part of the Perth Basin.

The post-Gondwana phase marks the separation of the Australian continent from Gondwana. During this period sedimentation continued in intracratonic basins, particularly in the Canning Basin, and marginal sag basins were developed along the zones of separation. The separation began erratically along the North West Shelf in the Middle Jurassic. Separation along the west coast began in the Early Cretaceous. Sedimentation in the intracratonic basins also ended in the Early Cretaceous following a significant marine incursion which affected the Canning and Officer Basins.

Chapter 6

Volcanic-associated massive-sulfide deposits

Summary of geology and mineralization

Distribution

Volcanic massive-sulfide (VMS) deposits and occurrences in Western Australia are confined to the Precambrian. Of 288 sites in the state, 87 are clearly VMS and 21 possibly so. Of these, there are 46 in the Yilgarn Craton (28 of these in the Murchison Province and 13 in the Eastern Goldfields Province) and 42 are in the Pilbara Craton. A further two in the Sylvania Inlier give a total of 90 in the Archaean (about 81%). All of these are located in greenstone belts.

A further 13 sites are within the linked Palaeoproterozoic Halls Creek and King Leopold Orogens, four in the Palaeoproterozoic Ashburton and Glengarry Basins of the Capricorn Orogen, and three in Mesoproterozoic rocks of the Musgrave Complex, a probable extension of the Paterson Orogen (Plate 1).

Metallogenic factors

The lithological, geochemical and structural setting of the various deposits and occurrences of VMS mineralization in the Archaean granite–greenstone terranes is discussed below in relation to particular terranes within the two cratons. Table 5 (p. 41) is noted here, however, to give an overview of some of the variety of these features in relation to this mineralization type and to indicate some trends which may be significant in terms of potential for further discoveries.

Pilbara Craton — North Pilbara granite–greenstone terrane

Geological framework

VMS mineralization within the Pilbara occurs at various stratigraphic levels, and in separate sub-basins, within the greenstones of the granite–greenstone terrane (Fig. 6).

This terrane is made up of granite–gneiss complexes (or batholiths) with intervening belts of variably folded volcanic and sedimentary sequences which were deposited between about 3.50 and 2.77 Ga (Thorpe et al., 1992a). In a recent summary of developments in the understanding of the terrane, Hickman (1990) stated that the pattern of granitoid domes and flanking belts was produced by solid-state diapirism of a pre-existing granitoid complex coupled with syntectonic granitoid intrusion. Granitoid ages cluster within four groups: 3500–3430 Ma, 3340–3265 Ma, about 3000 Ma, and about 2850 Ma (Krapez, 1993).

The stratigraphic succession of the greenstone sequences was first established as a result of GSWA regional mapping (Lipple, 1975; Hickman, 1983). The accumulation of more detailed mapping and chronological data from numerous research projects and studies in the last decade, however, has required some revision of that scheme (Hickman, 1990, Fig. 7), and has led to a lively reassessment in recent literature (Thorpe et al., 1992a,b; Barley, 1993; Krapez, 1993). Hickman's original subdivision (Hickman, 1983 *after* Lipple, 1975) into a lower volcanic-dominated group, the Warrawoona Group; an overlying sediment-dominated group, the Gorge Creek Group; and an upper volcanic and sedimentary group, the Whim Creek Group, was amended (Hickman, 1990) as a result of the recognition of a regional unconformity within the Gorge Creek Group. Table 4 shows the updated stratigraphy with the redefined Gorge Creek Group and the overlying De Grey Group.

The Warrawoona Group and lower Gorge Creek Group are considered to have been deposited as tabular successions in the east Pilbara (i.e. prior to major diapirism). Similar successions appear in the west Pilbara. No basal unconformity of the Warrawoona Group is preserved. Laterally extensive shallow-water, subaerial, and evaporitic units are present within the Warrawoona Group. The various sedimentary units represent proximal to distal clastic deposits associated with felsic volcanic centres. Intermediate to felsic volcanics of the Duffer Formation, which followed the more tholeiitic lavas of the Talga Talga Subgroup, make up the bulk of the Warrawoona Group and have a close association with VMS deposits and occurrences in the east Pilbara. Di Marco and Lowe (1989) concluded, on the basis of detailed sedimentological studies, that the tectonic setting of Duffer volcanism had some similarities with Phanerozoic arc assemblages, but that the lack of deep-water deposits and the non-linear distribution of volcanic centres suggested significant differences. Barley (1993) also recognized arc or near-arc settings in the

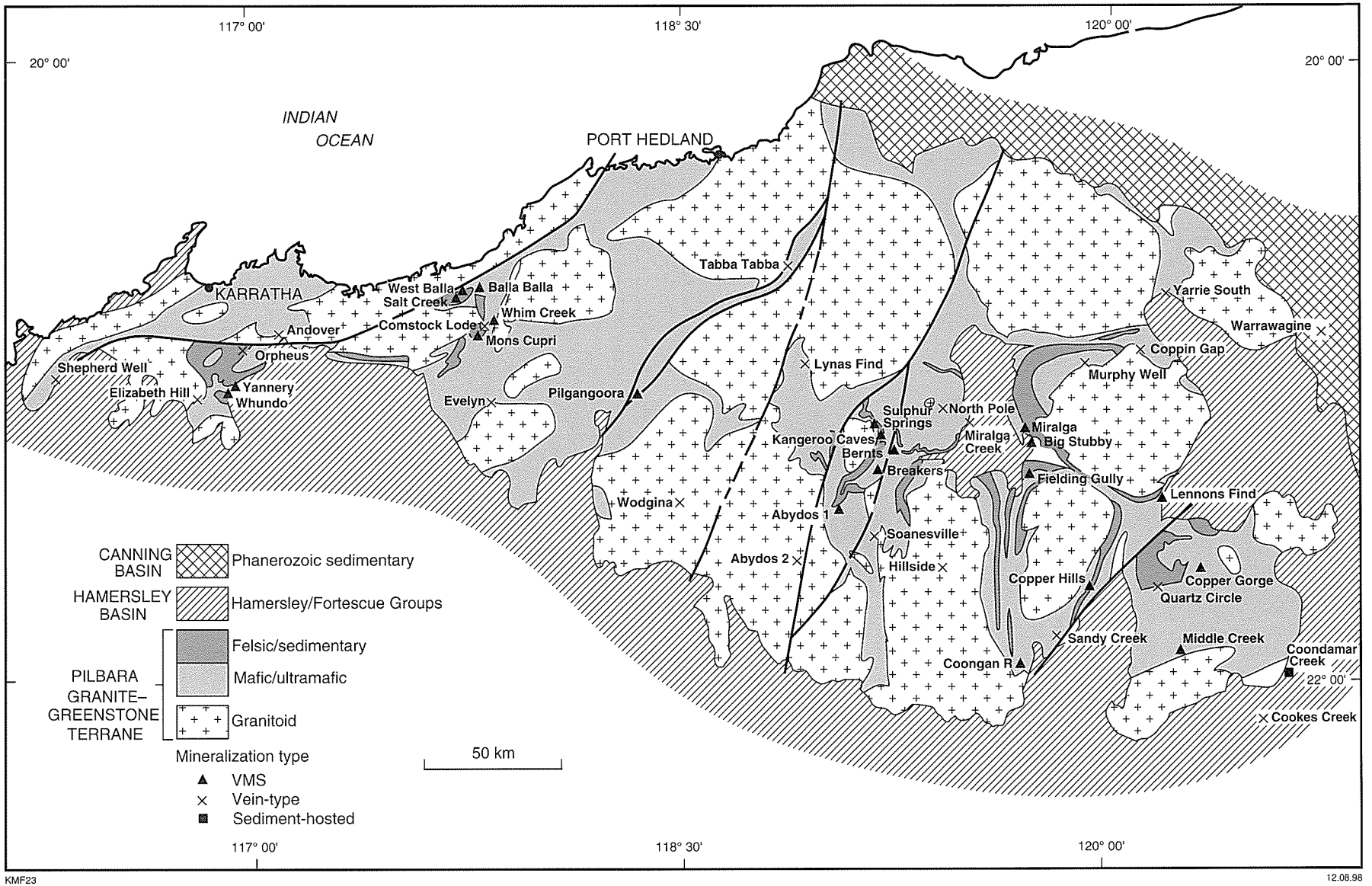

Figure 6. North Pilbara Craton — distribution of lead–zinc–silver occurrences in the Pilbara lithological and tectonic framework

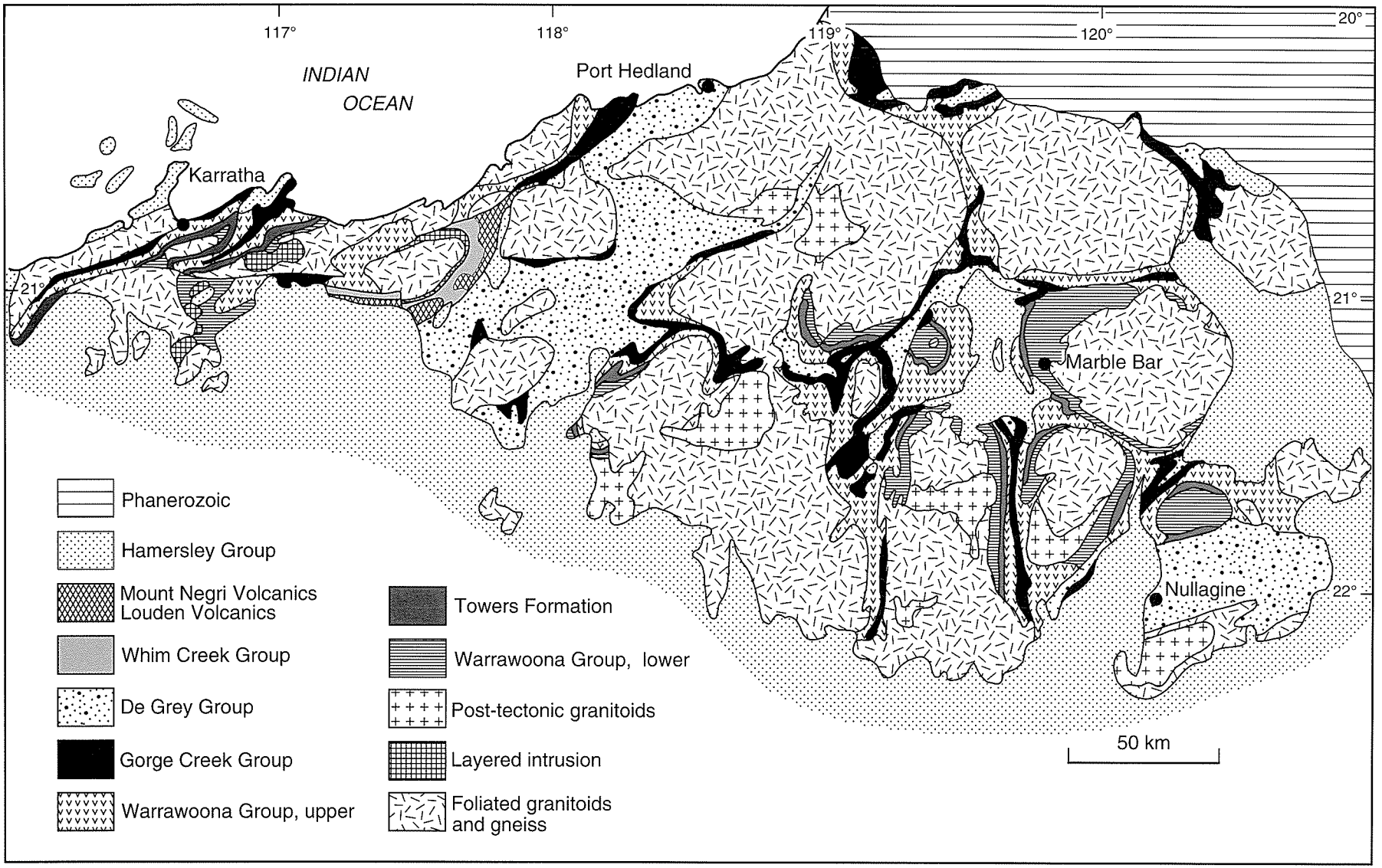

Figure 7. Principal stratigraphic subdivisions of the Pilbara granite–greenstone terrane (*after* Hickman, 1990)

Table 4. Stratigraphy, crustal evolution and mineralization of the Pilbara Supergroup (after **Hickman, 1990**)

Age (Ma)	*Group*	*Formation*	*Average thickness (km)*	*Lithology, comments*	*Depositional environment*	*Deformation, major intrusions*	*Mineralization event*
		Mount Negri Volcanics	0.2	Variolitic tholeiite and andesite. Stratigraphic relations between Mount Negri Volcanics and Louden Volcanics, uncertain. Mount Negri Volcanics unconformably overlie Whim Creek Group	Continental volcanism, probably restricted to the area of the Whim Creek basin	Post-tectonic granite–monzogranite (2840 Ma)	Pegmatite minerals, especially Sn and Ta
		Louden Volcanics	1.0	Ultramafic, mafic, and intermediate volcanics and intrusive units		?D_4. Open folds (age uncertain) Layered intrusions	PGE and Ni (2925 Ma)
				Unconformity			
	WHIM CREEK GROUP	Rushall Slate	0.2	Cleaved semi-pelite and pelite (slate), local tuff and andesite proximal facies of the volcanic-sedimentary succession	Ensialic fault-bounded basin. Slate and volcanics are distal and Granite–monzogranite	D_3. Strike-slip faults and transpressional folding. Conjugate folds. Volcanogenic Cu–Pb–Zn	
2990		Mons Cupri Volcanics	0.5	Rhyolite and pyroclastic overlain by intermediate lava, pyroclastics, chert, and sandstone			
		Warambie Basalt	0.2	Amygdaloidal tholeiitic basalt, local volcaniclastic breccia and clastic sedimentary rocks			
		Tectonic contact			Erosion of local granitoids	D_2 M. Mosquito Creek Orogeny. Two phases of upright folding. Granodiorite–granite	Epigenetic gold
	DE GREY GROUP	Mosquito Creek Formation and similar formations	5.0	Psammitic to pelitic schist. Greywacke turbidites. Minor conglomerate, chert, and BIF	Isolated intracratonic basins located in rapidly subsiding areas. Deep erosion of folded Warrawoona and Gorge Creek		
		Lalla Rookh Sandstone and similar formations	3.0	Sandstone and conglomerate. Some De Grey Group successions include basalt	Groups to expose underlying granitoids		Placer gold
				Regional unconformity			
3270–3310						D_2W. Warrawoona Orogeny. First major regional diapirism. Metamorphism to upper amphibolite facies. Granodiorite–monzogranite	Epigenetic gold. Porphyry-related Cu–Mo (Coppin Gap)
	GORGE CREEK GROUP	Honeyeater Basalt	1.0	Pillow tholeiite and minor high-Mg basalt	Local shield or fissure eruption		
		Cleaverville Formation	1.0	BIF and chert intercalated with mudstone, shale, and tuff	Basin plain to lower- or mid-fan deposits, probably over hundreds of kilometres		
		Charteris Basalt	1.0	Pillow tholeiite and minor high-Mg basalt	Local shield or fissure eruption		

Table 4. (continued)

Age (Ma)	*Group*	*Formation*	*Average thickness (km)*	*Lithology, comments*	*Depositional environment*	*Deformation, major intrusions*	*Mineralization event*
		Corboy Formation	1.5	Sandstone, siltstone, shale, and minor chert	Shallow shelf; some turbidites		
					Local unconformity		
3325		Wyman Formation	1.0	Porphyritic rhyolite. Local tuff, agglomerate and basalt. Age and common basal unconformity require exclusion from the Warrawoona Group	Widespread, but laterally discontinuous felsic volcanism	Tonalite–monzogranite	Massive Cu–Zn (Sulphur Springs)
					Unconformity		
					Extensive erosion of underlying formations	D_1–D_2. Early diapric movement in some areas. D_1, recumbent folds and thrusts towards the base	Epigenetic gold Porphyry-related Cu–Zn (Miralga Creek, 3449 Ma) of the Warrawoona Group
3452	WARRAWOONA GROUP	Euro Basalt	2.0	Pillow tholeiite with minor chert and felsic volcanic units	Shallow-water lava plain, broken by islands of eroding Duffer Formation volcanic cones and active Salgash felsic centres. Basalt chiefly erupted from fissure along present greenstone belt areas		
3457	Salgash Subgroup	Panorama Formation	1.0	Sandstone with felsic lava, tuff, and agglomerate overlain by chert			
		Apex Basalt	2.0	Pillow tholeiite and komatiite. Local periodotitic komatiite. Thin cherts common			
		Towers Formation	0.5	Thick chert units separated by basalt, felsic volcanics or clastic sediments	Shallow-water deposition. Carbonates, volcanogenic sediment, evaporites and silica gels		Barite (partly replacing gypsum)
				Hiatus			
3465–3471					Erosion of Duffer Formation centres		
		Duffer Formation	5.0	Andesitic to rhyolitic lava, pyroclastics, and volcanogenic sediments. Some sandstone, chert and basalt	Partly subaerial intermediate-felsic volcanic centres spaced at about 50 km. Extensive aprons of shallow-water volcanogenic sediments	Tonalite–granodiorite	Volcanogenic Cu–Pb–Zn–Ag (3465)
					Local unconformity		
						Local deformation	
		Mount Ada Basalt	2.0	Pillow and massive tholeiite. Minor chert, shale and felsic tuff			
	Talga Talga Sub-group	McPhee Formation	0.1	Carbonate–quartz ± chlorite schist, with thin BIF and chert units	Ensialic, relatively shallow-water platform extending across hundreds of kilometres. Lava plains from fissure eruptions or gently sloping shield volcanoes		
?3500		North Star Basalt	2.0	Massive and pillow tholeiite. Some komatiite and rare chert			

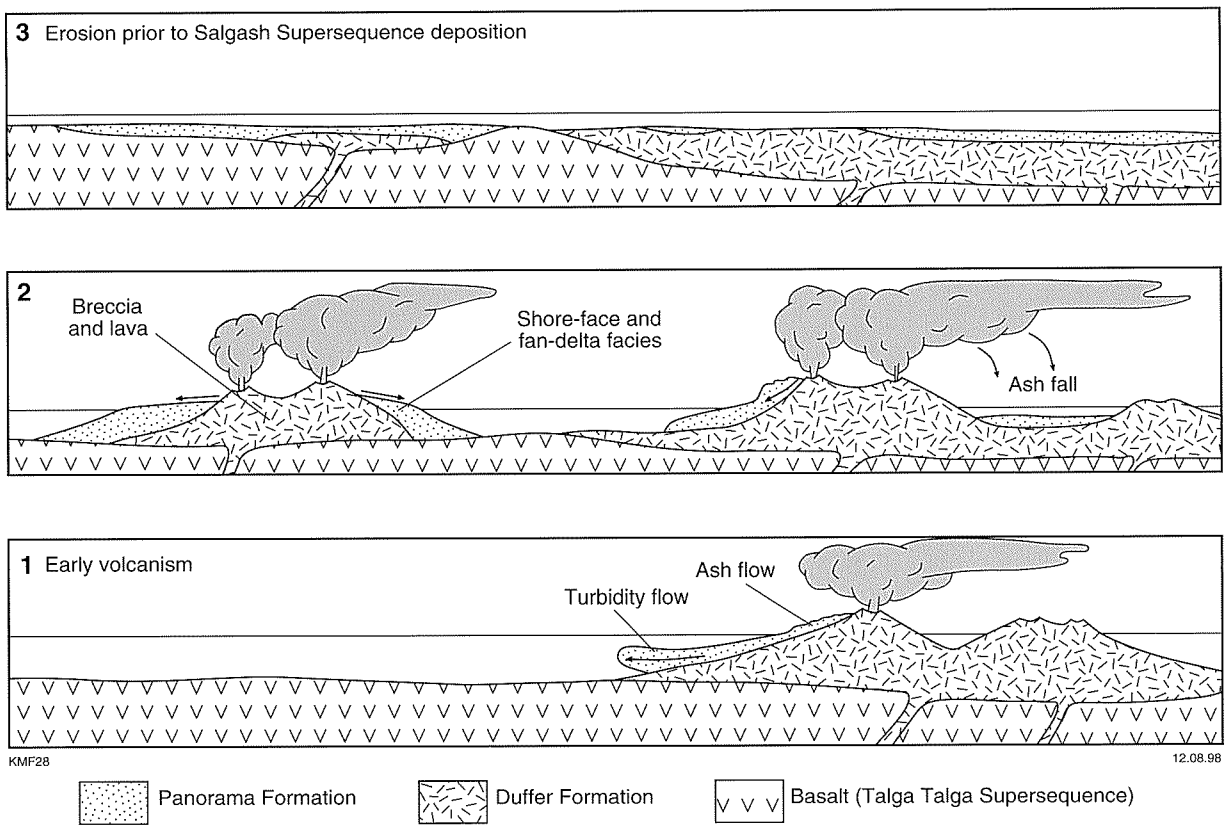

Figure 8. Interpreted evolution of the Duffer Supersequence (Formation) in the east Pilbara (Krapez, 1993, *modified from* DiMarco and Lowe, 1989 and Barley, 1993)

Warrawoona Group and considered the compositional range of the volcanics to be similar to younger tholeiitic and calc-alkaline suites developed over subduction zones. The evolving depositional setting of the Duffer Formation of the Warrawoona Group is depicted in Figure 8. The upper part of the Warrawoona Group, the Salgash Subgroup, is dominated by basaltic volcanism following a hiatus represented by cherts of the Towers Formation.

Widespread, but laterally discontinuous felsic volcanism follows an unconformity at the top of the Warrawoona Group, related to a major phase of granitoid diapirism and felsic magmatism. The Wyman Formation (3.325 Ga) is associated with VMS mineralization at Sulphur Springs, on the flanks of the Strelley Dome. The overlying Gorge Creek Group is sediment-dominated with intermittent basaltic volcanism (Hickman, 1990). However, recent dating of the Sulphur Springs mineralization, and the synvolcanic Strelley Granite, in the range 3.24 to 3.26 Ga (see below), has led Morant (1995) to suggest that the informally named Strelley succession is not part of the Wyman Formation. Hickman (1990) interpreted the Cleaverville Formation as extending across the greater part of the Pilbara granite–greenstone terrane, deposited in a variety of environments. Further diapirism and widespread orogenic activity occurred at the end of the Gorge Creek Group and are indicated by a regional unconformity.

Subsequent volcanism and sedimentation in the De Grey and Whim Creek Groups is considered to have been substantially confined to the present areas of outcrop and deposited in separate, fault-controlled basins. Bimodal volcanism in the Mons Cupri Volcanics of the Whim Creek Group (2.99 Ga, Barley et al., 1994) provides a third locus for VMS mineralization in the west Pilbara. The environment is interpreted as terrestrial to marine within a rapidly subsiding ensialic graben.

Deformation within the greenstones, including major upright folding, has been interpreted as related to diapirism. As mentioned above, however, diapirism occurred over a period between 3.34 and 2.95 Ga in at least four phases, and with variable timing in different areas. A later phase of horizontal, or subhorizontal, deformation is indicated by major strike-slip faults and related folding between 3.0 and 2.8 Ga.

Some qualifications of the above summary of granite–greenstone evolution in the Pilbara are suggested by the comprehensive stratigraphic reassessment of Krapez (1993). The study incorporates recent detailed stratigraphic and structural mapping and analysis and an update of geochronological data. First- and second-order sequence-stratigraphic techniques, normally applied to Phanerozoic terrains, are adopted and the resulting scheme related to first-order Wilson-style cycles of sea-level changes and craton break-up and assembly.

This reassessment gives more prominence to north-east–southwest trending lineaments, active over a long period, which are considered to divide the Pilbara Craton into five tectonostratigraphic domains and control the distribution of volcanism and sedimentation in separate basins (Fig. 9). Table 5 (*after* Krapez, 1993) shows the stratigraphic/domain distribution in simplified form.

The four main stratigraphic groups in the Pilbara are elevated to megasequence status and a comparison of Tables 4 and 5 shows some significant differences from the scheme of Hickman (1990). They are considered to represent four megacycles of fore-arc, arc, and/or back-arc geotectonic evolution and, as such, have a significant bearing on the recognition of environments favourable to the formation of VMS deposits. Among the fairly major changes are the restriction of the first pair of megacycles (Warrawoona and Gorge Creek, 3.49 to 3.11 Ga) predominantly to the east Pilbara (domains 2 and 3), whereas the second pair (Roebourne and Mount Negri, 3.11 to 2.77 Ga) are predominantly of the west Pilbara. Domains 4 and 5 are almost totally made up of Roebourne and Mount Negri sequences. On the basis of this interpretation Krapez (1993) has suggested a model which implies diachronous westward growth of the Pilbara greenstone succession.

It should be pointed out, however, that the isotopic age of 3.11 Ga, based on zircon data in the Mount Sholl area (Horwitz and Pidgeon, 1993), does not necessarily have relevance in the east Pilbara. This date is also in some doubt in the west Pilbara due to its source being in proximity to a shear zone intruded by granitoid (Hickman, A.H., 1995, pers. comm.). Hickman (1990) considered the Sholl Belt to be part of the Warrawoona Group, a view shared by Hoatson et al. (1992). In the absence of detailed stratigraphic studies and unambiguous geochronological data, Collins and Marshall (b, this volume) accept the figure of 3.11 Ga. In the Whim Creek belt, Collins and Marshall (a, this volume) consider the Warrawoona Group, recognized through its pronounced and distinctive magnetic signature, to underlie most of its western end.

Many other separations and realignments of previously defined units have been effected within the framework erected by Krapez (1993). For example, the volcanic unit previously correlated with the McPhee Formation (lower Warrawoona Group in the east Pilbara) is placed within the Gorge Creek fore-arc cycle along with the overlying Mosquito Creek Formation.

Also emphasized in this study is the possibility of unrecognized structural repetitions in many of the belts and the need for more detailed mapping to resolve or refine the stratigraphy. These conjectural features are in part invoked to account for differences between the revised stratigraphy and that of Hickman (1990).

While acknowledging the need for further detailed and regional studies to fully resolve the differences between the two schemes, they offer the opportunity to examine the distribution of VMS-favourable, calc-alkaline felsic volcanism and related arc and back-arc basinal settings. Relating this to the distribution of known deposits and occurrences may highlight areas of relatively untested potential.

Mineralization

As noted above, VMS mineralization discovered to date in the Pilbara Craton is predominantly located in calc-alkaline volcanic/sedimentary sequences, specifically the Duffer and Wyman Formations and the Whim Creek Group.

Barley (1992) has drawn attention to differences between the settings and styles of mineralization in the east and west Pilbara and has attempted to draw parallels with the contrasting styles and models of Phanerozoic and Archaean, particularly Canadian, VMS deposits.

In the east most occurrences of mineralization, including the larger deposits at Big Stubby and Lennons Find, contain zinc, lead and copper with barite and are within the Duffer Formation (~3.465 Ga) of the Warrawoona Group in shallow to deeper water felsic calc-alkaline lavas, pyroclastics and volcanogenic sedimentary rocks deposited in volcanic-arc and near-arc basins (Figs 10 and 11). For the Warrawoona Group, and more specifically the Duffer Formation host rocks, the ranges of SiO_2, large ion lithophile (LILE) and REE abundances and high levels of Pb (>20 ppm) (*see* Table 12) led Barley (1992, 1995) to consider the relatively shallow-water dacites and rhyolites to have more in common with modern calc-alkaline volcanics erupted through continental crust or thick sedimentary wedges than more typical island-arc volcanics. The shallow water/subaerial setting is also supported by widespread hydrothermal alteration, which has produced strongly carbonated rocks, with increasing intensity in the Duffer and Salgash sequences (Barley, 1984). The mineralization at Big Stubby and Lennons Find, with significant barite and high lead contents, and the association with porphyry/epithermal copper–zinc–gold mineralization such as at Miralga Creek (*see* **Chapter 8**), are also indicative of parallels with Phanerozoic settings and Kuroko-type deposits.

The recently discovered Panorama Zn–Pb–Cu mineral province is located within the Strelley succession (~3.24–3.26 Ga) and overlying units of the Gorge Creek Group. This mineralization is also barite rich and occurs at the top of the Strelley succession, which is made up of silicic and felsic volcanic and volcaniclastic rocks interpreted to have been deposited in alluvial to submarine environments in a back-arc cratonic rift basin or island-arc setting. Buick and Doepel (this volume) suggest at least moderately deep water for the succession, owing to the presence of turbidites and indications of a high confining pressure. Vearncombe (1995) suggested a depth range between 1000 and 2000 m. For mineralization at Panorama, model Pb–Pb ages of around 3.26 Ga have been recorded (Vearncombe et al., 1994). A SHRIMP U–Pb age of 3.24 Ga for the Strelley Granite has been reported by Morant (1995).

In the west Pilbara mineralization is within the partly subaerial volcanic, volcaniclastic and terrigenous Whim

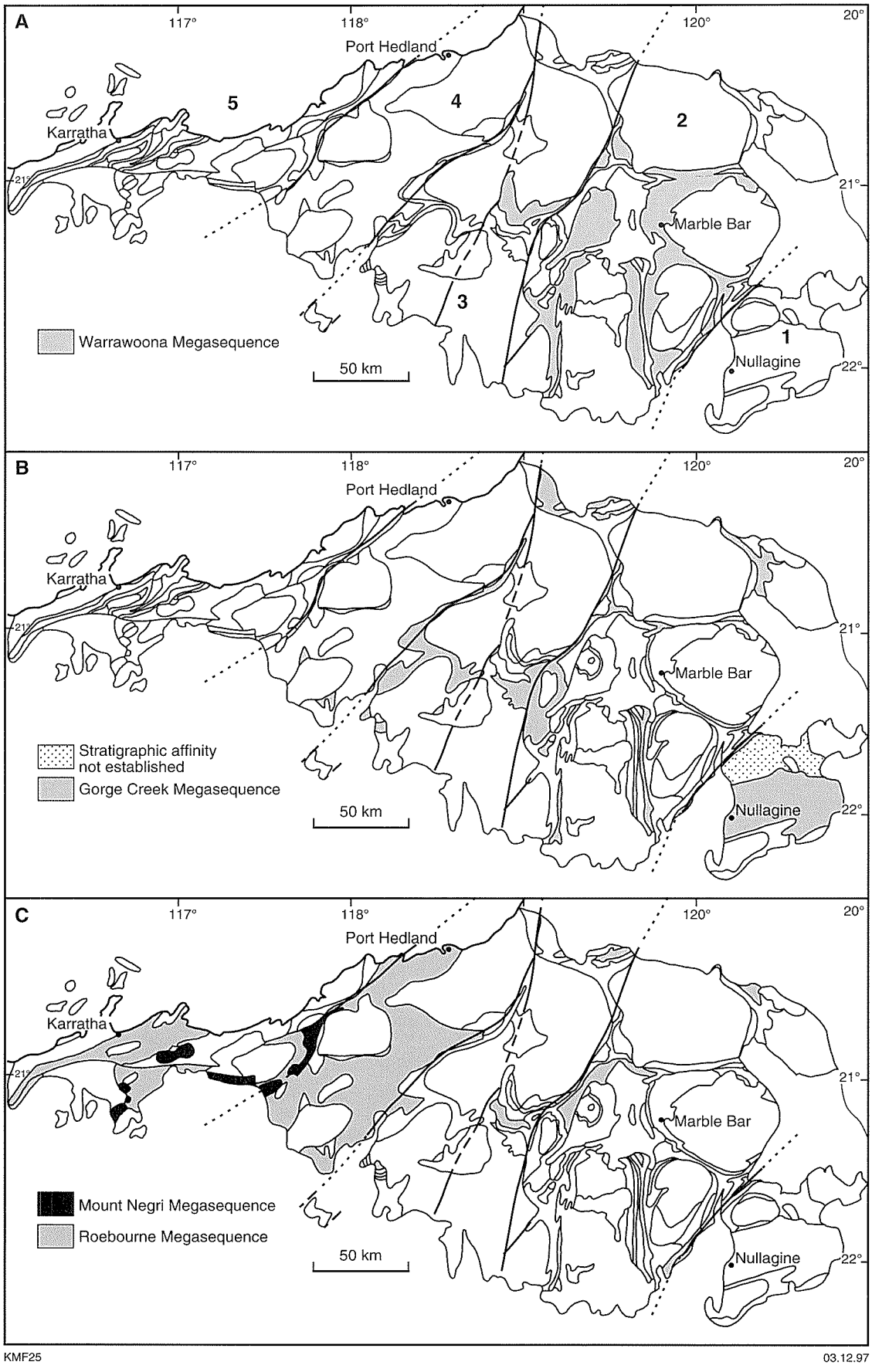

Figure 9. Outcrop of megasequence-status stratigraphic units in the Pilbara Craton (*after* Krapez, 1993)

Table 5. Supersequence stratigraphy of Archaean greenstone belts of the Pilbara Craton, showing lateral equivalence in the five tectono-stratigraphic domains (after **Krapez, 1993**)

Megasequence		*Component supersequences* — *Domain 5*			*Domain 4*		*Domain 3*		*Domain 2*		*Domain 1*		*Age (Ga)*
MOUNT NEGRI		**Negri**	Intracratonic graben: Mafic volcanics, Fluvial sediments										
		~~ *1st order unconformity* ~~~											2.95–2.925
ROEBOURNE	Retroarc geotectonic set	**Whim Creek**	Transitional rift: Mafic–felsic volcanism, Volcaniclastic and terrigenous sediments	Retroarc geotectonic set	**Lalla Rookh Budjan Creek**	Strike and slip graben: Terrigenous clastic sediments							
		Cleaverville	Ocean basin platform: Iron-formation		**Goldsworthy**	Retroarc basin *molasse*: Terrigenous clastic sediments, Mafic volcanics							
		Regal–Sholl	Arc-forearc/Ocean basin-island: Felsic volcani- and pyroclastics, Marine sediments/mafic volcanics		**Mallina**	Retroarc basin *flysch*: Terrigenous clastic sediments, Felsic volcanics							
		~~ *1st order unconformity* ~~~											3.26–3.11
				Backarc geotectonic set	**Paddy Market**	Marginal foredeep: Turbidites and iron-formation			Forearc geotectonic set	**Mosquito Creek**	Forearc basin: Epi- and volcaniclastic sedimentation		
GORGE CREEK					**Corboy**	Back-arc cratonic basin: Volcaniclastic and terrigenous sediments, Mafic volcanics				**McPhee**	Volcanic arc and inter-arc basin: Silicic volcanics, Tholeiitic volcanics, Calc-alkaline volcanics		
							Back-arc cratonic rift basin: Silicic and felsic volcanics and volcaniclastics	**Wyman**		Mafic volcanics			
													3.325
		~~ *1st order unconformity* ~~~											3.43–3.34
WARRAWOONA							**Salgash**	Marginal basin: Mafic volcanics, Volcaniclastic sediments					
													3.455
							Duffer	Volcanic arc and near-arc basins: Shallow marine volcaniclastics, Felsic volcanics/mafic volcanics					
													3.475
							Talga Talga	Oceanic island remnant					
		~~ *Tectono-magmatic boundary* ~~~											3.49

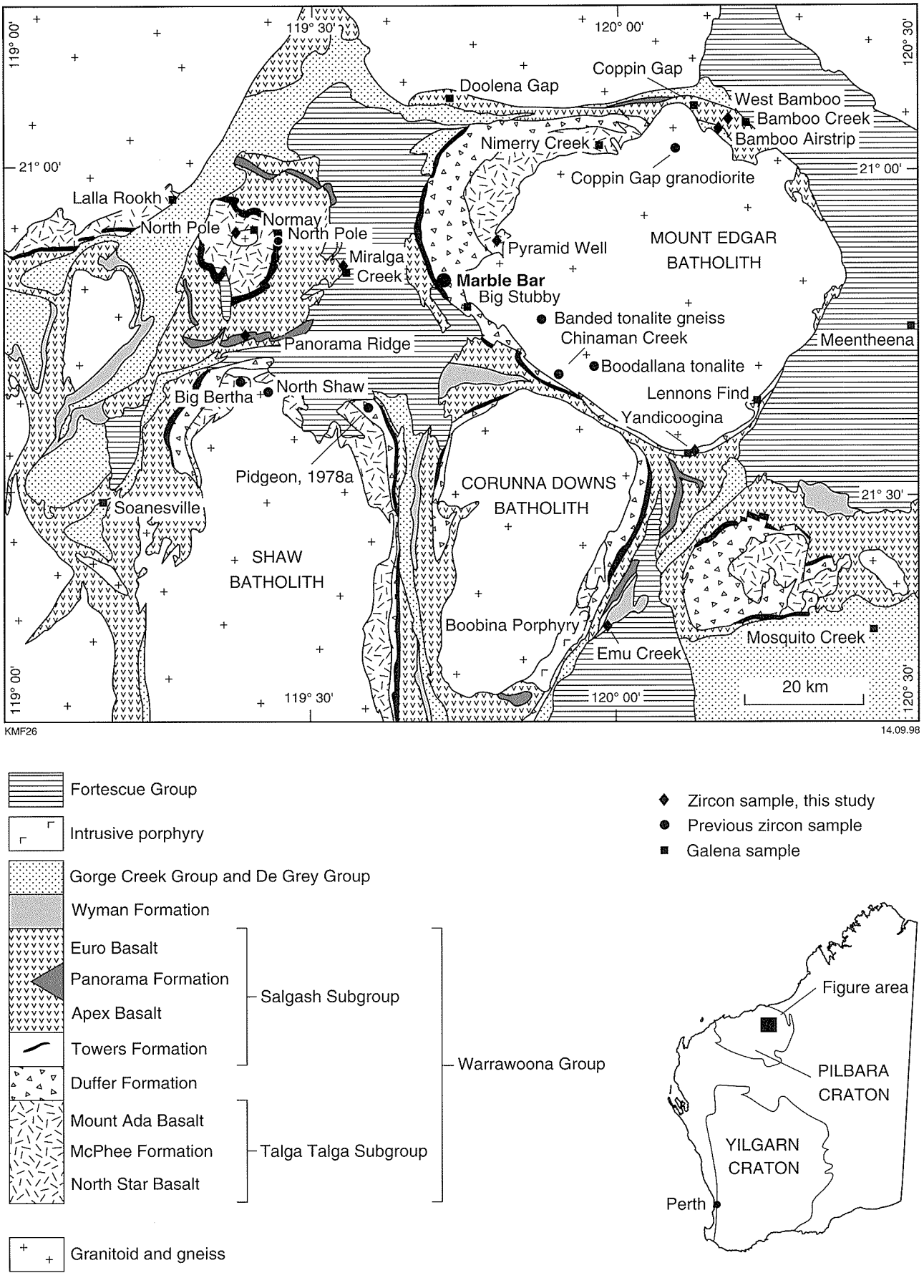

Figure 10. Geological compilation map of the Marble Bar region showing locations of lead–zinc–copper prospects and deposits, zircon geochronology sites and galena specimens (*after* Thorpe et al., 1992a)

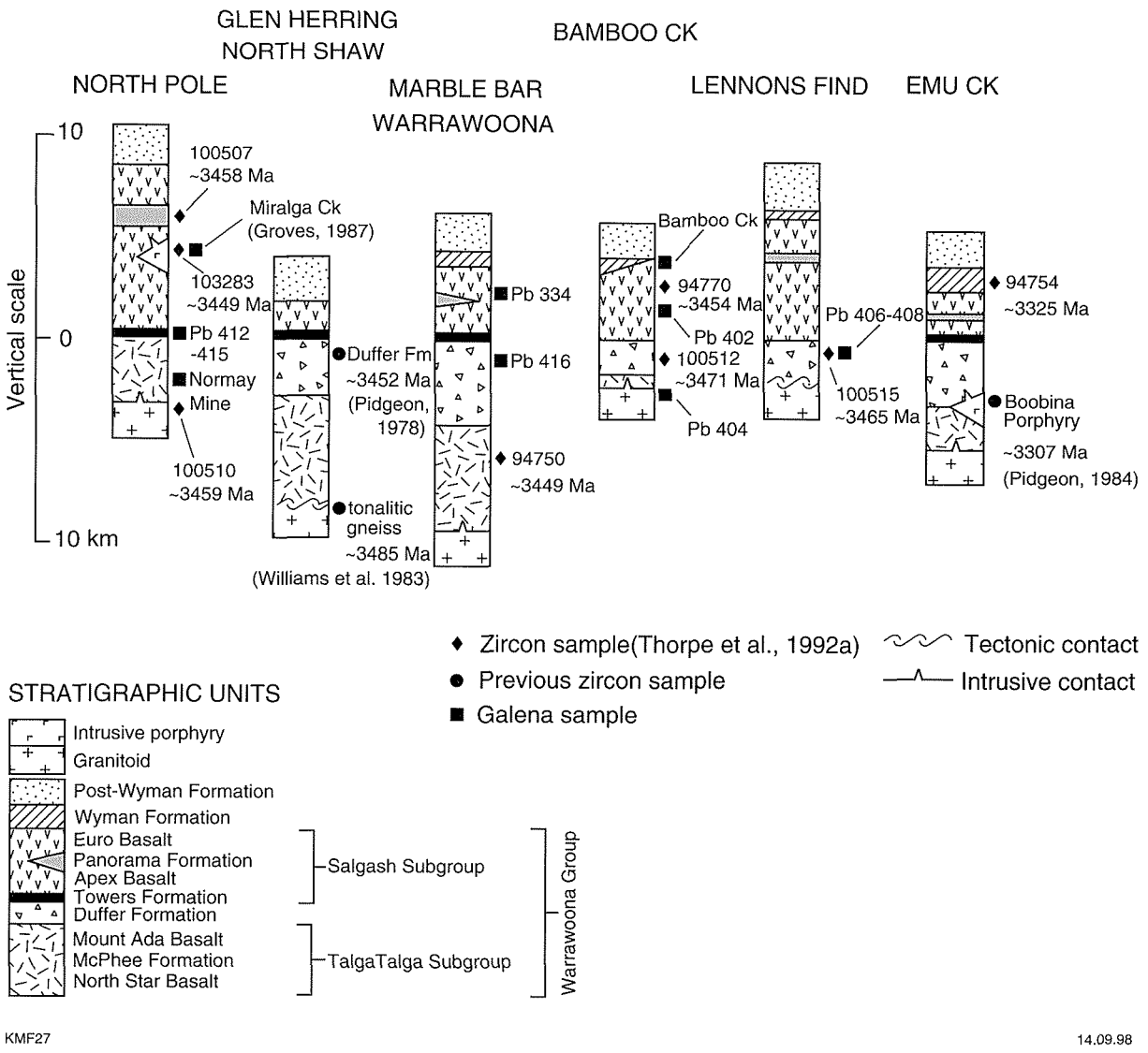

Figure 11. Stratigraphic columns for the Marble Bar region showing positions of geochronology sites and galena specimens (*after* Thorpe et al., 1992a)

Creek Group (~2.99 Ga), deposited in a rift-controlled cratonic basin and possibly associated with the development of resurgent submarine calderas in the belt (Collins and Marshall (a), this volume). Stockwork and lensoid Zn–Pb–Cu mineralization at Mons Cupri seems to have formed in relatively shallow water within the rapidly subsiding basin. This is suggested by the presence of terrigenous sediments of local derivation within the sequence. Stratabound Cu–Zn mineralization at Whim Creek and Zn–Pb–Cu mineralization at Salt Creek is associated with more distal, deeper water facies in the basin. The small volcanic-hosted Cu–Zn sulfide deposits at Whundo, Whundo West and Yannery in the Sholl Belt of the west Pilbara (Collins and Marshall (b), this volume) are typical of Archaean volcanogenic deposits, being located at a major stratigraphic change from mafic to more felsic volcanism within a bimodal sequence.

In the Whim Creek Group the dacitic and rhyolitic units also have relatively high large-ion lithophile element and lead contents, fractionated REE patterns and negative Eu anomalies and are transitional between calc-alkaline and tholeiitic compositions. At Mons Cupri the stratiform Zn–Pb–Cu lens in chert and volcaniclastic rocks is underlain by a copper-rich stockwork zone affected by iron-rich chlorite and carbonate alteration. On the basis of host-rock chemical features and the metal ratios of the mineralization, particularly high lead contents, Barley (1992) considered that it has strong affinities with modern Kuroko-type deposits. Stratabound mineralization at Whundo and at Whim Creek, however, is low in lead and considered more typical of Archaean VMS deposits. The somewhat conflicting evidence in the west Pilbara suggests that the use of lithogeochemical profiles as a means of determining the 'fertility' and style of host/mineralization VMS assemblages (*see* **Chapter 9**) may as

yet be an imperfect guide, and possibly affected by secondary features (Whitford and Ashley, 1992).

Barley (1992) and Barley and Groves (1984) argued that shallow-water environments with extensive reworking of pyroclastic deposits, associated with the east Pilbara VMS mineralization, are less prospective for this type of mineralization than deeper water environments characterized by mass-flow deposition of tuff breccias, turbidites, turbiditic tuffs, shales and chemical sediments. At water depths of less than 250 m it seems likely that boiling of hydrothermal fluids occurs well below the sediment–water interface allowing little or no precipitation of lead and zinc, and certainly no copper, at the sea floor. If sea-floor mineralization did occur at shallow depths it is also likely that oxidation and erosion would prevent its preservation. This seems to be reflected in the relatively small size of the deposits in the east Pilbara.

Exploration history

A number of volcanogenic copper–lead–zinc sulfide bodies in the Pilbara greenstones were discovered by prospectors and worked to a degree in the 1890s and early 1900s. In the west Pilbara, the Whim Creek copper deposit was discovered around 1886 but production peaked between 1909 and 1914. Mons Cupri, discovered in 1897, was also worked for copper prior to the First World War. Whundo has been known since 1912 and both Whundo and Yannery were mined sporadically for copper from the 1920s to about 1976. In the east Pilbara, Lennons Find was discovered in 1907 and worked intermittently from then to the 1950s. Gossans were known in the Big Stubby area at the turn of the century but the only activity at that time was the excavation of a minor trench.

Modern exploration for volcanogenic targets began in the Pilbara in the 1960s with Westfield/Whim Creek carrying out regional reconnaissance extending into the Ashburton Basin Gascoyne Complex and Bangemall Basin (I 3227). Whim Creek also carried out detailed evaluations of the Whim Creek mine and, with Texasgulf, the Mons Cupri deposit (I 2097). The presence of these known deposits, and the recognition of the potential of the Pilbara for Canadian-style VMS deposits, led to the reassessment and evaluation of prospects such as Lennons Find by Westfield (I 3227) and later Cominco and Serem (I 6230), and Big Stubby by Newmont and Narla. A flow-on effect saw continuing exploration through the 1970s and early 1980s particularly in the Whim Creek Belt and in the broad belts of the east Pilbara including the Marble Bar Belt, the Warrawoona Syncline, the McPhee Dome, the Coongan and Kelly Belts, and the Shaw and Soansville Belts. Many of the prospects located in the east Pilbara were interpreted as being hosted at a particular stratigraphic level corresponding with the felsic volcanics of the Duffer Formation in the Warrawoona Group. More recent exploration in the Whim Creek Belt and the Sholl Belt is considered in detail in the next section.

From the mid-1980s the exploration focus shifted towards gold. Although exploration for volcanogenic targets declined, a notable exception to this trend was the work of the Sipa–Ashling joint venture in the Panorama area on the eastern margins of the Strelley Granite (Buick and Doepel, this volume).

Deposits, prospects and occurrences

West Pilbara

Whim Creek group (Mons Cupri, Salt Creek, Whim Creek)

Volcanogenic base-metal deposits of the Whim Creek Belt

Contribution by P. L. F. Collins[1] and A. E. Marshall[2] (a)

Lead–zinc–silver mineralization within the Whim Creek volcanic belt in the western Pilbara Craton, in north-western Western Australia (Fig. 6), is dominated by volcanogenic base-metal sulfide deposits, the largest being at Whim Creek, Mons Cupri and Salt Creek (Fig. 12). Although individually relatively small for this type of ore deposit, in the order of 0.7–3 Mt of stratiform sulfide mineralization, they are a major resource of lead, zinc, copper, silver and gold in the Pilbara Craton with a combined resource of some 6 Mt of oxidized and sulfide ore (Table 6).

The Mons Cupri and Whim Creek deposits are among the best-preserved volcanogenic massive-sulfide deposits in Archaean cratons. Published descriptions of these and other deposits in the Whim Creek Belt have been prepared by Low (1963), Miller and Gair (1975), Reynolds et al. (1975), Marston (1979), Smith (1980), Gunn and Chisholm (1984), and Lebel and Fallon (1994). They have also been described briefly in broader studies dealing with the geology of the volcanic belt (e.g. Fitton et al., 1975; Hickman, 1983; Barley, 1987) and in general reviews of Western Australian base-metal deposits (e.g. Blockley, 1971; Davies and Blockley, 1990; Barley, 1992). Additional data for this review have been drawn from theses by Koehler (1974), Farrell (1978), Taylor (1978) and Tanner (1990), from a number of unpublished company reports, and unpublished mapping by the authors.

There is no recorded production of zinc from the Whim Creek volcanic belt and the only silver–lead ore produced has been won from the Comstock lode (formerly Colorado silver–lead mine) about 600 m south of Mons Cupri Hill. Although the Comstock lode apparently was first mined in 1898, the total recorded production of 191.5 t of hand-picked ore grading 40.8% Pb and 150 g/t Ag came from a few short periods of mining between 1915 and 1953 (Blockley, 1971).

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Table 6. Tonnage and grade data for principal volcanogenic sulfide deposits in the Whim Creek volcanic belt and Sholl Belt, west Pilbara

Deposit *Ore type*	*Tonnage* *Mt*	*Zn* *%*	*Pb* *%*	*Cu* *%*	*Ag* *g/t*	*Au*[a] *g/t*	*Zn* *number*[b]	*Source*[c]
Whim Creek volcanic belt [2.99 Ga]								
Whim Creek								
Oxide ore	1.367	0.10	0.24	1.59	9.60	–	29	1
Transition ore	0.305	0.52	0.39	2.02	8.91	–	57	1
Sulfide ore	1.035	1.30	0.20	1.59	8.57	–	87	1
Total reserves (at av wt%)	**2.707**	**0.61**	**0.21**	**1.64**	**9.13**	**–**	**74**	**1**
Mons Cupri [2.93 Ga]								
Mineable reserves:								
Oxide ore	1.509	–	–	1.13	–	–	–	2
Sulfide ore	1.384	2.48	1.13	1.74	46	0.49	69	2
Geological resource:								
Stratabound ore	1	5.3	3.0	1.0	56	–	64	3
Stockwork ore	11–15	–	–	1.1	–	–		3
Salt Creek [2.94, 2.95 Ga]								
Geological resource								
Lens A	0.475	8.4	3.3	1.25	43	–	72	4
Lens B	0.1	8.9	2.2	1.1	68	–	80	4
Sholl Belt [3.11 Ga]								
Whundo–Whundo West								
Geological resource	2	1.3	–	2	11	–	99	5

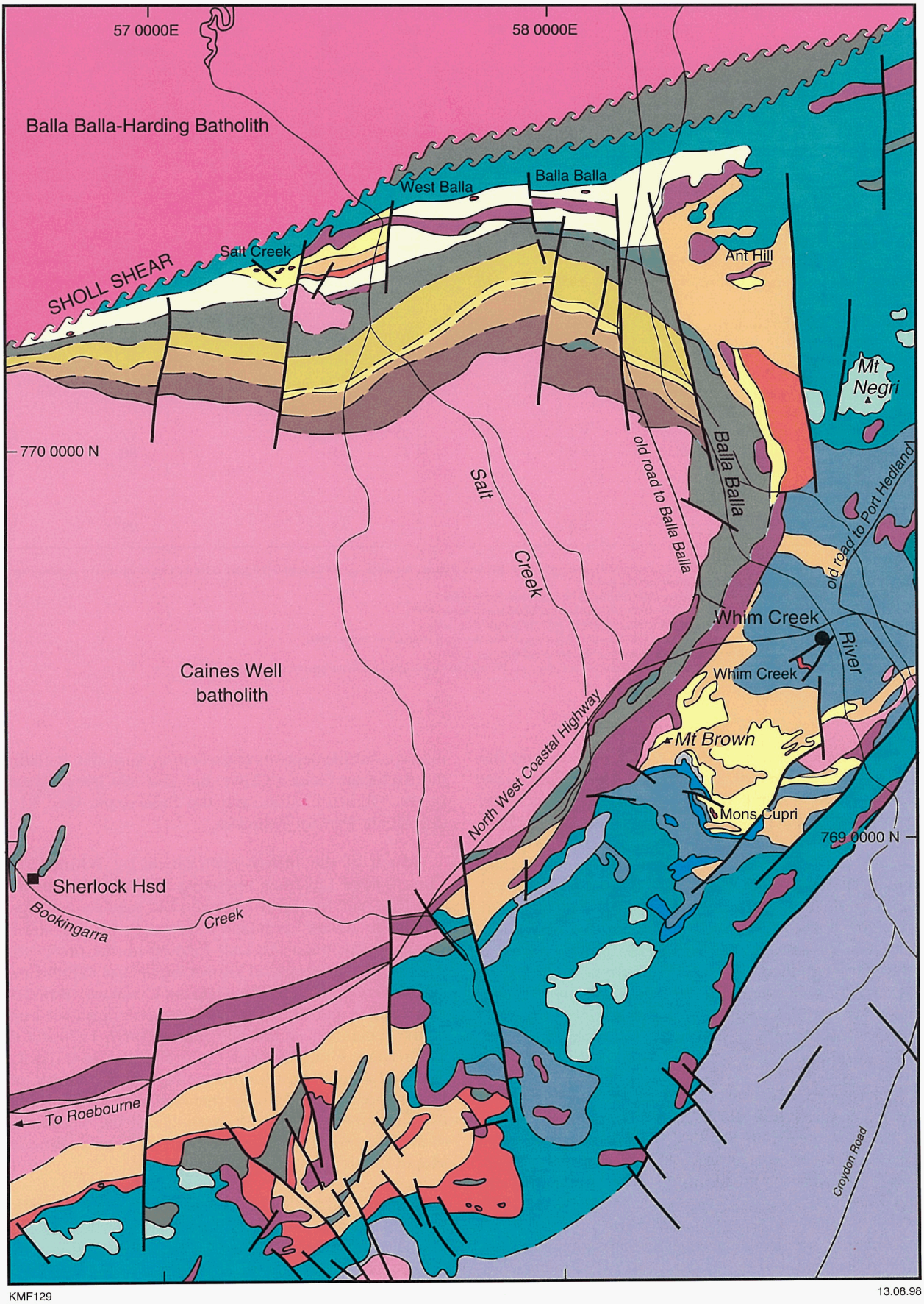
NOTES: (a) Deposits in the Whim Creek Belt contain minor gold (generally <1 g/t), but assay data are incomplete and the only published grade is for the 'sulfide ore reserve' at Mons Cupri.
(b) Zn number = 100Zn/(Zn + Pb); Huston and Large (1987)
(c) Data sources: 1. In situ ore reserves,1978; Dominion Mining annual report, 1992
2. In situ ore reserves, 1978, 1981; Dominion Mining annual report, 1992
3. Estimated geological resource (Miller, 1973; Miller and Gair,1975)
4. Geological resource, lens A; estimated geological resource, lens B (Smith and Clemen, 1980)
5. Geological resource (Marston 1979; Davies and Blockley, 1990)
(d) Geochronological data in [] are zircon U–Pb ages of the host rocks and Pb-Pb model ages of galena from the deposits (references in text)

The Whim Creek and Mons Cupri deposits and the smaller Rushalls, Federal, and Stranger deposits also were discovered and first mined at the end of the 19th century, but only for copper. During the first half of the 20th century most of the copper produced from Western Australia came from these and other supergene enriched deposits in the Pilbara Craton (Marston, 1979). Total copper production from the Whim Creek volcanic belt during the period 1890–1964 amounted to 114 579 t at 10.1% Cu but there has not been any mining since the 1960s. Although there is no recorded production of zinc, lead, silver or gold from these deposits, some silver at least would have been included in the supergene copper ore (cf. Whundo deposits in the Sholl Belt; Collins and Marshall (b), this volume).

Systematic exploration for base metals in the Whim Creek volcanic belt commenced in the mid-1960s and has continued into the 1990s, involving geological mapping, soil, stream-sediment and bedrock geochemistry, ground and airborne geophysical surveys, and drilling. Most of this exploration was undertaken between 1968 and 1980, during a period of successful application of volcanogenic ore-deposit models to base-metal exploration in Australia (Legge et al., 1984). This period included recognition of the potential of the Mons Cupri deposit and discovery of the Salt Creek deposit in the Whim Creek Belt and the discovery of volcanogenic massive-sulfide deposits elsewhere in Australia, including the Archaean Golden Grove and Teutonic Bore deposits in the Yilgarn Craton, and the Palaeozoic Que River deposits in western Tasmania.

Much of the initial exploration by Whim Creek Consolidated Ltd (then operating as Westfield Minerals WA NL) and Texasgulf Australia Ltd (and its associated companies Australian Inland Exploration Co. Inc and Elf Aquitaine Australia Pty Ltd) focused on the prospective geology in the vicinity of known deposits at Whim Creek and Mons Cupri. Utah Development Company carried out an extensive but unsuccessful work program over much of the remainder of the belt during 1969–1974. At the same time, Consolidated Gold Fields Australia Ltd explored a small area to the north of Whim Creek, and Pickands Mather and Co International and Mallina Mining and Exploration tested the remainder of the western end of the felsic volcanic sequence between Nerellys Bore and Mount Fraser.

During 1975–79, Texasgulf continued exploration along the northern flank of the belt after it was realized that the volcanic sequence in the Balla Balla – Salt Creek area is similar to the sequence at Mons Cupri. This lead to the discovery of the Salt Creek deposit in 1977. At the same time, exploration by Texasgulf along the southern flank of the volcanic belt from Mons Cupri west


57 0000E
58 0000E
Balla Balla-Harding Batholith
West Balla
Balla Balla
SHOLL SHEAR
Salt Creek
Ant Hill
Mt Negri
770 0000 N
Salt Creek
old road to Balla Balla
Balla Balla
old road to Port Hedland
Whim Creek
River
Whim Creek
Caines Well batholith
North West Coastal Highway
Mt Brown
Mons Cupri
769 0000 N
Sherlock Hsd
Bookingarra Creek
To Roebourne
Croydon Road
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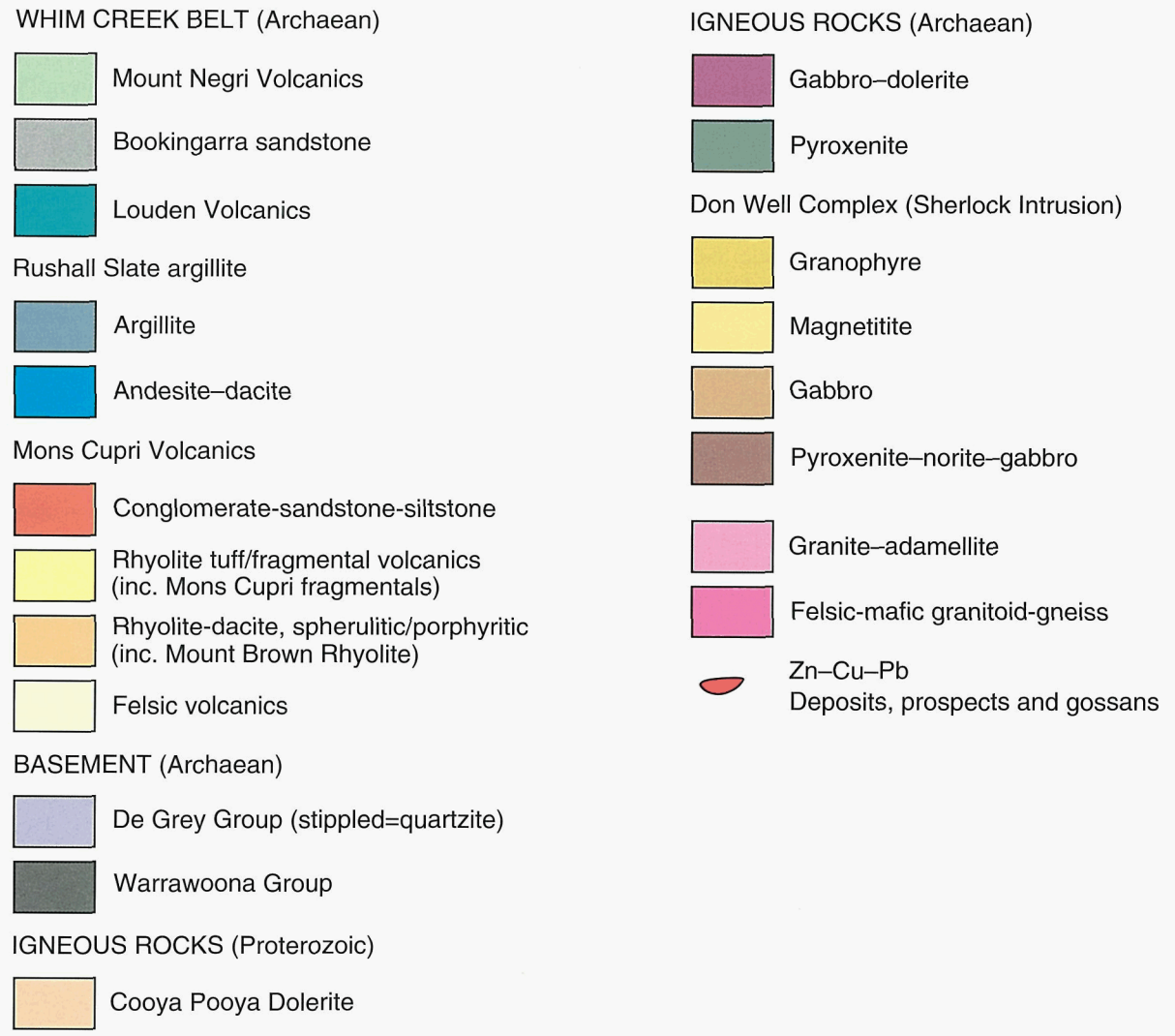


Figure 12. Geology of the Whim Creek volcanic belt, west Pilbara, and location of major volcanogenic sulfide deposits within the belt (*compiled by* Collins and Marshall, 1995)

to the Sherlock River identified several gossans, including some at the Good Luck, Good Gear and Mays Find prospects. Since 1980, exploration programs conducted by Esso Exploration Australia Ltd, Western Mining Corporation Ltd, Duval Mining Australia Ltd, and Dominion Mining Ltd have identified a number of additional prospects but found no significant base-metal or precious-metal mineralization. More recent work by Dominion Mining at Whim Creek and Mons Cupri investigated the feasibility of mining the copper-enriched oxidized components of each resource. Subsequent exploration by Dalrymple Resources focused on the VMS potential adjacent to the Whim Creek and Mons Cupri copper deposits.

Most of the more prospective geology away from the three main deposits is currently being explored by Dalrymple and Sons of Gwalia, who have an interest in several exploration licences and prospecting licences covering much of the remainder of the volcanic belt.

Whim Creek Volcanic Belt

The Whim Creek Belt (Hickman, 1983) is a continuous arcuate belt of mixed felsic and mafic volcanic and sedimentary rocks, some 80 km long and 5–10 km wide, that extends from west of the Sherlock River around the southern, eastern and northern flanks of the ovoid Caines Well batholith (Fig. 12). Although the batholith was labelled the Caines Well Granite by Hickman (1983), it is referred to here as the Caines Well batholith because of its composite nature. The western limit of the southern arm of the volcanic arc is blanketed by Proterozoic rocks, though some workers (e.g. Horwitz, 1988) have suggested that it may extend further west and link up with the Sholl Belt. However, recent zircon U–Pb geochronology indicates that the ages of the two volcanic sequences differ by about 100 m.y. (cf. Horwitz and Pidgeon, 1993; Barley et al., 1994). On the northern flank, the Whim Creek volcanic belt is wedged out between the Caines Well batholith and the Sholl Fault (Fig. 12).

Rocks of the Whim Creek volcanic belt are the youngest tectono-stratigraphic unit in the Pilbara Supergroup (Table 7) and have escaped the main deformation events that affected the remainder of the Pilbara Craton (Barley, 1987). The 2 km-thick volcano-sedimentary sequence unconformably overlies granitoids of the Caines Well batholith and supracrustal sequences of the Warrawoona Group (Fitton et al., 1975; Hickman, 1981, 1990). These rocks also form the basement to the Whim Creek Belt, as indicated by image-processed aeromagnetic data. Rocks of the Warawoona Group, which include komatiitic volcanics, have a pronounced magnetic signature and underlie most of the western end of the belt (Fig. 12) and may outcrop locally within the belt. Two outcrops of ultramafic rock that are described by Miller and Gair (1975) are considered to be tectonically emplaced inliers of highly altered Warrawoona Group rocks. A third outcrop of talc–chlorite–carbonate–magnetite, described by Miller and Gair (1975), is an exotic block of Warawoona Group. The remainder of the belt is underlain by rocks which have a subdued magnetic signature and are interpreted to be the Caines Well batholith or other granitoids. The Gorge Creek Group, also of very low magnetic signature, apparently does not extend north of the Loudens Fault (Fig. 7).

Geochronological data indicate that the age of Whim Creek volcanism, and accompanying base-metal sulfide mineralization, is in the range 3.0–2.95 Ga, based on a number of Rb–Sr isochron, Pb–Pb isochron, Pb–Pb model and Sm–Nd model ages ranging between 3.0 and 2.93 Ga (Compston and Ariens, 1968; Richards, 1983; Richards and Blockley, 1984; Korsch and Gulson, 1986; Fletcher, I. R., pers. comm. *in* Sylvester and de Laeter, 1987) and a zircon U–Pb age of 2.99 Ga for rhyolite from near Mount Fraser at the western end of the belt (Trendall et al., 1990; Barley et al., 1994). The Whim Creek Belt is unconformably overlain by the Mount Roe Basalt, the basal formation of the Archaean Fortescue Group (Table 7).

A stratigraphic succession proposed by Fitton et al. (1975) and redefined by Hickman (1977, 1981, 1983) for the volcano-sedimentary sequence of the Whim Creek Belt is used as a framework here (Table 7), though this has been the subject of much debate (cf. Hickman, 1983; Horwitz, 1979, 1990a; Horwitz and Guj, 1985). Of the five formations recognized within the belt, the three lower formations, the Warrambie Basalt, Mons Cupri Volcanics and Rushall Slate make up the Whim Creek Group

Table 7. Stratigraphy of the Whim Creek volcanic belt in its regional context in the Pilbara granitoid–greenstone terrane (*modified after* **Fitton et al., 1975; Hickman, 1983, 1990; Horwitz, 1979, 1990).**

Stratigraphic unit			*Thickness (km)*
Mount Bruce Supergroup	Turee Group		3.9
	Hamersley Group		2.5
	Fortescue Group		7.6
		Mount Roe Basalt [2770 Ma] [a]	
~ ~	*Unconformity*	~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~	
		Negri Volcanics	0.2
	~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~	*?Unconformity* ~	
		Bookingarra Sandstone	<0.1
	~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~	*Local unconformity* ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~	
		Louden Volcanics	1.0
~ ~	*Unconformity* ~		
	Whim Creek Group	Rushall Slate	>0.2
		Mons Cupri Volcanics	0.5–0.8
		Mons Cupri 'fragmentals'	
		Mount Brown Rhyolite [2990 Ma] [a]	
		Warrambie Basalt	<0.2
Pilbara Supergroup	~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~	*Unconformity* ~	
	De Grey Group		8.0
	~ ~ ~ ~ ~ ~ ~ ~	*Unconformity* [3270–3310 Ma] [a] ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~	
	Gorge Creek Group [3325 Ma][a]		5.5
	~ ~ ~ ~ ~ ~ ~ ~ ~ ~	*Unconformity* ~	
	Warrawoona Group [3450–3500 Ma][a]		14.6

NOTE: (a) Geochronology data in [] are based on zircon U–Pb ages from Hickman (1990), Trendall et al. (1990) and Barley et al. (1994)

(Hickman, 1981, 1983; Table 7). This is overlain unconformably by a sequence of mafic volcanics which is subdivided by Hickman (1977, 1983) into the Louden Volcanics and Negri Volcanics (Table 7), though other workers (e.g. Fitton et al., 1975; Horwitz, 1979; Barley, 1987) have regarded both formations as the Negri Volcanics (or Mount Negri Volcanics *of* Miller and Gair, 1975). In Krapez's (1993) sequence-stratigraphic scheme for the supracrustal belts of the Pilbara Block, the Whim Creek Group is referred to as the Whim Creek Supersequence and the younger basaltic formations are combined as the Mount Negri Megasequence.

The Warrambie Basalt (Fitton et al., 1975) consists of up to 300 m of amygdaloidal, plagioclase-phyric lavas of andesite to tholeiitic basalt composition, with minor intercalated tuffaceous units. At Mount Fraser, the mafic volcanic sequence includes a basal granite breccia and cobble–boulder conglomerate with sandstone and siltstone interbeds (Fitton et al., 1975; Taylor, 1978; Barley, 1987). The sedimentary unit is up to 30 m thick and disconformably overlies the Caines Well batholith and amphibolite-facies metavolcanic rocks of the Warrawoona Group (Fitton et al., 1975, fig. 1). This conglomerate, and granitoid boulders in basal units of the Whim Creek Group near Mons Cupri and on the west flank of Mount Brown (Smith, 1975) and near Salt Creek (Smith and Clemen, 1980), indicate widespread exposure of the Caines Well batholith at the onset of Whim Creek volcanism.

The Mons Cupri Volcanics (Fitton et al., 1975) is a complex sequence of felsic volcanic, volcaniclastic and epiclastic sedimentary rock and felsic intrusive bodies that attains a maximum thickness of about 1000 m. Rapid facies variations, typical of a volcanic environment, preclude accurate stratigraphic correlation along the belt except for a quartz- and feldspar-phyric spherulitic rhyolite member, the Mount Brown Rhyolite (Fitton et al., 1975), that can be traced throughout the belt. Most workers consider this rhyolite to be of extrusive or pyroclastic origin, but it may in part be a subvolcanic intrusive (Sylvester, 1976) or a sill emplaced within the layered sequence (Trendall, A. F., 1994, pers. comm.). On the southern arm of the belt, the Mons Cupri Volcanics occurs mainly as a thin ribbon of felsic volcanics, subparallel to the boundary with the Caines Well batholith (Fig. 12). However, in at least two places the Mons Cupri Volcanics extends across the belt as large ?domal felsic volcanic centres 15–25 km^2 in area (Fig. 12). The Whim Creek and Mons Cupri deposits are on the northern and southern flanks, respectively, of one these volcanic centres, referred to here as the Mount Brown volcanic centre. The other major volcanic centre between Good Luck Well and Stones Well, about 15 km east of the Sherlock River, is referred to as the Nerellys Bore volcanic centre (Fig. 12). In each case, a lava-dominated central zone that includes the Mount Brown Rhyolite is surrounded by intercalated fragmental volcanics and epiclastic sequences. In addition, there may be a third ?domal volcanic centre in the Ant Hill area about 10 km to the north of Whim Creek (Chisholm, 1983b), but this is partially covered by younger formations (Fig. 12).

The Rushall Slate (Hickman, 1983) is an upward-fining sequence 200–400 m thick of turbiditic sandstone, siltstone and argillite, with minor andesitic lavas or sills, that conformably overlies the Mons Cupri Volcanics. It is thickest in three internal depocentres, at Whim Creek, southwest of Mons Cupri, and south of Good Luck Well, which are separated by the Mount Brown and Nerellys Bore felsic volcanic centres (Fig. 12). In the Whim Creek area these pelitic rocks have been referred to as the Whim Creek argillites (Koehler, 1974), as essentially unmetamorphosed black slate, siltstone and minor sandstone beds (Reynolds et al., 1975), and as phyllites (Farrell, 1978; Marston, 1979). The name Rushall Slate is used here to preserve consistency in stratigraphic nomenclature.

The mafic units that unconformably overlie the Whim Creek Group are 400–800 m thick throughout most of the volcanic belt but may be up to 2 km thick in the Mount Negri area to the north of Whim Creek (Fitton et al., 1975; Hickman, 1983; Barley, 1987). The Louden Volcanics is a succession of intermediate, basaltic and ultramafic volcanic and intrusive rocks, commonly with pillow structures and spinifex textures, whereas the Negri Volcanics is predominantly variolitic tholeiitic basalt–andesite lavas (Hickman, 1983). Although lavas from the two formations have similar geochemical characteristics and may represent a differentiation series (Barley, 1987), they have distinct textural differences and are separated by an unconformity (Hickman, 1983). This unconformity may be exposed to the southwest of Mons Cupri where the continuation of an angular unconformity between the Whim Creek Group and an overlying thin sequence of rudaceous sedimentary rocks, referred to as the Bookingarra sandstone (Table 7), forms an erosional surface on spinifex textured basalt (Louden Volcanics). The Bookingarra sandstone consists of a basal massive, matrix supported, cobble–boulder conglomerate that is overlain by a well-bedded sequence of granule–pebble conglomerate, sandstone and siliceous sinter deposits with minor variolitic basalt. These rocks accumulated in a narrow northeast–southwest trending half graben with a growth fault bounding its northwest flank.

Several bodies of dolerite–gabbro and peridotite–pyroxenite that have invaded the Whim Creek volcanic belt may be linked to emplacement of the Sherlock Intrusion*, which may be of similar age to other layered complexes in the west Pilbara. The Sherlock Intrusion is a large, layered mafic–ultramafic intrusion that outcrops along the northern boundary of the Caines Well batholith between the Sherlock and Balla Balla Rivers (Fig. 12). At the base of the differentiated intrusion there is an interlayered sequence of orthopyroxenite–norite–anorthosite–anorthositic gabbro up to 800 m thick. This is overlain by 600–800 m of gabbro that includes a 35 m-thick seam of stratiform concentrations of vanadiferous magnetite and ilmenite, with sodic granophyre at the top of the north-facing intrusion (Overton, 1976; Baxter, 1976). Fitton et al. (1975) included the Sherlock Intrusion in their Millindinna Complex, but all layered complexes in the west Pilbara are now considered to be separate intrusives (Hickman, 1983); a concept supported by Pb isotope data (Korsch and Gulson, 1986). An arcuate dyke-

* Name defined in GSWA mapping of SHERLOCK 1:100 000 sheet

like mass of gabbro that may be cogenetic with the Sherlock Intrusion can be traced around and parallel to the eastern and southern margin of the batholith (Fig. 12). This gabbro has a Sm–Nd whole-rock/mineral age of 2830 ± 20 Ma and a Pb–Pb whole-rock age of 2960 ± 20 Ma (Korsch and Gulson, 1986). Despite the disparity in isotopic ages, Korsch and Gulson (1986) argued that the time difference between accumulation of the Whim Creek Group and emplacement of the gabbro was probably short.

The timing of emplacement of stock-like granitoid bodies within the belt is uncertain. These include a relatively large adamellite body that outcrops 3–4 km northeast of Mons Cupri and 2–3 km southeast of Whim Creek, and smaller bodies that have been mapped on the north flank of Mount Brown and south of the Salt Creek deposit (Fig. 12). It is not known whether these granitoids are part of the basement, subvolcanic intrusive(s), or later granitoid intrusions unrelated to the Whim Creek volcanism.

The formations that make up the Whim Creek volcanic belt tend to be concentrically arranged about the Caines Well batholith with the oldest formations resting on or against the batholith and the youngest formations farthest away (Fig. 12). The rocks commonly have shallow dips, mostly 10–30°, but steepen to subvertical adjacent to steeply dipping faults. This is most prevalent in the region between Sherlock Bay and Balla Balla where dips to bedding are consistently near vertical and the main foliation in the rocks is subparallel to the adjacent Sholl Fault (Fig. 12). South of Balla Balla the dip of bedding flattens markedly, similar to that elsewhere in the belt. The outer margins of the Whim Creek Belt appear to be largely faulted and a series of northwest- and north-trending faults and shear zones cross the volcanic belt at regular intervals of 10–12 km (Fig. 12). Barley (1987) has identified two phases of folding with an early phase of upright open folds plunging at low to moderate angles to the northeast or southwest, and with a slaty cleavage dipping steeply to the southeast. The early folds locally are refolded by east-trending folds of variable plunge, which may have a weak axial planar cleavage. Small kink-style folds are developed locally and deform both these older structures.

Mons Cupri volcanic-hosted deposit

The Mons Cupri deposit (20°52'50"S, 117°48'20"E) is the largest of the volcanogenic sulfide deposits in the Whim Creek belt. It outcrops as a steep-sided hill about 4 km south-southeast of Whim Creek (Fig. 12) and is readily accessible by track from the Northwest Coastal Highway. There are several published descriptions of the geology and mineralization at Mons Cupri (e.g. Miller, 1973; Miller and Gair, 1975; Sylvester, 1976; Marston, 1979; Tanner, 1990), and brief descriptions in broader studies dealing with base-metal resources and the geology of the Whim Creek volcanic belt (e.g. Blockley, 1971; Hickman, 1983; Barley, 1987, 1992).

Although there is a sizeable resource of zinc, lead, copper, silver and gold at Mons Cupri (Table 6), it has been mined only for supergene-enriched copper ore in an exposed section of stockwork mineralization. There is no recorded production of other metals. Proportions of base-metals in the primary sulfide mineralization are atypical of most Archaean volcanogenic massive-sulfide deposits (Fig. 13). The lead grade in the stratiform sulfide component is much higher than in most deposits of this age, but is similar to that in other volcanogenic sulfide deposits in the Pilbara Craton (Barley, 1992). The silver and gold grades at Mons Cupri are comparable with other Zn–Pb–Cu volcanogenic sulfide deposits (Franklin et al., 1981; Lydon, 1988), although assay data for gold are incomplete.

History of mining and exploration

The Mons Cupri deposit was first recorded in 1897 and its early history of mining and exploration is documented by Finucane and Sullivan (1939), Low (1963), Miller and Gair (1975) and Marston (1979). After two periods of copper production during 1899–1901 and 1907–1917, the deposit was largely ignored until 1965 when Whim Creek Consolidated NL was granted mining tenements that covered both the Whim Creek and Mons Cupri deposits. In 1968, Texasgulf Australia Ltd acquired an interest in the tenements and embarked on a major exploration program based on conceptual models of volcanogenic massive-sulfide deposits. The first diamond drillhole (MC1), in May 1968, intersected 26.5 m of significant pyrite–sphalerite–galena–chalcopyrite mineralization, including 14.5 m grading 1.96% Zn, 1.83% Pb, 1.78% Cu and 62 g/t Ag at the top of this intersection. The ensuing exploration of Mons Cupri and its environs included 32 000 m of drilling in a further 143 diamond drillholes and 25 percussion holes that were completed during 1968–72, though most of the systematic drilling was in 1968 and 1969. An additional 1573 m in 15 diamond drillholes were completed in 1980 for metallurgical testwork. Texasgulf Australia relinquished its option in 1984 and since then there has been no further exploration of the deposit other than re-evaluation of previous work and re-assessment of ore reserves. In 1991, Dominion Mining Ltd completed an investigation of the feasibility of mining leachable copper ore from the oxidized portions of the deposit.

As the Mons Cupri deposit was already known from the beginning of this century, albeit as a copper deposit rather than as a volcanogenic massive-sulfide deposit, there is no recorded systematic exploration prior to 1967. Geological mapping and geophysical surveys were conducted during 1967–68 and a weak ground EM anomaly and coincident IP anomaly in a favourable geological position provided the target for the first diamond drillhole (Chisholm, 1983a). Since then, Mons Cupri has been the focus of much surface exploration, mostly in order to better define its geological setting and depositional environment. Also, a number of orientation surveys have been undertaken to test geochemical and geophysical signatures for application elsewhere in the Whim Creek Belt.

Several soil, stream-sediment, rock and mercury-vapour surveys were conducted during 1970–1980 (Smith, 1980; Chisholm, 1983a). Copper, lead, bismuth and zinc are strongly anomalous in soils above and surrounding the

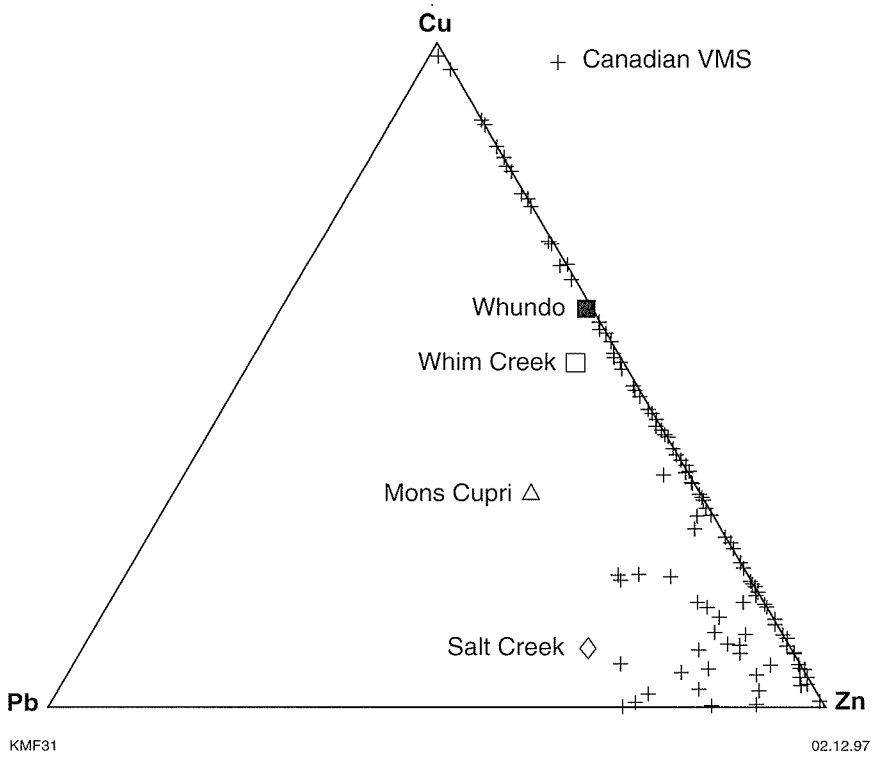


Figure 13. Comparison of Cu, Pb and Zn ratios of west Pilbara volcanogenic sulfide deposits (from data in Table 1) and Canadian Archaean volcanogenic sulfide deposits (various data sources)

deposit and arsenic and cobalt form less pronounced anomalies on the flanks of the stockwork zone. Mercury in soils also has been found to outline the mineralization and mercury vapour has been detected up to 750 m from mineralization. However, the highest values on the crest of Mons Cupri hill may be due to 'leakage' of mercury from the numerous drillholes (Smith, 1980; Chisholm, 1983a). The boundary between the Mons Cupri Volcanics and the Rushall Slate, at the stratigraphic level of the ore horizon, is anomalous in zinc and to a lesser extent lead and copper throughout the Mons Cupri district.

Numerous ground and airborne geophysical surveys conducted at Mons Cupri, including magnetic, electromagnetic, gravity, and induced polarization surveys, are reviewed by Gunn and Chisholm (1984) and Lebel and Fallon (1994). They concluded that the Mons Cupri deposit is a difficult geophysical target. The mineralization has been found to be chargeable but not conductive and therefore most likely to respond to induced polarization methods but defeat detection by electromagnetic techniques. This is attributed to a number of factors including a relatively low total sulfide content, the depth below the surface of the more massive sulfide component of the ore body being beyond the effective detectable limits of the instruments used, and the coating of sulfide grains by silica inhibiting electrical continuity (Gunn and Chisholm, 1984; Lebel and Fallon, 1994). A low-order magnetic anomaly (70 nanoteslas) coincident with the deposit is attributed to chlorite–magnetite alteration assemblages in the deeper parts of the alteration pipe (Lebel and Fallon, 1994).

Geological setting

The Mons Cupri deposit is within the upper parts of the Mons Cupri Volcanics on the southern flank of the Mount Brown volcanic centre (Fig. 12). The Mount Brown Rhyolite is most prominent in the centre of the volcanic pile and is surrounded by a 300–600 m-thick sequence of intercalated pyroclastic and epiclastic rocks, and felsic intrusive bodies.

In the vicinity of Mons Cupri, the Mount Brown Rhyolite is overlain by about 600 m of coarse-grained rhyolite fragmental volcanics that flank a massive feldspar-phyric dacite–rhyolite body referred to as the Domal rhyolite (Fig. 14; Miller and Gair, 1975; Smith, 1975). The rhyolite fragmental unit (Mons Cupri rhyolite fragmental *of* Miller and Gair, 1975) is a massive agglomerate consisting of angular and some rounded fragments, mostly 30–100 mm but up to 1.5 m across. Fragments are composed predominantly of the adjacent Domal rhyolite with some granitoid and amygdaloidal basalt, all in a fine-grained tuffaceous matrix. Miller and Gair (1975) describe five facies variations but there is little evidence of sedimentary structures except for thin laminated tuffaceous chert units at the top of the formation. Along strike to the north and northwest of Mons Cupri the rhyolite fragmental unit grades into matrix

and clast-supported cobble–boulder conglomerate with interbedded tuff and siltstone (Fig. 14; Smith, 1975; Miller and Gair, 1975; Barley, 1987) which have been interpreted as a series of subaqueous fan-delta deposits (Barley, 1987; Tanner, 1990). At the top of the rhyolite fragmental unit is an 18–20 m-thick felsic pyroclastic or epiclastic rock referred to as the Cistern rhyolite (Miller and Gair, 1975; Smith, 1975). This massive, generally featureless formation has also been described as a quartz–feldspar porphyry sill (Miller, 1973), as a sequence of possibly reworked rhyolite crystal tuff or tuffaceous arkose (Smith, 1975), and as a welded tuff or rhyolite sill (Miller and Gair, 1975).

The Mons Cupri Volcanics is conformably overlain by at least 210 m of argillite, siltstone and minor turbiditic sandstone of the Rushall Slate that locally includes dacitic and andesitic lavas and tuffaceous units (Fig. 14). At Mons Cupri, the rhyolite fragmental and Cistern rhyolite at the top of the Mons Cupri Volcanics are overlain by about 15 m of argillite, known locally as the Cap shale, which in turn is overlain by up to 75 m of andesitic lava and tuff of the Comstock andesite (Fig. 14), the thickest of the volcanic units within the Rushall Slate.

The volcanic sequence may have been intruded by late-stage granitoids, such as the small ?subvolcanic ?granite–adamellite plugs which outcrop 0.5–1 km east of Mons Cupri. Several of the deeper drillholes at Mons Cupri also have intersected leucocratic granite at a consistent depth of 400–450 m below the surface (Miller and Gair, 1975; Smith, 1975) but it is not known whether this granite is part of the basement, a subvolcanic intrusive, or a later granitoid intrusion. The timing of emplacement of the larger high-level ?subvolcanic sericite- and chlorite-altered adamellite (Mons Cupri Granite *of* Sylvester, 1976) that outcrops 3–4 km northeast of Mons Cupri (Fig. 12) also is uncertain, though it has a Rb–Sr isotopic age of 2366 Ma (Sylvester and de Laeter, 1987).

The overall structure of the Mons Cupri area is relatively simple with most formations dipping away from the Mount Brown volcanic centre at shallow to moderate angles (Smith, 1980). At Mons Cupri, the upper units of the Mons Cupri Volcanics and overlying Rushall Slate have a consistent dip of 15–30° west (Fig. 14). The only major fold in the area is a northwest-trending overturned syncline–anticline couplet to the north of Mons Cupri (Fig. 14). This is the only fold of its type in the Whim Creek Belt and may be associated with one of the larger faults in the area. The sequence is also cut by several ?younger northeast-trending faults that are subparallel to major faults to the southeast of the mine (Figs 12 and 14).

Mineralization

There are two styles of base-metal sulfide mineralization at Mons Cupri, both within the thickest part of the rhyolite fragmental unit in the upper part of the Mons Cupri Volcanics on the north flank of the Domal rhyolite (Fig. 14). A conformable lead–zinc(–copper) sulfide lens in volcaniclastic and cherty sediments near the top of the rhyolite fragmental unit is underlain by disseminated and stockwork copper(–zinc) sulfide mineralization within a large pipe-like alteration zone (Figs 15 and 16). The relative sizes of the two ore types have not been fully established as resource evaluation has focused on estimation of copper-enriched ore in the oxidized part of the stockwork zone and lead–zinc–copper sulfide ore below (Table 7), without distinction between the two primary ore types (Fig. 17). The only indication of their relative sizes is that given by Miller (1973) and Miller and Gair (1975) who estimated about 1 Mt of stratabound sulfide ore and 11–15 Mt in the underlying stockwork zone (Table 6, Fig. 15). Most of the lead, zinc and silver is in the stratabound ore which typically has grades of 6.5–16% Zn, 5–11% Pb, 0.5–1.2% Cu and 60–160 g/t Ag compared with the stockwork zone which averages 0.24% Zn, 0.08% Pb, 0.84% Cu and 10 g/t Ag (Smith, 1980).

The stratiform mineralization forms an ovoid lens, about 250 m wide and 400 m long, that forms a stratabound cap over the western end of the stockwork system (Figs 15 and 16). Fine- to medium-grained pyrite, sphalerite and galena with minor chalcopyrite and tetrahedrite and trace amounts of bournonite and linnaeite are confined to bands within a 3–15 m-thick unit of tuffaceous sandstone, siltstone and chert. Some of these bands show colloform and crustification textures (Miller, 1973; Miller and Gair, 1975; Tanner, 1990). The bands of sulfide mineralization and interbedded host sediments are traversed by thin veinlets of chalcedonic quartz with chalcopyrite, commonly with crustiform texture (Miller and Gair, 1975). The only surface expression of this mineralization is a small lead-rich gossan that outcrops on the western flank of Mons Cupri hill (Finucane and Sullivan, 1939). This was later shown to be the feather edge of the stratiform deposit (Miller and Gair, 1975). Analyses of the stratiform sulfide mineralization reported by Smith (1980) indicate relatively high levels of tin (200–300 ppm), which is most likely in cassiterite, similar to the Whim Creek deposit (Nickel, 1982). The stratiform sulfide mineralization also has relatively high levels of a number of other chalcophile elements (Smith, 1980), but has relatively low levels of barium (<800 ppm) for a volcanogenic sulfide deposit. Some of these elements (antimony, arsenic and bismuth) are in the sulfosalts, cadmium most likely is within sphalerite, and cobalt and nickel are probably in the pyrite (Marston, 1979).

The stockwork mineralization consists of an anastomosing network of chalcedonic quartz and carbonate veins (1–10 cm thick) with chalcopyrite and minor sphalerite and galena that is confined to a large west-plunging pipe-like alteration zone that has a down-plunge length of at least 350–400 m (REF). The easterly trending stockwork system and its enclosing alteration zone dips steeply to the south and has a funnel-shaped sectional outline that narrows from about 250 m across at the palaeosurface to about 20 m wide at depth (Figs 15 and 16; Miller and Gair, 1975). In plan, the cone-shaped stockwork and alteration zone is about 1 km long and is widest where it is exposed beneath the overlying Cistern rhyolite and Rushall Slate (Figs 14 and 16). This zone tapers rapidly to the east (Fig. 14), possibly into a shear zone, and thins to a narrow zone beneath the stratabound lens to the west (Fig. 16). The stockwork mineralization apparently is zoned, with

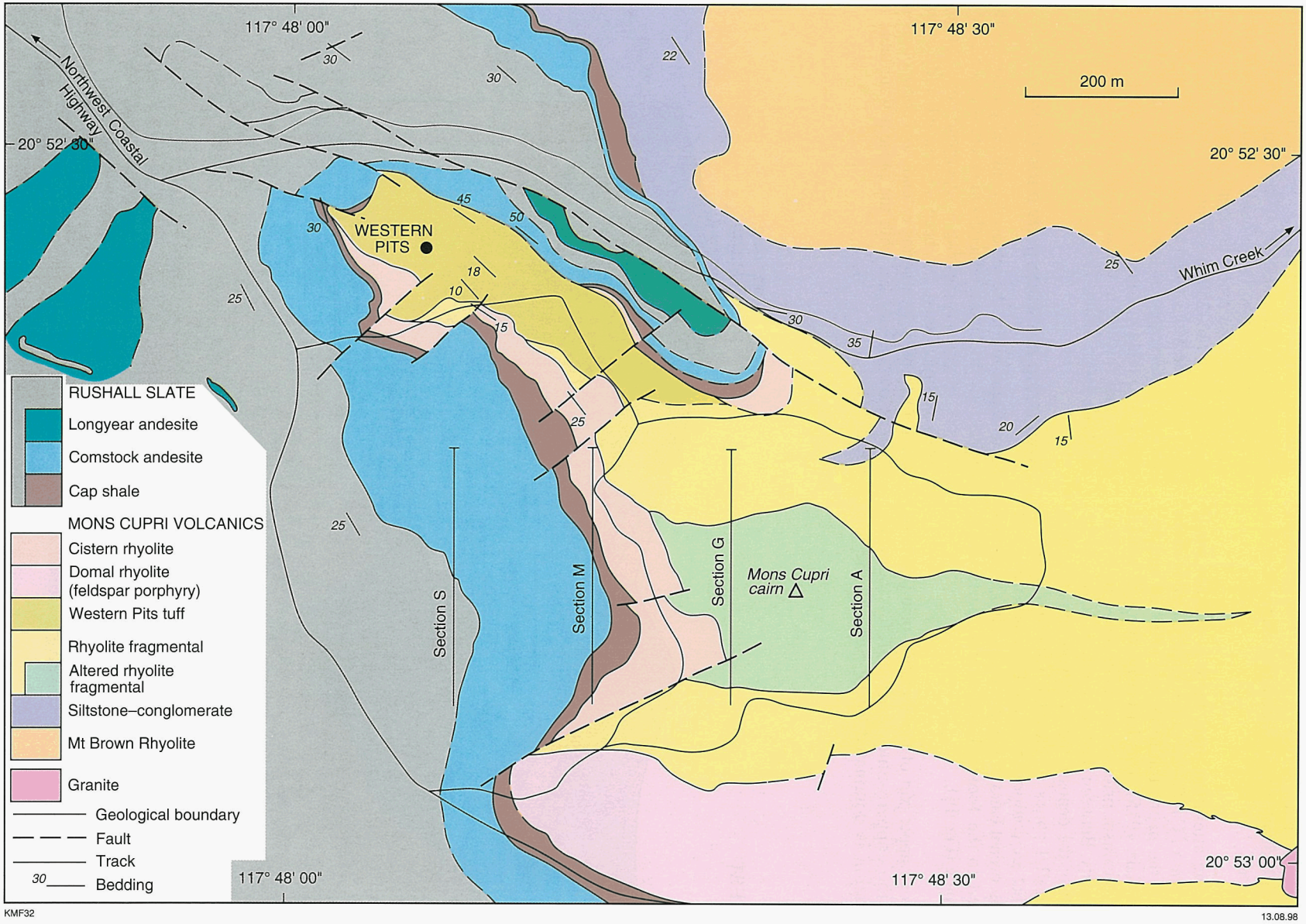


Figure 14. Geology of the Mons Cupri area (*after* Miller and Gair, 1975; unpublished mapping by L. J. Miller and H. S. Gair, 1969; Linn, 1971). Section lines A, G, M, S shown on Figure 16

the highest grades in the upper 30 m directly beneath the stratabound ore where there is a dense network of chalcedonic quartz–chalcopyrite veins and disseminated chalcopyrite in altered host rocks (Fig. 16). Copper grades decrease with depth and towards the margins of the stockwork zone.

Within the alteration pipe, there is another small ?stratiform lens of Cu–Pb–Zn sulfide mineralization about 50 m below the main stratiform lens (Figs 15 and 16; Miller and Gair, 1975). This lens may represent a brief hiatus in volcanism prior to the main phase of hydrothermal activity. Between the two stratiform lenses, in the central part of the deposit, the stockwork mineralization has subparallel zones of elevated Cu–Pb–Zn grades (Fig. 16) that are conformable with the palaeosurface. At depth, a discordant band of low-grade Cu–Pb–Zn sulfides is confined to the footwall and central parts of the alteration pipe (Fig. 16).

The broad upper part of the alteration pipe that hosts much of the copper(–zinc–lead) sulfide stockwork mineralization is dominated by Fe-rich chlorite and carbonate (mostly siderite) which grades laterally into a heterogeneous chlorite–carbonate–sericite alteration halo (Tanner, 1990). At depth, the chlorite–carbonate alteration grades into a talc–chlorite–magnetite alteration assemblage (Miller and Gair, 1975; Smith, 1975). There is a second, but poorly defined, subsurface chlorite–carbonate alteration zone with copper mineralization to the north of, and 150–250 m stucturally and stratigraphically below, the Mons Cupri alteration pipe. Deep drilling has also intersected at least two other talc–chlorite–magnetite alteration zones within the rhyolite fragmental and Domal rhyolite to the south of Mons Cupri (Miller and Gair, 1975; Smith, 1975).

Weathering and supergene enrichment

Mons Cupri hill is the exposed oxidized portion of the cupriferous stockwork mineralization and is essentially a network of gossans capping a supergene zone (Smith, 1980). Although there has been no detailed study of the weathered profile, weathering extends to a depth of about 75 m below the surface, with the present watertable at about 20 m.

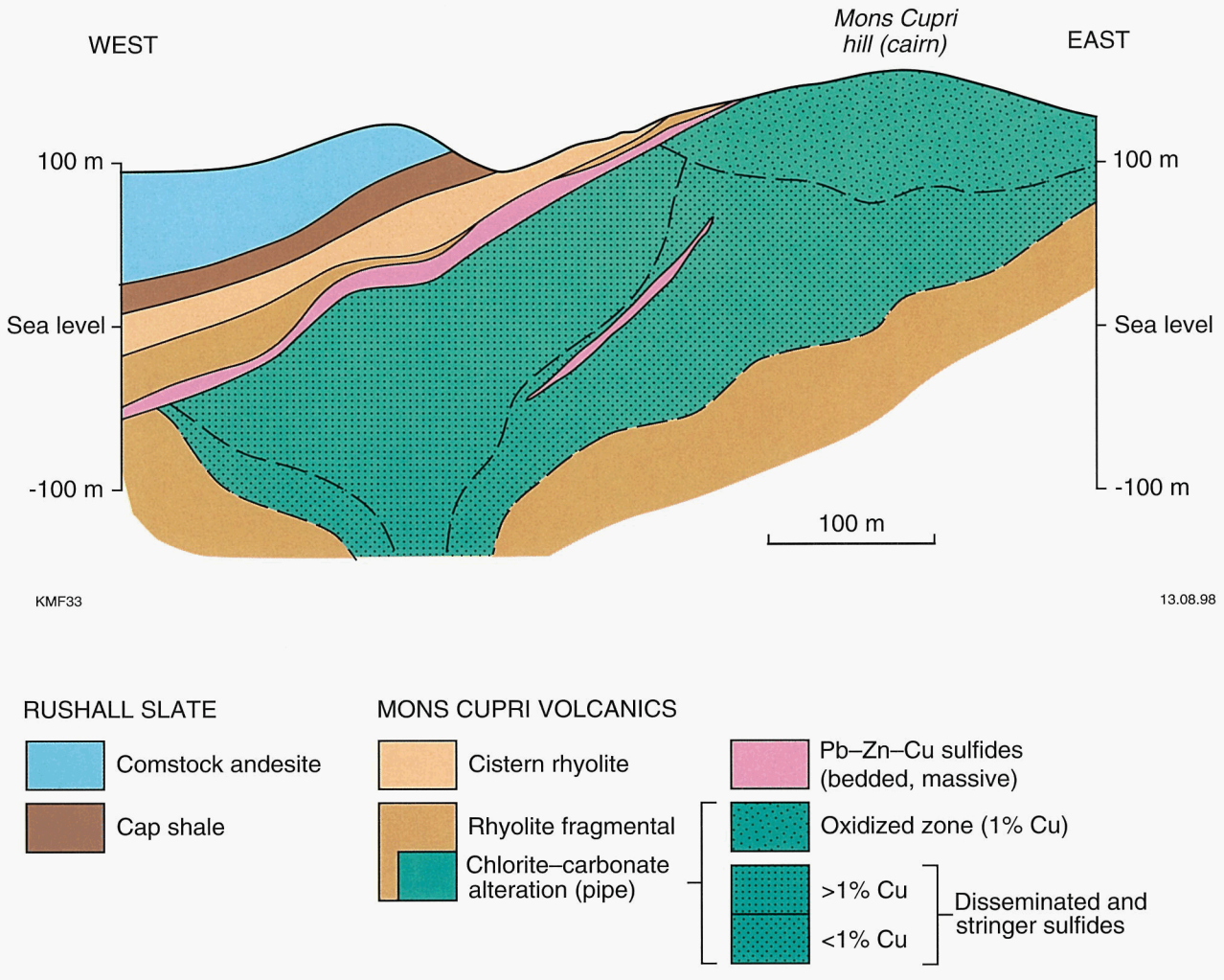


Figure 15. Longitudinal section of the Mons Cupri deposit (*modified from* Miller and Gair, 1975)

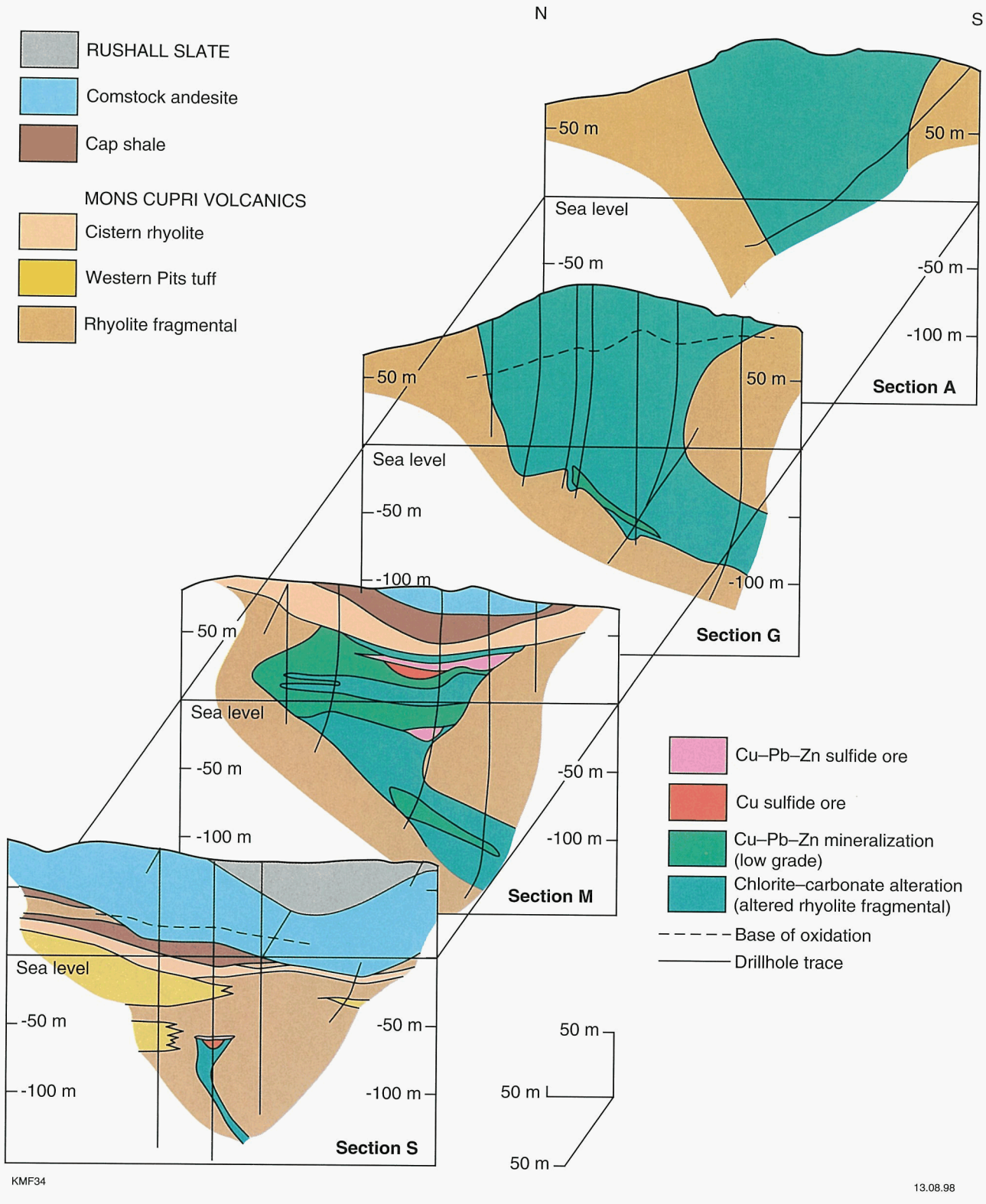


Figure 16. Oblique projection of serial north–south cross sections (looking east) of the Mons Cupri deposit (based on sections *compiled by* Linn, 1974). Locations of sections are shown on Figure 14

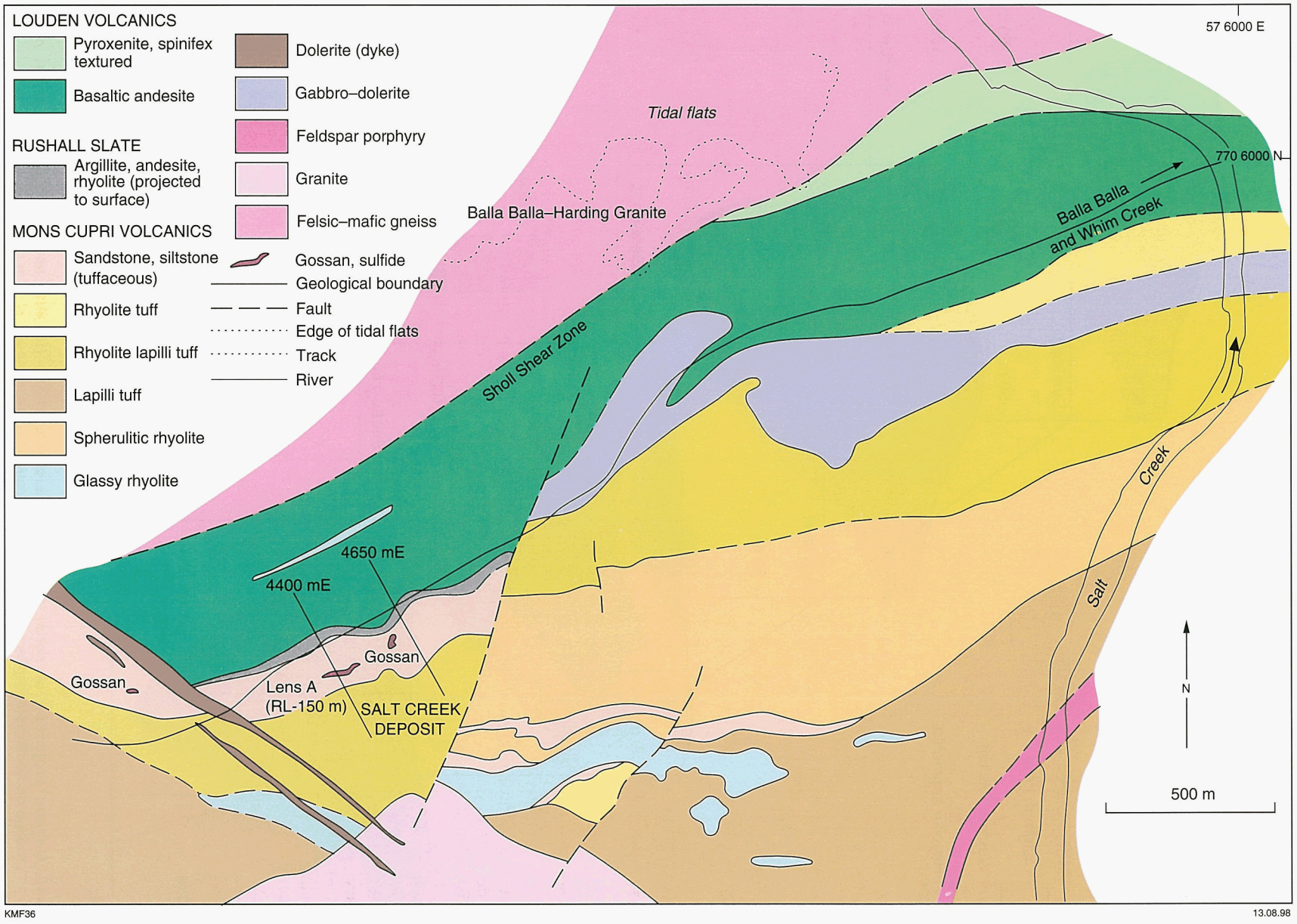


Figure 17. Geology of the Salt Creek area (*based on* unpublished mapping by M. E. Smith, A. Clemen and T. Grobicki, 1979; Gunn and Chisholm, 1984)

Deeply weathered parts of the chlorite-altered rhyolite fragmental pile contain siliceous veinlets of malachite and minor azurite but no secondary zinc or lead minerals have been identified (Smith, 1980), reflecting the low levels of these metals in the stockwork zone. Copper tends to be slightly enriched in the gossans and supergene zone whereas zinc and lead are both markedly depleted in the gossans compared with their levels in the primary sulfide mineralization (Smith, 1980).

Most of the stratabound mineralization is below the level of oxidation and has been protected from much of the weathering by the overlying Rushall Slate. However, where the stratabound lens outcrops as a small gossan on the western flank of Mons Cupri hill it is markedly enriched in lead and silver (up to 30% Pb, 115 g/t Ag) and depleted in zinc and copper, whereas an underlying supergene zone is enriched in copper, slightly depleted in lead and silver and markedly depleted in zinc (Smith, 1980; Chisholm, 1983a).

A number of gossan samples that have been analysed for a range of other chalcophile elements indicate depletion of antimony, arsenic, bismuth, cadmium, cobalt, molybdenum and tin in gossans in comparison with levels in the stratiform sulfide mineralization (Smith, 1980; Chisholm, 1983a). However, the location of these gossan samples is uncertain and cannot be related to the stratiform or stockwork mineralization.

Genesis

The Mons Cupri deposit is a well preserved example of an Archaean volcanic-hosted massive-sulfide deposit. The large chlorite alteration zone with its cupriferous stockwork veining represents a hydrothermal feeder system which is capped by a proximal stratiform zinc–lead–copper sulfide lens. A Pb model age of 2930 ± 10 Ma for galena from Mons Cupri (Richards, 1983) is similar to Pb model ages of other volcanogenic sulfide deposits in the belt and is consistent with other estimates of the age of Whim Creek volcanism.

Previous workers (Miller, 1973; Miller and Gair, 1975) have drawn analogies between Mons Cupri and the Tertiary Kuroko-type volcanogenic massive-sulfide deposits in Japan, though Miller and Gair (1975) proposed that Mons Cupri formed from hot-spring fluids that did not reach the surface of the rhyolite fragmental pile. Although there are some similarities between the Mons Cupri and Kuroko deposits, Barley (1992) has suggested that the iron-rich chlorite and carbonate alteration that grades into a marginal sericite–chlorite alteration assemblage at Mons Cupri and its association with silicic pyroclastic and epiclastic rocks are more typical of Canadian Archaean Mattabi-type mineralization (Morton and Franklin, 1987).

The size and vertical extent of the copper mineralization in the stockwork zone and its enclosing alteration halo are disproportionately large in comparison with the small overlying stratiform sulfide lens. This may be explained by erosion of a much larger conformable sulfide lens (or lenses) that originally extended up-dip above the present surface, or by conditions of formation of primary mineralization. Barley (1992) attributes the small conformable lens to the probable boiling of hydrothermal fluids and deposition of copper sulfides before reaching a sea floor (cf. Solomon and Walshe, 1979). This is consistent with a relatively shallow-water environment, as inferred from the host sedimentary facies and fluid inclusion data (Tanner, 1990). However, the extensive stockwork mineralization (and alteration halo) may be better attributed to permeability of the host rock rather than to boiling of the mineralizing fluid. As the rhyolite fragmental unit would have been relatively permeable, migration of hydrothermal fluids within the host rock would have been comparatively widespread. Subsequent cooling of the hydrothermal fluid during its dispersal throughout the host rock could then have caused deposition of copper sulfides within the stockwork zone before exhalation of the fluid onto the floor of a shallow sea.

Salt Creek volcanic-hosted massive-sulfide deposit

The Salt Creek deposit (20°45'10"S, 117°42'45"E) is 16 km northwest of Whim Creek, and about 17 km north-northwest of the Mons Cupri deposit (Fig. 12). It is situated at the northern edge of a vast flat-lying coastal plain which extends for some 15–20 km inland to a tract of dissected hills in the Whim Creek – Mons Cupri area. The coastal flats are broken only by scattered low hills that rise to 25 m above sea level. The Salt Creek deposit is located on the northern flank of one of these hills and within 1.5 km of coastal tidal mud flats which extend a further 5–7 km to the Indian Ocean. Access is via gravel tracks that leave the Balla Balla Road 7 km north of Whim Creek.

There has been no mining of the Salt Creek deposit and the only published description is that by Gunn and Chisholm (1984), though it is mentioned briefly in reviews of volcanogenic deposits and in broader studies dealing with the geology of the Whim Creek Belt (Hickman, 1983; Barley, 1987, 1992). Most of the information used to compile this description of the Salt Creek deposit is from an unpublished report by Smith and Clemen (1980), though some of the interpretations are original.

History of exploration

As the main body of mineralization at Salt Creek does not outcrop and was unknown until it was drilled in 1978, it is worthwhile to briefly relate the history of exploration in the area. The following account of the discovery of the Salt Creek deposit is summarized from a report by Smith and Clemen (1980).

Although the Salt Creek deposit is within an area that was subjected to mining activity from the end of the 19th century there was no sign of previous prospecting in the immediate vicinity, even though there are two small gossans above the deposit that remained unrecognized until 1977. The closest previous prospecting and mining activity is a number of small pits in magnetite-rich layers

of the 'Don Well complex' (Sherlock Intrusion), presumably excavated by copper miners for magnetite flux at Whim Creek and Mons Cupri.

Recorded exploration of the coastal area between Balla Balla and Sherlock Bay commenced in 1960, but most of this early work was directed at vanadium–iron–titanium deposits in the Don Well layered complex and evaluation of the nickel–copper potential of some small ultramafic bodies. Exploration of the Balla Balla vanadiferous magnetite deposit, about 8 km east-southeast of Salt Creek and 10 km south of Balla Balla, was undertaken by Mangore (Australia) Pty Ltd during 1960–63 and Garrick Agnew Pty Ltd from 1966 to about 1975 and included detailed geological mapping of the layered complex, ground magnetic surveys and extensive sampling. In 1967, the Utah Development Company pegged a large area surrounding the Balla Balla prospect for vanadium and base metals. Exploration by Utah included extensive geological mapping, geophysical surveys and bedrock sampling over most of their tenements before they were relinquished in 1974. Utah's tenements included the felsic volcanics in the Salt Creek area and the eastern highly siliceous gossan at Salt Creek was found during their exploration program but apparently was misidentified as quartzite.

In 1968, Texasgulf Australia Ltd completed a regional aeromagnetic survey of the coastal area between Port Hedland and Roebourne (flying height of 150 m, 2.4 km line spacing) as part of their investigation of the volcanogenic massive-sulfide potential of the west Pilbara. This survey revealed a prominent aeromagnetic anomaly over the Balla Balla vanadiferous titanomagnetite deposits and indicated that the magnetite seam(s) extended a further 12 km to the west. Subsequent exploration of the area underlying the anomaly by Garrick Agnew and Texasgulf included detailed geological mapping and ground magnetic surveys along some 20 km of strike length of the Don Well layered complex, and the drilling of 59 holes for geochemical sampling in 1974. At the same time (1972), Texasgulf pegged additional ground to the north of the magnetite prospects to investigate the nickel potential of a small ultramafic body outcropping about 8 km south of Balla Balla (Fig. 12). This area was later found to contain outcropping base-metal mineralization along a boundary between rhyolitic and andesitic volcanics.

During detailed mapping of the Sherlock Intrusion in 1975, several gossans with anomalous base-metal values (up to 0.24% Zn, 0.99% Pb, 0.28% Cu and 2 g/t Ag) were discovered about 7 km south of Balla Balla (Fig. 12). This led to a shift in exploration emphasis toward base metals with more extensive geological mapping, ground magnetic and gravity surveys and drilling of numerous shallow holes for bedrock geochemical samples. Subsequent percussion drilling of these gossans at the end of 1975 and again in mid-1976 intersected several metres of low-grade pyrite–sphalerite mineralization in felsic volcanic rocks (Balla Balla prospect). At the same time, following compilation of a regional geological map of the Mons Cupri – Balla Balla – Sherlock Bay area, it was realized that the felsic volcanic rocks hosting the Balla Balla mineralized horizon probably were stratigraphically equivalent to the volcanic sequence hosting the volcanogenic sulfide deposit at Mons Cupri. Discovery of highly anomalous base-metal values (up to 2.4% Pb, 0.95% Zn, 0.1% Cu and 22.5 g/t Ag) in rhyolitic volcanics 2 km west of the Balla Balla gossans (West Balla prospect) provided additional incentive to extend exploration farther west toward exposures of felsic volcanics in the Salt Creek area.

Encouraged by the discovery of base-metal sulfide mineralization in a favourable geological environment, Texasgulf continued detailed geological mapping and bedrock geochemical sampling in the area to the west of the Balla Balla and West Balla prospects and a more detailed low-level aeromagnetic survey was flown at the end of 1976 (60 m flying height, 150 m line spacing). In March 1977, two small but highly anomalous gossans were discovered about 2 km to the west of the course of Salt Creek and 450 m apart (Fig. 17). Although the highly siliceous gossans do not exhibit obvious secondary mineralization they contain up to 2.7% Zn, 7.1% Pb, 0.54% Cu and 1298 g/t Ag. Initial drilling focused on the eastern gossan but the first diamond drillhole (NUD1) was drilled downdip into mafic volcanics (Fig. 18). The second hole (NUD2), collared in September 1977 and also adjacent to the eastern gossan but drilled from the opposite direction (Fig. 18), intersected a broad zone of sulfide mineralization with 14.8 m of disseminated and stringer sulfides at a depth of about 160 m below surface, including a 4.3 m section enriched in copper (Table 8). A third hole (NUD3), drilled 100 m to the east of NUD2, intersected 1.4 m of massive sphalerite and galena in argillite at a depth of about 140 m below surface (Table 8).

The encouraging results in two of the first three holes drilled to test the gossans were followed by five barren holes (NUD4–8), though NUD8 intersected a thin zone of disseminated sulfides (Table 8). In March 1978, one more hole was drilled to test a pronounced bedrock geochemical anomaly (up to 2250 g/t Zn, 2000 g/t Pb and 120 g/t Cu) that had been found between the two gossans in an area devoid of outcrop. This hole (NUD9) intersected 16.2 m of disseminated, stringer and massive and banded sulfides at a depth of 100–110 m below surface. Subsequent drilling of a further 16 holes to mid-1979 outlined two zones of mineralization, referred to as lens A and lens B (Table 8; Figs 17 and 18). Since 1980, there has been little further exploration of the deposit apart from some downhole geophysical testing by Aberfoyle in 1990–91 and re-evaluation of the geological resource, for which the latest estimates indicate 0.65 Mt at 9.1% Zn, 3.53% Pb, 1.18% Cu and 46 g/t Ag (Dewson, 1992). Although assay data for gold are incomplete, typical grades in some of the later drilling are about 0.5 g/t ranging up to 1.5 g/t Au (Smith and Clemen, 1980).

The Salt Creek deposit was found primarily as a result of the application of conceptual models, geological mapping, and soil and bedrock geochemistry. In an area subject to coastal flooding and with an extensive thin blanket of windblown sand, RAB drilling to weathered bedrock was found to be the most effective means of acquiring geological data to supplement the relatively sparse outcrop and for collecting geochemical samples

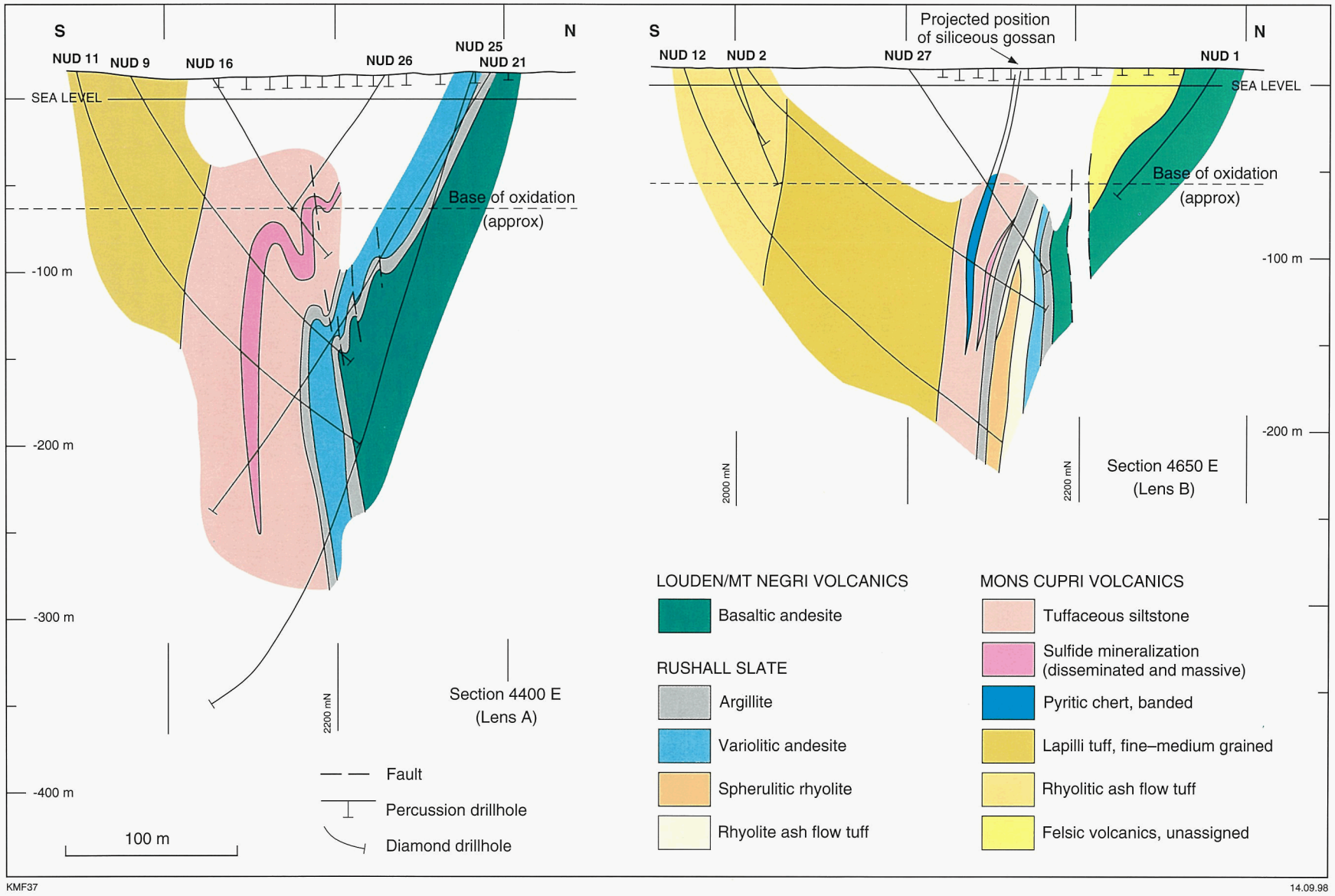


Figure 18. North–south cross sections of the Salt Creek deposit (looking west) through lens A at 4400 mE and lens B at 4650 mE (*based on* unpublished sections by A. Clemen, M. E. Smith and P. Delancy, 1979). Locations of the sections are shown on Figure 17

Table 8. Drillhole intersections of sulfide mineralization at Salt Creek (*compiled* from **Smith and Clemen, 1980**)

DDH no.	*Drilled thickness (m)*	*True width (m)*	*Depth* [a] *(m)*	*Zn (%)*	*Pb (%)*	*Cu (%)*	*Ag (g/t)*	*Cu/Pb + Zn*	*Zn no.* [b]
LENS A									
NUD 9	16.2	12.0	106	4.75	0.52	0.80	16	0.15	90
NUD 11	17.9	14.3	167	2.39	0.77	3.56	19	1.13	76
NUD 13	9.6	8.0	160	5.43	2.0	0.06	20	0.01	73
NUD 16	19.2	10.3	86	13.75	7.43	0.23	110	0.01	65
including	14.9	8.0	88	16.46	8.99	0.28	128	0.01	65
NUD 18	21.6	10.0	175	14.35	1.31	0.44	33	0.03	92
NUD 21	9.9	6.5	222	9.57	6.21	1.78	43	0.11	61
LENS B									
NUD 2	14.8	13.8	117	1.33	0.3	0.95	15	0.58	82
including	4.3	4.0	120	1.54	0.28	3.19	38	1.75	85
NUD 8	1.65	–	~180	1.45	1.01	0.08	26	0.03	59
including	0.55	–	~180	3.94	2.82	0.93	71	0.14	58
NUD 23	8.6	–	~50	6.2	1.38	0.04	36	0.01	82
OTHER INTERSECTIONS[c]									
NUD 3	1.4	1.2	~140	47.75	13.13	0.1	330	0.00	94
NUD 6	5.0	–	~95	0.15	0.04	0.02	1	0.10	80

NOTES: (a) Vertical depth below surface to the centre of the intersection
(b) Zinc number = 100 Zn/(Pb + Zn); Huston and Large (1987)
(c) The intersection in NUD 3 is within the lower of two argillite units which overlie the Mons Cupri Volcanics and NUD 6 is in a similar situation (Smith and Clemen, 1980; table 3)

(Smith and Clemen, 1980). Although copper and zinc anomalies can be related to surface expressions of known mineralization, lead gave the most concise indication of underlying mineralization. Mercury in soils also highlighted the gossans and subsurface mineralization, but Smith and Clemen (1980) consider mercury dispersion in the soil at Salt Creek to be too widespread for accurate delineation of underlying sulfide mineralization.

Several ground geophysical surveys were conducted after discovery of the Salt Creek deposit to test for any geophysical signature that could be applied to further exploration in the area (Gunn and Chisholm, 1984). Surface electromagnetic and downhole IP surveys showed that the sulfide mineralization at Salt Creek is chargeable, but not conductive, and that conductive responses detected are due to near-surface weathering effects (Gunn and Chisholm, 1984). The high salinity of the surface and ground waters in the Salt Creek area may also interfere with electrical and electromagnetic methods. The non-conductive nature of the mineralization was confirmed by downhole EM surveys conducted by Aberfoyle in 1990–91. The sulfide bodies are thought to be either too small or too deep to give an identifiable gravity anomaly, though a localized weak anomaly (0.2 milligal) may be attributed to the shallow end of lens A (Smith and Clemen, 1980). Although disseminated magnetite has been reported in some of the sulfide intersections (Smith and Clemen, 1980), the Salt Creek deposit was not detected by regional and low-level aeromagnetic surveys conducted in 1968 and 1976, nor was it revealed by a ground magnetic survey in 1977–78 (Gunn and Chisholm, 1984). The lack of magnetic response may be partially due to its proximity to the Sherlock Intrusion which may mask any subtle anomalies generated by magnetite in the sulfide mineralization.

Geological setting

The Salt Creek deposit is within the northern arm of the Whim Creek volcanic belt, on the northern flank of the Caines Well batholith, and north of the Sherlock Intrusion (Fig. 12). It is about 1 km south of the Sholl Fault, which separates the Whim Creek Belt from the Balla Balla and Harding Granites, and metamorphosed rocks of the Warrawoona Group to the north (Fig. 12). Although mapped as a single fault structure, the Sholl Fault is a major shear zone which regionally may be 1 km or more in width. The Salt Creek deposit is on the southern fringe of this shear zone.

The volcano-sedimentary succession at Salt Creek is correlated with, and is of similar age to, that elsewhere in the Whim Creek Belt (Figs 12 and 18; Table 4), though the lowest formation, the Warrambie Basalt, has not been mapped in the Balla Balla – Salt Creek area (Figs 12 and

17). A Pb model age of 2950 ± 10 Ma for galena from Salt Creek (Richards and Blockley, 1984) and a Pb–Pb whole-rock isochron age of 2940 ± 60 Ma for weathered felsic volcanics (Gulson et al., 1986) are slightly younger than other estimates of the age of the Whim Creek volcanics but consistent with a Pb model age of the Mons Cupri deposit (Richards, 1983).

The sequence is dominated by a pile of felsic volcanic and epiclastic rocks 1–1.2 km thick, including spherulitic rhyolite, arkosic sandstone and siltstone and lapilli tuff, that are correlated with the Mons Cupri Volcanics (Table 9). This is conformably overlain by a unit of argillite and andesitic lava flows, 25–60 m thick, that is correlated with the Rushall Slate. These rocks in turn are overlain by a thick pile of mafic–ultramafic volcanics that may be correlated with the Louden Volcanics (Table 9). The total thickness of the volcano-sedimentary pile in the Salt Creek area is about 2 km, but there may have been some tectonic thickening or thinning of the sequence during movement on the nearby Sholl Fault.

The east-northeasterly trending host sequence generally has vertical to steep northerly dips, though at Salt Creek it dips steeply to the south (Fig. 18). Sedimentary structures such as graded bedding and clay drapes preserved in epiclastic units and flow-top breccias in rhyolite lava flows indicate a north-facing succession, locally overturned (Smith and Clemen, 1980), with the oldest formation apparently resting against the Caines Well batholith and the youngest formations farthest away adjacent to the Sholl Fault. This is consistent with the concentric disposition of stratigraphic units about the Caines Well batholith elsewhere in the volcanic belt (Fig. 12). The steep dips to bedding and a pervasive bedding-parallel foliation throughout the sequence are subparallel to the nearby Sholl Fault and probably are associated with movement along this structure. What appears to be a pronounced rodding of some volcanic units plunging 50–60° east to east-northeast also may be associated with this shear zone. There are numerous small-scale folds but no major folds have been identified in the area (Smith and Clemen, 1980).

Mineralization

Stratabound zinc–lead–copper sulfide mineralization at Salt Creek has been found towards the top of a tuffaceous siltstone unit 100–150 m thick, which is the uppermost unit of a conformable pile of felsic volcanic and volcaniclastic sedimentary rocks, 1 km thick, that are correlated with the Mons Cupri Volcanics (Table 9; Smith and Clemen, 1980). There are at least two lenses (A and B) of sulfide mineralization (Smith and Clemen, 1980) at

Table 9. Stratigraphy of the volcanic pile at Salt Creek and correlations with formations elsewhere in the Whim Creek volcanic belt. Lithological data are *based on* Smith and Clemen (1980)

Lithological unit	*Thickness (m)*	*Formation (correlate)*
Granodioritic gneiss, with bands of mafic and felsic gneiss ('Harding and Balla Balla Granite')		
---------- *Fault* ----------		
Basaltic andesite lavas and tuff with spinifex-textured pyroxenite flow	450	LOUDEN VOLCANICS
~ *?Unconformity* ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~		
Argillite	0–10	
Andesite lavas, variolitic texture	10–50	
Spherulitic rhyolite, rhyolitic ash flow tuff	0–20	RUSHALL SLATE
Argillite and laminated tuffaceous siltstone	10–25	
Minor Zn–Pb–Cu sulfide mineralization		
~ *?Unconformity* ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~		
Tuffaceous siltstone with fine-grained arkosic sandstone and minor pyritic interbeds	100–150	
Zn–Pb–Cu sulfide mineralization in the upper parts of this unit		***Salt Creek deposit (lens A and B)***
Rhyolite lapilli tuff (localized silica and potassic alteration)	<400	
Spherulitic rhyolite (lavas)	<400	MONS CUPRI VOLCANICS
Thinly bedded sandstone and siltstone	25	
Spherulitic rhyolite (lava)	70	
Massive, well-bedded grit and arkosic sandstone	<60	
'Glassy' rhylolite (porphyritic to perlitic, commonly spherulitic)	<140	
Lapilli tuff (with minor subrounded granitoid fragments)	<500	
~ *Unconformity* ~		
Granitoid (Caines Well batholith) and Warrawoona Group		

a similar stratigraphic level to the Mons Cupri deposit and a possible third thin lens within the lower of the two argillite units at the base of the Rushall Slate (Table 9; Fig. 18). The lens within the Rushall Slate previously had been linked with lens B (Smith and Clemen, 1980; Gunn and Chisholm, 1984) but it is unlikely that this type of stratiform mineralization would transgress bedding and it is now considered that there are at least two horizons of mineralization at Salt Creek. Apparently only lens B occurs as outcrops, in the eastern of the two siliceous gossans discovered in 1977, whereas the surface expression of lens A is equivalent to the geochemical anomaly that was tested by drillhole NUD9 (Figs 12 and 19).

Base-metal and silver grades of the two main lenses are typical of the lead-enriched volcanogenic sulfide deposits in the Pilbara Craton, in contrast to most Archaean volcanogenic massive-sulfide deposits (Fig. 13). Proportions of base metals in the two lenses in the Mons Cupri Volcanics and the thin lens in the Rushall Slate are similar, though one intersection in each of lenses A and B is markedly enriched in copper (Fig. 19). Overall, base-metal ratios at Salt Creek are similar to those of the Mons Cupri deposit and the Zn–Pb lode at Whim Creek (Figs 13 and 19).

Lens A, the largest of the two lenses at the top of the Mons Cupri Volcanics, consists of several thin layers of massive and banded sulfides interbedded with tuffaceous siltstone and extensive stringer vein mineralization that collectively form a ?vertically plunging tabular body 6.5–14.3 m thick (average about 10 m), 120 m wide along strike, and an unfolded down-plunge length of at least 250 m (Fig. 18). The massive-sulfide layers and stringer veins consist of medium- to coarse-grained pyrite, sphalerite, chalcopyrite and galena with magnetite and interstitial carbonate, chlorite, quartz and minor rutile. Sphalerite and other sulfides are notably coarser grained than at Mons Cupri and Whim Creek, which may be due to recrystallization during deformation associated with the Sholl Fault. The more massive layers seem to be confined to two levels, separated by a relatively low-grade zone 2–4 m thick that can be traced throughout most of the lens. Stratigraphically below the massive sulfide lens is a localized zone of pyrite–chalcopyrite stringer mineralization that coincides with more-intense chloritic alteration of the tuffaceous siltstone (Smith and Clemen, 1980). The lens is enclosed by a broad zone of sericite and carbonate alteration that coincides with an envelope of sodium depletion in the host sedimentary rocks.

Although there are only six drillhole intersections of lens A, there appears to be some lateral variation in mineralogy with hole NUD11, in the centre of the western flank of the lens, enriched in copper and depleted in zinc and lead. This intersection has a Cu:(Zn+Pb) ratio of 1.13 compared with ratios of 0.01–0.15 for the other five intersections (Table 8; Fig. 19). The mineralized section in hole NUD11 is dominated by pyrite and chalcopyrite with minor magnetite as massive bands and in stringer veins (up to 19.25% Cu). The section also contains three thin bands, 0.15–0.8 m thick, of massive sphalerite (15.5–35% Zn) but only the thickest of these is enriched in galena (14.75% Pb).

The dimensions of the smaller eastern lens B are poorly defined with significant sulfide mineralization intersected only in holes NUD2 and NUD23 (Fig. 18; Table 8). It is likely that these intersections are for a single lens 4.0–6.25 m thick and extending vertically for at least 100 m; however, the lens may also extend for about 100 m to the east where there are thin bands of sulfide mineralization at the same stratigraphic level (in NUD8). The mineralogy of lens B is similar to that of lens A and, if the three drillhole intersections are in the same lens, also appears to be laterally zoned. The deeper intersection (NUD2) includes 4 m of semi-massive, banded and stringer veins of pyrite and chalcopyrite that overlies about 14 m of stringer vein and disseminated pyrite with minor sphalerite. The disseminated sulfides are partly within a unit of pyritic banded chert, 5–6 m thick, that may be equivalent to the siliceous gossan (Fig. 18). The shallower intersection (NUD23) and the eastern intersection (NUD8) are dominated by disseminated, stringer vein and massive sphalerite and galena with little chalcopyrite and very low Cu:(Pb+Zn) ratios compared with relatively high Cu:(Pb+Zn) ratios for the massive and disseminated sulfide mineralization in NUD2 (Table 8).

A third thin sulfide ?lens within the lower of the two argillite units that overlies the tuffaceous siltstone which hosts lenses A and B has been intersected in two drillholes (Table 8). The intersection in NUD3 consists of 1.4 m of massive and bedded sphalerite and galena, but with negligible chalcopyrite, in an envelope 1.5 m wide of disseminated sphalerite and galena (Table 8; Smith and Clemen, 1980). The other intersection of this ?lens in NUD6, 100 m to the east, is of similar thickness with 5 m of disseminated pyrite and sphalerite but with only a band 4 cm thick of massive sulfides (Smith and Clemen, 1980).

The discontinuous nature of this mineralization may be a primary feature of the deposit, with accumulation of sulfides in shallow, areally restricted subaqueous depressions. Alternatively, it may be attributed to dislocation of a larger lens either by faulting or shearing associated with, and subparallel to, the nearby Sholl Fault which acutely transgresses bedding in the Salt Creek area, or by faults that obliquely cross-cut the volcanic sequence (Fig. 17). There is insufficient information to determine the cause of the lenticular nature of the mineralization, though the recognition of sulfide mineralization at two different stratigraphic horizons supports the concept of a series of discontinuous lenses rather than a single tabular body that has been dislocated by later deformation.

Weathering and supergene enrichment

Lack of outcrop and limited shallow drilling precludes an evaluation of weathering on the Salt Creek deposit. Only the eastern of the two siliceous gossans can be equated to sulfide mineralization, and this to a pyritic chert which underlies the main banded and disseminated mineralization in lens B. However, there is marked enrichment in base metals and silver in both these gossans in comparison with average grades in the sulfide lenses. The only

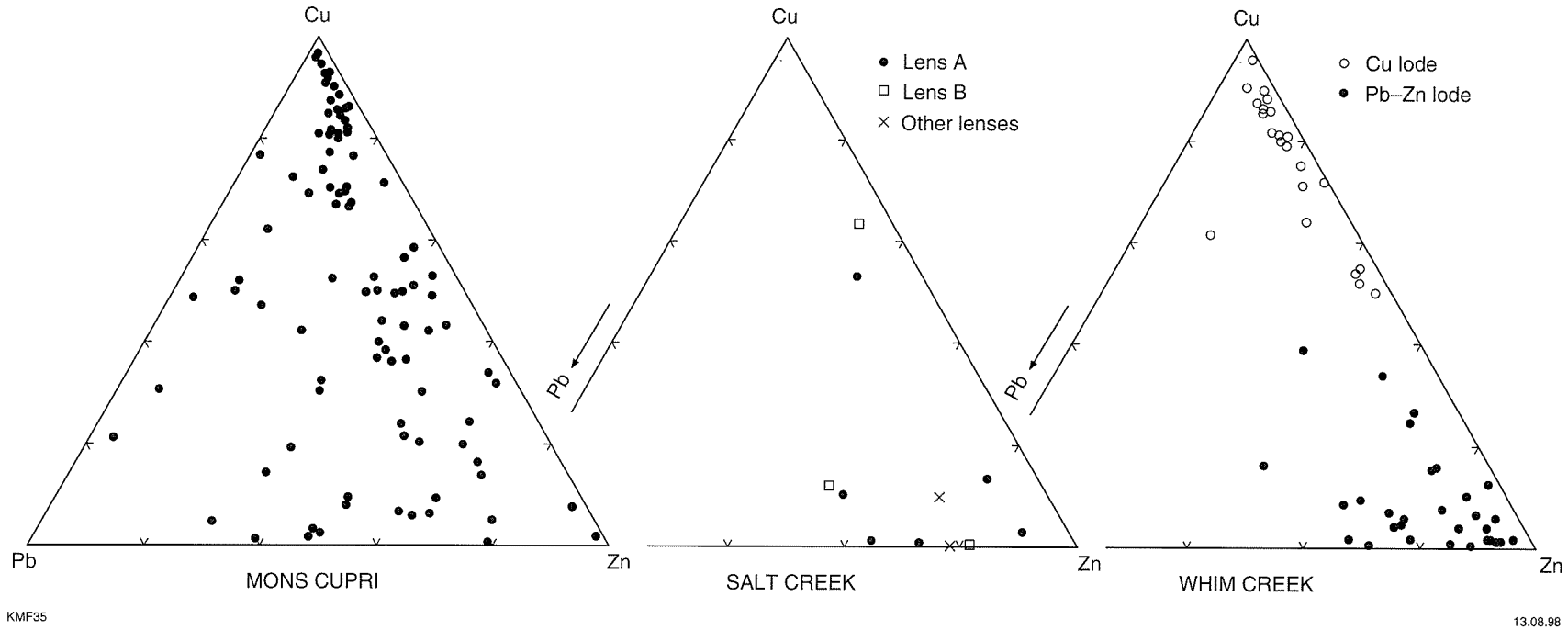


Figure 19. Copper–lead–zinc ratios of grades in drillhole intersections of the Mons Cupri, Salt Creek and Whim Creek deposits (*compiled from* data in Farrell, 1978; Smith and Clemen, 1980; Chisholm, 1983a). The Salt Creek and Whim Creek data are for primary sulfide mineralization, whereas the Mons Cupri data are for 105 intersections of combined sulfide and oxide mineralization. Data for Whim Creek are separated into a copper lode and lead–zinc lode, and the three lenses at Salt Creek are plotted separately

supergene enrichment is in one of the few near-surface intersections (NUD 23) about 50 m below the eastern gossan. This intersection, well within the oxidized zone, contains sphalerite and galena as well as lead and zinc carbonates filling cavities and fractures, but no secondary copper minerals (Smith and Clemen, 1980). High silver grades (≤485 g/t Ag) in a shallow intersection of lens A also are attributed to supergene enrichment (Smith and Clemen, 1980).

Genesis

The Salt Creek deposit has many features consistent with volcanogenic exhalative deposits, including stratabound massive and bedded sulfide mineralization, apparent metal zonation from a copper-dominant base to lead–zinc top, and footwall stringer mineralization associated with chlorite alteration of the host rocks. Sulfides most likely accumulated in shallow, restricted subaqueous depressions with fluids percolating through semi-consolidated epiclastic rocks. A central barren zone within lens A may represent a brief period of more rapid accumulation of sediment or a pause in exhalation of fluids and precipitation of sulfides. Although there is no apparent hydrothermal feeder zone beneath the deposit, lateral zonation in Cu:(Zn+Pb) ratios within lens A indicates proximity to a feeder vent at the western flank of this lens (Smith and Clemen, 1980).

The form of mineralization at Salt Creek appears to be similar to that at Whim Creek, though at slightly different stratigraphic levels. Both are hosted by fine-grained sedimentary rocks and have pyrite–chalcopyrite-dominant stringer mineralization within chlorite-altered host rocks beneath thin stratabound layers of more massive and banded sulfides.

Whim Creek sediment-hosted volcanogenic deposit

The sediment-hosted copper–zinc deposit at the Whim Creek mine (20°50'50"S, 117°49'40"E) outcrops as a low ridge less than 1 km south of the Whim Creek Hotel, alongside the Northwest Coastal Highway, midway between Roebourne and Port Hedland (Figs 12 and 20). It is about 4 km north-northeast of the volcanic-hosted massive-sulfide deposit at Mons Cupri on the opposite flank of the Mount Brown felsic volcanic pile that separates the Whim Creek and Mons Cupri shale basins (Fig. 12).

The deposit has been described in detail by Reynolds et al. (1975) and Marston (1979), and more briefly in broader studies dealing with the geology of the Whim Creek Belt (e.g. Fitton et al., 1975; Hickman, 1983; Barley, 1987, 1992). Detailed studies of the host rocks and mineralogy and geochemistry of the ore horizon have been undertaken by Koehler (1974) and Farrell (1978).

History of mining and exploration

Copper mineralization at Whim Creek (previously known as Whim Well) had been discovered by 1888 (Woodward, 1890) and mined intermittently from 1889 until 1964. During this period about 112 000 t of supergene enriched ore averaging 10.1% Cu were produced, mostly from gossans and oxidized ore (Reynolds et al., 1975). There is no recorded production of zinc, lead or silver from the Whim Creek mine, though a small amount of silver was most likely included in the supergene ore (cf. **Whundo deposits** — Collins and Marshall (b), this volume).

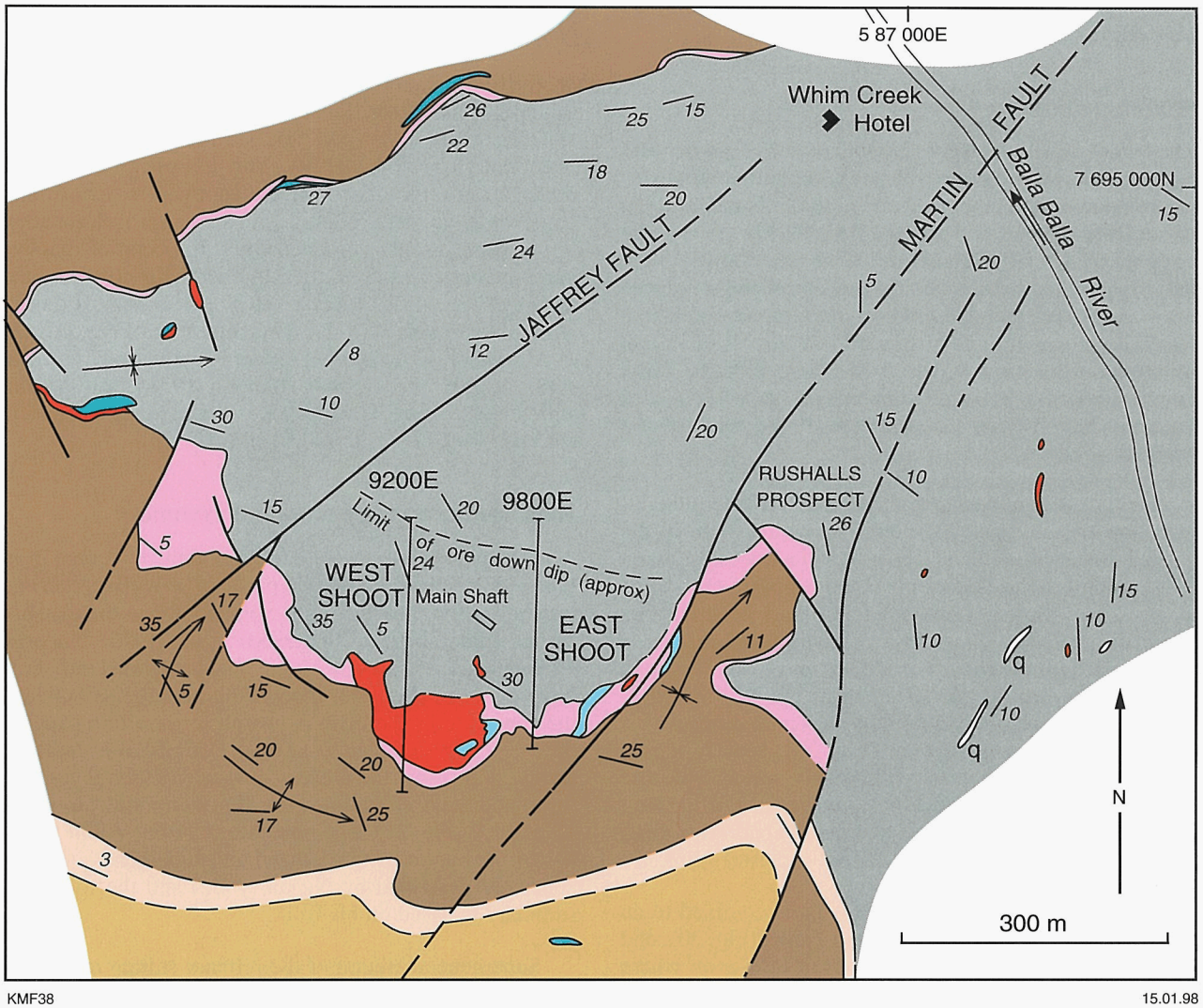
The history of mining and exploration at Whim Creek to about 1978 is well documented by Low (1963), Reynolds et al. (1975) and Marston (1979). It is one of the most intensely explored mineral deposits in Western Australia. During the period 1963–1975, some 16 450 m of diamond core drilling and 7260 m of percussion drilling in over 400 holes resulted in a reserve of 2.916 Mt at 0.6% Zn, 0.3% Pb, 1.63% Cu and 9 g/t Ag at a cutoff grade of 0.3% Cu. Since 1975, no further exploration has been carried out other than re-evaluation of ore reserves and metallurgical studies of the ore by Whim Creek Consolidated NL and more recently by Dominion Mining Ltd. The latest revision to the grades and tonnages are listed in Table 6. Most of this work has focused on the copper potential of the deposit, including a feasibility study in 1991 to determine the amenability of Whim Creek ore to hydrometallurgical processes as it contains measured reserves of 1.67 Mt of acid leachable ore at 1.45% Cu (Poustie, A., 1994, pers. comm.).

As the deposit has been known for over a century there is no documented exploration history. Apart from detailed geological mapping and systematic drilling the only other exploration of the deposit has been geochemical characterization of the ore horizon. A regional aeromagnetic survey conducted in 1968 and an airborne EM survey in 1971 did not reveal the deposit, and anomalies detected by an IP survey in 1973 were inconclusive.

Geological setting

The Whim Creek deposit is a stratabound body within the Rushall Slate, which here is at least 400 m thick. Stratigraphically, therefore, this is the youngest of the major volcanogenic sulfide deposits within the Whim Creek volcanic belt (Table 7). The Rushall Slate conformably overlies the Mons Cupri Volcanics, which outcrops less than 0.5 km to the south of the mine (Figs 12 and 20) and has been intersected in deep drillholes at the Whim Creek mine. A lithic tuff 10–14 m thick at the base of the Rushall Slate (Fig. 20) may be correlated with the Cistern formation at Mons Cupri (Smith, 1975).

The Rushall Slate is a monotonous sequence of argillite, siltstone and turbiditic greywacke, with some thin andesite sills clustered above and below the mineralized horizon. The andesite here is not as extensive as that at Mons Cupri. The reddish-brown partially weathered (dark grey-green where fresh) fine-grained sedimentary rock is composed mostly of quartz, chlorite and muscovite with minor and accessory pyrite, sphalerite, chalcopyrite, rutile, sphene and epidote (Farrell, 1978). In the vicinity of the mine, Reynolds et al. (1975) have divided the Rushall Slate into a footwall and hangingwall sequence though elsewhere in the Whim Creek basin, in the absence of the mineralized horizon, the two sequences generally



RUSHALL SLATE

- Hangingwall sequence
- Andesite
- Ore horizon
- Chert (+ ore horizon)
- Footwall sequence

MONS CUPRI VOLCANICS

- Tuffaceous siltstone
- Felsic volcanics

- q Vein quartz
- Gossan
- 30 Bedding
- Fault
- Antiform, plunge
- Synform, plunge
- Shaft

Figure 20. Geology of the Whim Creek mine area (*after* T. Koehler, 1974 (unpublished mapping); Marston, 1979)

cannot be distinguished. At Whim Creek the footwall sequence has more coarse-grained siliciclastic beds than does the hangingwall sequence (Marston, 1979), with chalcopyrite as the dominant accessory sulfide phase dispersed within short (<50 mm) stringer veinlets and as fine disseminations. In the hangingwall sequence pyrite is the dominant sulfide phase, with euhedral grains clustered in rod-like lenses or disseminated throughout the rock (Reynolds et al., 1975; Farrell, 1978; Marston 1979).

Bedding at Whim Creek defines an open northeast-plunging synclinal structure (Fig. 20). There is a well developed slaty cleavage dipping southeast on the limbs of the syncline but to the east or northwest in much of the axial zone where the bulk of the mineralization occurs (Marston 1979). The mineralized horizon outcrops 150–200 m to the south and southwest of the main shaft along the summit of hills encircling the trough of the syncline. The host sequence is disrupted by southwest-trending

faults and the thickest part of the ore horizon is confined between two of these faults (Fig. 20).

Mineralization

The Whim Creek deposit is essentially a Cu–Zn deposit, typical of most Archaean volcanogenic sulfide deposits, but compared with other deposits in the Pilbara Craton, it is depleted in lead and silver (Table 6; Fig. 13). If the copper grades of the sulfide resource (Table 6) are indicative of that from which the gossanous and supergene ore was derived, then the total original resource at Whim Creek is estimated to be of the order of 3.4 Mt of sulfide mineralization. This makes it the largest of the three known volcanogenic sulfide deposits in the Whim Creek volcanic belt in terms of the size of the stratabound resource (Table 6).

The ore is confined to a single conformable mineralized horizon which is 150–200 m above the base of the Rushall Slate (Figs 20 and 21) and can be traced for about 5 km around the perimeter of a circular basin (Reynolds et al., 1975) that is believed to be part of a caldera structure (Collins, 1990). Throughout most of its strike length the mineralized horizon is 1.5–3 m thick but thickens rapidly to 10–15 m at the Whim Creek deposit, where base-metal mineralization outcrops over a strike length of some 600 m (Fig. 20). Mostly it is a recrystallized pyritic chert with poorly sorted, chloritic siltstone and felsic tuffaceous interbeds, and varying proportions of layers, veinlets and disseminations of fine- to coarse-grained sulfides and quartz(–siderite) veins.

Mineralization of economic interest is confined to an area between the Jaffrey and Martin Faults (Fig. 20), and extends downdip for some 200–300 m to a zone where the dip of bedding steepens from 20–25° to about 50° northeast (Fig. 21). This apparently marks the limit of downdip extensions of potential ore, though thin beds of sphalerite have been traced for a further 60 m down the steeper dip (Koehler, 1974; Reynolds et al., 1975). There are two northeasterly plunging synclinal ore shoots, referred to as the east and west shoots, that are separated by an open anticlinal structure, though mineralization is continuous between the two shoots (Fig. 20; Reynolds et al., 1975; Marston, 1979).

Primary mineralization consists of pyrite (cobalt-rich), pyrrhotite, chalcopyrite and sphalerite (zinc:iron ratios of 7:1 to 20:1) with minor galena, magnetite and arsenopyrite (Koehler, 1974; Reynolds et al., 1975; Farrell, 1978; Marston,1979). Pyrrhotite is more common than pyrite in the east shoot, which shows as a distinct low-order magnetic anomaly. Sphalerite apparently is more common in the west shoot. Traces of tetrahedrite reported by Farrell (1978) have been shown to be strongly argentiferous with up to 17 wt% Ag (Nickel, 1982) and may account for most of the silver in the deposit. Trace amounts of a number of bismuth, cobalt, antimony, nickel and tin sulfides and sulfosalts are reported by Nickel (1982), including bismuthinite, stannite, cobaltite, ullmannite, meneghinite, bournonite, emplectite, and tucekite. Cassiterite is relatively abundant in the ore (up to 250 ppm Sn in primary sulfide ore) as disseminated anhedral grains, up to 20 microns in diameter, and cogenetic with the sulfide phases (Nickel, 1982).

Sulfide mineralization has several textural forms, including stratiform lenses of massive and laminated sulfides, stockwork veins and sulfide-cemented microbreccias (Marston, 1979). The hangingwall of the mineralization is sharp, but the footwall is diffuse and based on assay data. There is a distinct vertical zonation in the deposit with a lower copper-rich zone of massive and disseminated pyrite, pyrrhotite and chalcopyrite, and an upper zinc–lead–silver zone of pyrite and sphalerite with minor galena (Fig. 17; Reynolds et al., 1975; Farrell, 1978). There is no apparent lateral variation in base-metal ratios within the deposit (Farrell, 1978), though the anticlinal structure between the two ore shoots is a pyritic siliceous rock depleted in base metals.

Weathering and supergene enrichment

All production from the Whim Creek mine has come from the copper-enriched upper parts of a well preserved weathering profile that has developed above the primary sulfide mineralization (Reynolds et al., 1975; Marston, 1979; Nickel, 1982). The profile may be divided into three distinct zones (Fig. 21), though the boundaries between the zones are gradational. A gossan forms a thin capping on a leached oxidized zone that extends to a depth of about 25 m below the present surface and then gives way to a supergene alteration zone that commonly is about 15 m thick (Fig. 21). The mineralogy of the Whim Creek gossan and underlying oxidized and supergene alteration zones are described by Nickel (1982) and the following summary is based on his work.

Supergene alteration of the primary sulfide mineralization is characterized by an abundance of secondary copper sulfides, chiefly chalcocite and covellite, that have replaced chalcopyrite and to a lesser extent sphalerite and pyrite along grain boundaries and fractures in the primary sulfides. Minor secondary sphalerite has formed in veins or replaced chalcopyrite and pyrite in association with the secondary copper sulfides. The alteration becomes pervasive from a depth of about 40 m, but is developed irregularly to depths of about 75 m where fractures and faults have allowed ingress of oxygenated groundwater into the primary mineralization. The intensity of alteration increases towards the surface and, above about 30 m, chalcopyrite and sphalerite have been completely replaced by secondary copper sulfides. Pyrite is present throughout the supergene zone, but is less persistent with decreasing depth.

The oxidized zone contains abundant hematite, goethite, residual quartz and kaolinite and is characterized by malachite as the most abundant secondary copper mineral, with minor azurite and chrysocolla and traces of native copper. Cuprite and chalcanthite have also been reported in this zone (Koehler, 1974; Marston, 1979). A number of secondary lead minerals have been identified, commonly as pseudomorphs after galena, but there are no secondary zinc minerals. Residual grains of cassiterite are common in the oxide zone and Nickel (1982) also reports a small amount of secondary cassiterite.

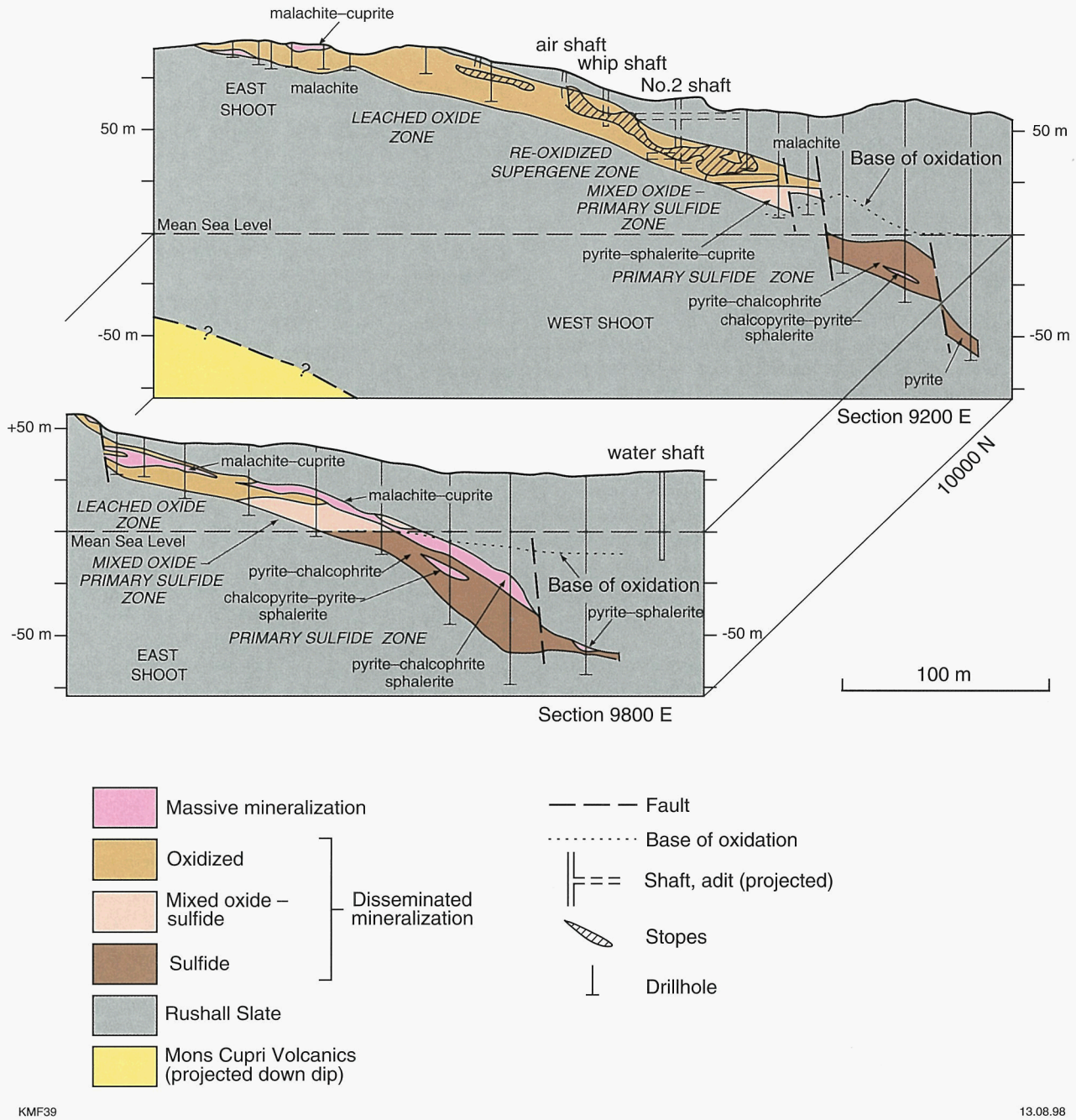


Figure 21. North–south cross sections through the Whim Creek deposit at 9200E and 9800E (looking west, imperial grid), showing the distribution of massive and disseminated mineralization and zonation in the weathering profile (*modified from* Marston, 1979). Locations of the sections are shown on Figure 20

A capping of hematite–goethite gossan contains abundant secondary copper and lead minerals, dominated by malachite, azurite, chrysocolla and cerussite, with a variety of alunite group minerals and several lead–copper arsenates, phosphates and vanadates. This abundance of secondary minerals is considered by Nickel (1982) to indicate a relatively immature gossan that has not fully developed, owing to changing climatic conditions and erosional stripping. Erratic distribution of secondary minerals within the gossan is reflected in analytical data, which show a wide variation in values though iron, lead, silver and copper tend to be enriched in the gossan in comparison with the primary sulfide ore. Tin also tends to be enriched in the gossan, consistent with the presence of residual grains of cassiterite throughout the weathered profile. Although secondary zinc minerals have been identified neither in the gossan, nor in the oxidized zone, the zinc content of the gossan (0.55%) and sulfide ore (0.72%) are about the same (Nickel, 1982). This indicates that zinc has not been totally leached from the upper levels

of the weathered profile, as suggested by some workers (e.g. Marston, 1979), and that it has been retained within the gossan, most likely within goethite, or in minor amounts in some of the other secondary minerals. Concentrations of most other pathfinder elements in the gossan are either slightly enriched (antimony, arsenic, bismuth) or slightly depleted (cobalt, nickel, molybdenum) compared with the primary sulfide mineralization. Immobile elements such as chromium, titanium and vanadium tend to be depleted in the gossan (Nickel, 1982).

Genesis

Previous workers (Koehler, 1974; Reynolds et al., 1975; Farrell, 1978; Marston, 1979) agree that the sulfide mineralization at Whim Creek is of volcanogenic exhalative origin and syngenetic with the enclosing sedimentary rocks. The deposit shows the following features characteristic of volocanogenic sulfide deposits: mineralogical zoning from chalcopyrite at the base to a sphalerite(–galena) enriched top; stratiform nature of massive and banded sulfide mineralization; Fe-chlorite alteration in and below the Whim Creek ore horizon; and widespread distribution of sulfidic chert at the same stratigraphic level as the mineralized horizon (equivalent to an exhalite horizon).

The absence of proximal volcanic rocks indicates that the Whim Creek deposit was relatively remote from an active contemporary volcanic centre, though the volcaniclastic nature of part of the mineralized horizon suggests coeval volcanic activity and interruption of the relatively stable depositional conditions that prevailed during accumulation of most of the Rushall Slate (Marston, 1979). Intercalation of epiclastic and probable pyroclastic sedimentary rocks with the stratiform sulfide layers is consistent with penecontemporaneous accumulation of sediment and precipitation of sulfides, possibly within a localized shallow depression on a sea floor. The lack of an obvious feeder zone within the footwall rocks does not necessarily indicate that the Whim Creek deposit formed distally from a site of fluid discharge. Widespread chlorite alteration of the footwall rocks and the stockwork nature of much of the mineralization are consistent with hydrothermal fluid having percolated through weakly lithified sediments over a large area rather than having been restricted to a pipe-like feeder zone.

Minor zinc–lead–silver occurrences

In addition to the volcanogenic base-metal sulfide deposits at Mons Cupri, Whim Creek and Salt Creek there are numerous small lead–zinc–silver occurrences that are scattered throughout the volcanic belt (Table 10; Fig. 12). These occurrences may be grouped into three styles of mineralization: stratabound ?volcanogenic sulfide deposits, epigenetic fault-controlled deposits, and small ?epithermal vein deposits. The stratiform and probable syngenetic nature of much of this mineralization and the epithermal-type mineralization indicates widespread volcanogenic hydrothermal activity during accumulation of the Whim Creek volcanic pile.

Most of the small stratabound volcanogenic sulfide occurrences are within either the Mons Cupri Volcanics or Rushall Slate and at the same or equivalent stratigraphic levels as the Mons Cupri, Whim Creek and Salt Creek deposits. They include occurrences found in the Mount Fraser – Red Hill area, the Henrys South, Opaline Bore and Good Gear prospects on the southern flank of the belt, occurrences in the Mays Find group of prospects southwest of Mons Cupri, the Rushalls and Stranger occurrences east of Whim Creek, and the Balla Balla prospects to the east of Salt Creek on the northern flank of the volcanic belt (Table 10; Fig. 12). In most cases, pyritic sediments (shale, chert, arkose, tuff) have been enriched in base metals, some with visible sphalerite, chalcopyrite and pyrrhotite. Metal ratios are variable in gossanous outcrops but in drill samples of primary sulfides these prospects have Zn:Pb ratios greater than one, which is consistent with most Archaean volcanogenic sulfide mineralization (average Zn:Pb = 1.44 at Mons Cupri and 2.55 at Salt Creek).

The Balla Balla prospects consist of several small stratabound base-metal sulfide deposits that have been found along a zone of mineralization between Balla Balla and Salt Creek, including the Balla Balla and West Balla deposits (Table 10; Fig. 12). Here, sulfide mineralization apparently is confined to a single tuffaceous horizon that has a strike length of at least 10 km and probably represents a distal facies of the formation that hosts the Salt Creek deposit (Chisholm, 1983b). Zinc ratios are of the order of 75–85, similar to those at the Salt Creek and Mons Cupri deposits, and all the Balla Balla prospects have low Cu:(Pb+Zn) ratios consistent with the distal nature of this mineralization, but their low silver grades are similar to those of the Whim Creek deposit.

Fault-controlled mineralization (e.g. Copper Bore, Henrys East) is found in rocks of the Whim Creek Group and Negri Volcanics. Gossans have variable metal ratios but, where drilled, this style of mineralization consistently has Zn:Pb ratios less than one in contrast to higher ratios in the stratabound deposits. Although small, these prospects indicate that at least some hydrothermal activity continued after accumulation of the Whim Creek Group.

Late-stage epithermal veining is predominantly within the Negri Volcanics, outcropping as either auriferous or lead–silver quartz veins and breccias, all with Zn:Pb ratios considerably less than one (e.g. Comstock Lode, Mays Find). Volcanic sinter deposits and silicified tuffs also have been reported in the Red Hill–Mount Fraser area at the western end of the belt (Alston, 1984) and some of the larger quartz veins have fine colloform silica banding and bladed quartz textures that also are indicative of an epithermal environment. The epithermal quartz veins have been tied to the final stages of caldera development in the belt (Collins, 1990) and may be the source of some stream-sediment gold anomalies (e.g. Bookingarra West).

Another style of base-metal mineralization occurs in the Ant Hill area, about 9 km south-southeast of Balla

Table 10. Minor base-metal occurrences in the Whim Creek volcanic belt (*compiled from* data in Blockley, 1971; Marston, 1979; Smith, 1980; Chisholm, 1983; Alston, 1984). Prospects are listed in order from the western end of the belt around the eastern flank to the Balla Balla area

Prospect [AMG coordinates] [a]	*Description of mineralization* [b]
Red Hill–Mount Fraser [59506815–59656835]	Several small gossans with elevated base metal values in the Mons Cupri Volcanics and Negri Volcanics. Volcanic sinter deposits and brecciated and silicified tuffs in the Mons Cupri Volcanics have up to 650 g/t Pb, 600 g/t Zn, 495 g/t Cu, 1.7 g/t Ag, 0.016 g/t Au
Copper Bore [59706810]	Minor base metal mineralization in the Copper Bore fault corridor. Best drillhole intersection (FDH1): 1 m at 1.6% Pb, 0.72% Zn, 180 g/t Cu, 6.5 g/t Ag
Henrys South [56516797]	Two small outcrops of gossan and gossanous chert (up to 142 g/t Pb, 112 g/t Zn, 88 g/t Cu, 0.4 g/t Au) at the stratigraphic ?top of the Mons Cupri Volcanics, close to unconformably overlying Negri Volcanics
Henrys East [56856813]	Thin pods (0.5–2 m thick) of gossan (up to 160 g/t Pb, 250 g/t Zn, 108 g/t Cu, 0.1 g/t Au) outcrop along a faulted contact between the Mons Cupri Volcanics and Negri Volcanics
Good Luck [57396831]	Localized lenses of gossan (up to 615 g/t Pb, 440 g/t Zn, 780 g/t Cu, 1.3 g/t Ag, 0.02 g/t Au) have developed above 0.5–1 m thick pyritic chert horizons (up to 90 g/t Pb, 465 g/t Zn, 175 g/t Cu) in pyroclastics, shale and chert of the Mons Cupri Volcanics
Opaline Bore [57256803]	A weakly developed stratabound gossan (2–20 m by 200 m) derived from pyritic chert within the Rushall Slate has low base-metal values (up to 134 g/t Pb, 180 g/t Zn, 86 g/t Cu, 0.4 g/t Ag, 0.5 g/t Au) but black pyritic shale beneath the chert contains up to 385 g/t Pb, 3000 g/t Zn, 320 g/t Cu and 0.6 g/t Ag
Esso gossan [57576814]	A siliceous gossan with elevated Pb, Zn, and Sn values is located within sheared and brecciated mafic volcanics of the Negri Volcanics
Nerelleys Bore [57806805]	Weakly developed gossans with low base-metal values have developed over silicified pyritic arkose horizons within the Rushall Slate
Good Gear [57906840]	An extensive area of anomalous rock-chip base-metal geochemistry (up to 1500 g/t Pb, 3750 g/t Zn, 950 g/t Cu) in tightly folded shales of the Rushall Slate that also contains traces of pyrrhotite and sphalerite
Bookingarra West [57666856, 57736864]	A 0.5 m thick quartz vein with galena in rhyolite–rhyodacite of the Mons Cupri Volcanics; and a 0.5–1 m thick auriferous gossanous quartz breccia (up to 0.75 g/t Au) within basalt of the Negri Volcanics
Mays Find 1 [57796874–57916884]	Several narrow zones (2–6 m thick) of ?stratabound sulfides in felsic volcanics with maximum values of 806 g/t Pb, 3055 g/t Zn, 1193 g/t Cu and 3.8 g/t Ag. A mineralized zone of late-stage quartz veining and brecciation within the Negri Volcanics has up to 9800 g/t Pb, 860 g/t Zn, 760 g/t Cu, 13.0 g/t Ag and 0.024 g/t Au
Mays Find 2 [57956888]	Several small gossans (0.5–1 m by 1–10 m) that outcrop over a strike length of about 1 km apparently have developed over pods of pyritic chert with up to 1279 g/t Pb, 2870 g/t Zn and 384 g/t Cu
Mays Find 3 [58036900]	Localized occurences of gossan in sheared basalt–dolerite. Quartz breccia veins are enriched in base metals (up to 10.1% Pb, 320 g/t Zn, 0.45% Cu) and silver (230 g/t), but are of limited extent
Western Hill [58176193]	Supergene copper mineralization in quartz veins in felsic volcanic rocks at the contact with a gabbroic mass. In 1961, 14.9 t of cupreous ore (10.5% Cu) were mined from small pits, but there is no recorded production of zinc, lead or silver
Western Pits (Mons Cupri northwest) [58356909]	Secondary copper, zinc, and lead mineralization (malachite with minor cerrusite) occurs as disseminations and anastamosing veinlets (<1 cm thick) in chloritized foliated volcaniclastic rocks of the Mons Cupri Volcanics, about 600 m northwest of Mons Cupri. Chalcopyrite, sphalerite and minor galena are disseminated within rhyolitic tuffs which average about 1% Cu and have up to 3% Zn. In 1961, 209 t of copper ore (7.8% Cu) was mined from several small opencuts, but there is no recorded production of zinc, lead or silver
Comstock lode (Colorado silver–lead mine) [58386901]	East–west trending anastomosing quartz veins with galena, anglesite, cerussite, pyromorphite, malachite, and azurite in the Comstock andesite have been mined where they coalesce to form a ladder vein deposit (2.5–31.5% Pb, 0.3–1.4% Zn, 15–400 g/t Ag). Intermittent production between 1915 and 1953 yielded 191.5 t of ore containing 78.2 t of lead and 28.77 kg of silver
Rushalls [59686945]	A 1 m-thick mineralized section in a faulted extension of the Whim Creek ore horizon in the nose of a northeast plunging antiform 250 m east-northeast of the main shaft, Whim Creek mine. Previously mined only for secondary copper ore (46.7 t at 12.2% Cu)
Federal City [58626956]	Small but rich cupriferous vein stockwork in arkose beneath the Rushall Slate (underlying alluvium) about 1.2 km north of the Whim Creek mine

Table 10. (continued)

Prospect [AMG coordinates] [(a)]	*Description of mineralization* [(b)]
Stranger (Croydon Road) [58836942]	Small quartz ± malachite veins and lenses subparallel to cleavage in and layering in the Rushall Slate 2 km east of the Whim Creek mine. Previously mined for secondary copper ore (10 t at 25% Cu), but the first of 2 drillholes beneath the workings intersected siliceous 'rhyolite' with 2.8 m at 9.00% Zn, 0.83% Pb, 0.67% Cu
New Hedland Road show [59047056]	Gossan and fragments of high-grade malachite–chalcocite in a pit in calcreted chlorite schist of the Whim Creek Group or older basement Archaean volcanics. Gossan analysed at 0.14% Pb, 0.03% Zn, 2.1% Cu, 2.1 g/t Ag, 2.1 g/t Au
Ant Hill [58507050]	Several gossans/ironstones (with up to 1.8% Pb, 2.5% Zn, 0.24% Cu, and 35 g/t Ag) outcrop in felsic volcanics of the Mons Cupri Volcanics along a local unconformable contact immediately beneath andesite of the Negri Volcanics
Balla Balla [58057065]	Pyrite, sphalerite and galena in stringer veins in tuffaceous siltstone and chert in correlates of the Mons Cupri Volcanics. The best intersection of 9 drillholes is in BBD7A: 5.27 m at 0.47% Pb, 2.52% Zn, 0.06% Cu, 10.7 g/t Ag
West Balla [57837064]	Pyrite, sphalerite and galena in stringer veins in siltstone and chert in correlates of the Mons Cupri Volcanics. The best intersection of 5 drillholes is in WBD4: 4 m at 0.72% Pb, 2.43% Zn, 0.11% Cu, 6.3 g/t Ag

NOTES: (a) Prospect locations in [] are in AMG coordinates to the nearest 100 m
(b) Assay data for Pb, Zn, Cu, Ag, and Au are included as an indication of maximum values of mineralization encountered

Balla, within the Ant Hill felsic volcanic centre (Fig. 12). Here, a domal mass of spherulitic rhyolite, correlated with the Mount Brown Rhyolite, is overlain by a thick pile of fragmental volcanics with laminated cherty interbeds towards the top of the sequence. The felsic volcanics are correlated with the Mons Cupri Volcanics and are unconformably overlain by a thick pile of amygdaloidal basalt that is correlated with the Negri Volcanics (Clemen, 1980). Base-metal mineralization is represented by several small ironstones or possible gossans with up to 2.5% Zn, 1.8% Pb, 0.24% Cu and 35 g/t Ag. The gossans are located within the Mons Cupri Volcanics but they are all adjacent to its unconformable boundary with the overlying Negri Volcanics. Although some of these ironstones may be gossans (or palaeogossans), most have base-metal ratios markedly different from those of gossans overlying other volcanogenic sulfide mineralization (Fig. 22) and most likely due to dissolution and reprecipitation of iron and base metals by groundwaters percolating along the unconformity.

Volcanogenic mineralization during volcanic-belt evolution

During accumulation of the volcano-sedimentary pile that makes up the Whim Creek Belt, there have been two phases of base-metal volcanogenic mineralization that can be tied to major changes in the geological environment. These environmental changes and the two phases of mineralization (dominated by the volcanogenic sulfide deposits at Mons Cupri, Whim Creek and Salt Creek) have been equated with the development of resurgent submarine calderas within the belt (Collins, 1990). The two most prominent of the 5–6 km diameter caldera-like structures are centred on Mons Cupri and on Whim Creek. Miller and Gair (1975) also proposed that the Mons Cupri deposit formed at the edge of a caldera lake but suggested a much larger structure centred at Whim Creek rather than the smaller caldera structures identified by Collins (1990).

The oldest formation in the Whim Creek volcanic belt, the Warrambie Basalt, accumulated in a subaerial environment when there was apparently widespread exposure of the Caines Well batholith. Subaerial to subaqueous conditions probably continued throughout most of the subsequent Mons Cupri volcanism, though the Mons Cupri and Salt Creek volcanogenic sulfide deposits indicate a subaqueous environment at the end of the period of felsic volcanic activity. This volcanism was most active in at least three equidistant centres resulting in relatively thick domal accumulations of felsic volcanic rocks that spread across the belt to form the Nerrellys Bore, Mount Brown and Ant Hill volcanic piles, with possibly a fourth volcanic pile in the Salt Creek area. Sediments of the Rushall Slate then accumulated in a deeper subaqueous environment in small depocentres flanking the felsic volcanic piles, but only one of these depocentres is known to host significant sulfide mineralization at Whim Creek.

Accumulation of the Whim Creek Group can be tied to the early stages in the development of calderas, though the timing of initial ring fractures within the Whim Creek volcanic belt is enigmatic. A prolonged period of felsic volcanism followed by sedimentation during the main stage of caldera development (Smith and Bailey, 1968; Ohmoto and Takahashi, 1983) may be equated with

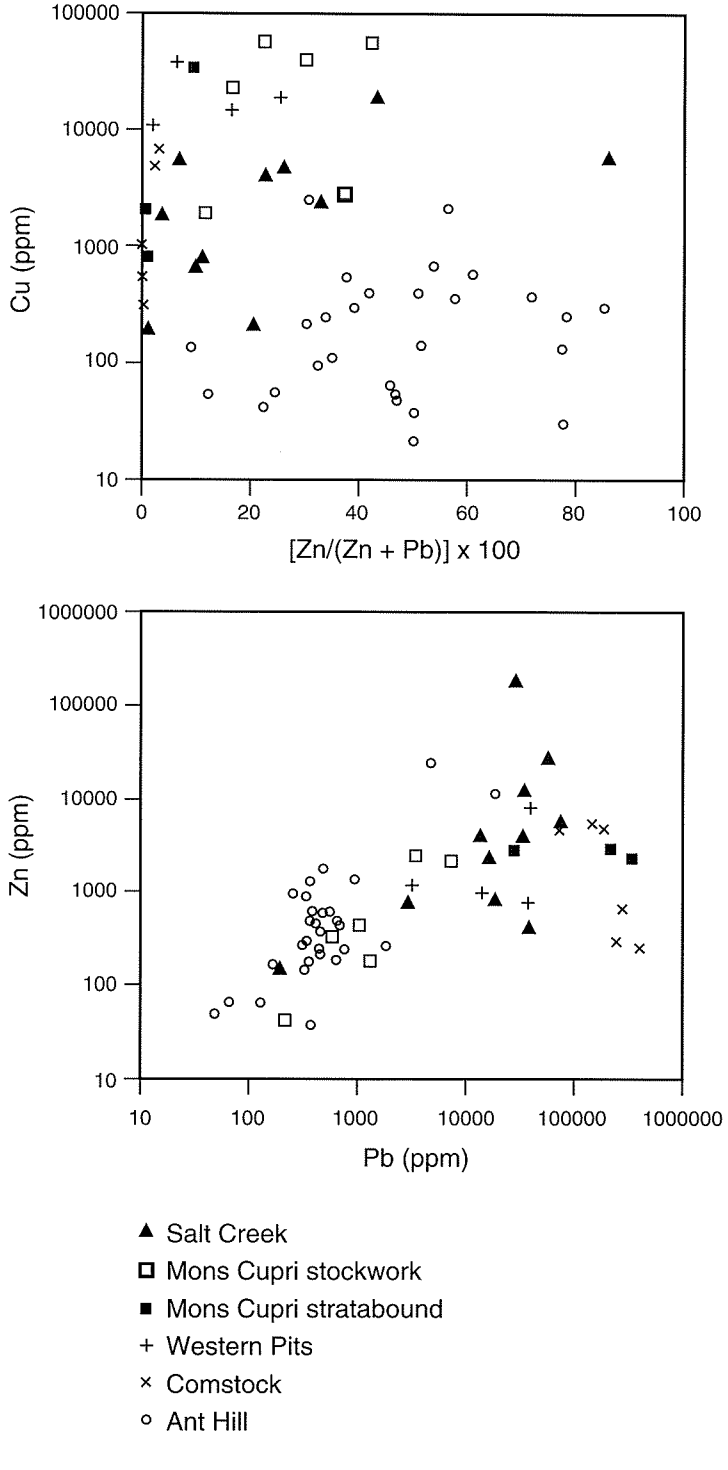


Figure 22. Zinc, lead and copper geochemistry of ?gossans at the Ant Hill prospect compared with gossans associated with volcanogenic sulfide mineralization at Salt Creek, Mons Cupri and Western Pits, and the Comstock deposit (data *from* Smith, 1980; Smith and Clemen, 1980; Chisholm, 1983a,b).Mons Cupri data are divided into gossans overlying the stratabound ore and those above the stockwork zone

accumulation of the Mons Cupri Volcanics and Rushall Slate (Collins, 1990). This stage of caldera development also includes volcanogenic massive-sulfide mineralization (Ohmoto, 1978; Ohmoto and Takahashi, 1983) which here is represented by the Mons Cupri, Salt Creek and Whim Creek deposits and smaller stratabound possible volcanogenic sulfide deposits elsewhere in the volcanic belt such as the Good Luck, Good Gear and Balla Balla prospects. The subaqueous fanglomerate deposits at the top of the Mons Cupri Volcanics are typical of steep-sided fault-bounded basins (Barley, 1987, 1992) and can be attributed to a period of rapid subsidence of the proposed caldera structures at the end of the Mons Cupri volcanism. This subsidence is necessary for the deeper subaqueous conditions which prevailed during the formation of the volcanogenic sulfide deposits and accumulation of the distal submarine-fan deposits and basinal pyritic black shales of the Rushall Slate (Barley, 1987).

The main volcanogenic sulfide deposits within the Whim Creek volcanic belt have formed at two stratigraphic levels, though not necessarily at different time intervals, and in different geological settings. The Mons Cupri deposit is positioned at the top of a thick sequence of coarse fragmental volcanics on the flank of a domal volcanic pile that most likely accumulated in a relatively shallow subaqueous environment. It has an extensive alteration and stockwork zone capped by a small massive and banded sulfide lens and is similar to Kuroko-type volcanogenic massive-sulfide deposits (e.g. Reynolds et al, 1975; Miller and Gair, 1975) and to Mattabi-type Archaean deposits (Barley, 1992).

In contrast, the Salt Creek and Whim Creek deposits are hosted by deeper marine fine-grained epiclastic sequences, though at different stratigraphic levels, and they are more like some Phanerozoic deposits. They consist of relatively thin lenses of massive and banded sulfides within stratabound envelopes of disseminated and stringer-vein sulfide mineralization in chlorite-altered host rocks. Neither deposit has a prominent feeder zone, but this may reflect their depositional environment with hydrothermal fluids percolating through semi-consolidated sediments. At Salt Creek and Whim Creek there is evidence of two distinct periods of mineralization. The main Salt Creek deposit is hosted by a pyroclastic–epiclastic sequence at the top of the Mons Cupri Volcanics with a probable small lens of sulfide mineralization contained in overlying argillite that is correlated with the Rushall Slate. At Whim Creek, most mineralization is within the Rushall Slate but there is some minor mineralization within the underlying Mons Cupri Volcanics (e.g. Federal City).

A period of deformation and uplift of the Whim Creek Group was followed by the accumulation of mafic–ultramafic volcanics of the Louden and Negri Volcanics under probable subaerial conditions prevailing at the conclusion of the Whim Creek volcanism. The unconformity between the Whim Creek Group and the Louden and Negri Volcanics equates with a period of resurgence of calderas which is then followed by mafic volcanism (Smith and Bailey, 1968; Ohmoto and Takahashi, 1983). Hot-spring activity in a subaerial environment during the waning stages of caldera development (Smith and Bailey, 1968; Ohmoto and Takahashi, 1983) is represented within the Whim Creek Belt by a second phase of volcanogenic mineralization. This resulted in widespread epithermal quartz veining, some with silver–lead and gold mineralization, which preceded localized accumulation of conglomerate, sandstone, chert and minor basalt of the Bookingarra Sandstone, and in the sinter deposits reported by Alston (1984) in the Mount Fraser area.

Exploration potential

The Whim Creek volcanic belt became one of the most intensely explored volcanic belts in Western Australia during the 1970s following the recognition in the late 1960s of Mons Cupri as a major volcanogenic sulfide deposit and the discovery in 1977 of the smaller sediment-hosted massive-sulfide deposit at Salt Creek. Much of this exploration was concentrated around the two major centres at Whim Creek and Mons Cupri and later on the more structurally complex Salt Creek area. Although Mons Cupri, Whim Creek and Salt Creek are relatively small for this type of deposit, it is well documented that volcanogenic massive-sulfide deposits tend to form in clusters (Sangster, 1980; Franklin et al., 1981); hence there is potential for still further discoveries of similar sized or even larger deposits nearby.

The remainder of the Whim Creek volcanic belt also has considerable potential for base-metal mineralization but much of the prospective stratigraphy is concealed by the Louden and Negri Volcanics, including the shale basins to the southwest of Mons Cupri and to the west of the Nerrellys Bore volcanic centre, and in the Ant Hill area to the north of Whim Creek. The flanks of domal felsic volcanic piles are considered most prospective for Mons Cupri-type deposits in fragmental volcanics, whereas exploration for the Whim Creek–Salt Creek style of mineralization is best directed at marginal sedimentary sub-basins.

Acknowledgments

Preparation of this contribution has utilized the unpublished work of a number of geologists who have worked in the Whim Creek district, including T. Alston, M. E. Barley, R. Butler, J. M. Chisholm, A. Clemen, H. S. Gair, T. Grobichi, T. E. Koehler, K. O. Linn, L. J. Miller and M. E. Smith. The authors acknowledge the contributions that their work has made to this review, particularly that work which has been incorporated in the accompanying geological map of the Whim Creek volcanic belt. Dominion Mining Ltd and A. Poustie are thanked for providing access to a number of unpublished company reports and maps on the volcanic belt.

SHEPHERD WELL (Devil Creek)[1]

Prospect: Zn; Pb; Ag; Cu; Au[2]
Location: 21°02'S, 116°20'E; 70 km south of Karratha

Felsic volcanics of the Whim Creek Group contain a mineralized 'cherty tuff', with dacitic interbeds, which grades to banded iron-formation along strike. Arimco/Cyprus (1989–90) tested the prospective horizon for VMS targets over 2 km of strike with stream-sediment and soil geochemistry. Soil sampling located low-order gold–lead–zinc anomalism at the volcano-sedimentary contact, presumably at the top of the Duffer Formation. Rock chips gave >9% combined lead and zinc. Ground magnetics and VLF EM traced the prospective unit beneath Hamersley Group cover. Follow-up RC drilling gave a best intersection of 8 m at 2.7% Zn, 1.57% Pb and 10–25 g/t Ag in a 'cherty tuff' with dacitic pyroclastic interbeds.

More recent examination in the field by the GSWA, however, suggests that the mineralization is controlled by a shear rather than stratiform (Hickman, A. H., 1998, pers. comm.).

Reference: GSWA-WAMEX - I 5759

Sholl Belt (Whundo, Whundo West, Yannery)

Volcanic-hosted massive-sulfide deposits at Whundo–Yannery in the Sholl Belt

Contribution by P. L. F. Collins[3] and A. E. Marshall[4] (b)

A cluster of small volcanic-hosted zinc–copper sulfide deposits in the Whundo–Yannery area (21°04'S, 116°55'E), about 50 km south-southeast of Dampier, is the only significant base-metal sulfide mineralization in the Sholl Belt at the western end of the Pilbara granitoid–greenstone terrane (Figs 7 and 23). Although most interest in the Whundo–Yannery area has been in the intense secondary enrichment of copper in gossans and oxidized portions of ore shoots, and all previous mining has been entirely in oxidized and supergene ore, there remains a significant resource of zinc, copper and silver. The Whundo and Yannery mines are readily accessible by a service road for the Dampier–Tom Price railway line, which leaves the Northwest Coastal Highway about 10 km west of the Karratha turnoff, and then by track which leaves the service road near the 34 Mile Camp, 35 km from the highway (Figs 23 and 24). The Yannery mine is 2.5 km and the Whundo mines about 3.5 km southwest of the camp along this track.

Early mining and exploration of the Whundo–Yannery deposits have been documented by Blatchford (1913) and Low (1963) and they are mentioned by Blockley (1971) and Davies and Blockley (1990). Detailed descriptions of the geology and mineralization are presented by Colman (1973), Roberts (1974), Reynolds et al. (1975) and Marston (1979). Additional data presented here are drawn from unpublished company reports.

History of mining and exploration

Gossanous outcrops of supergene enriched copper mineralization in the Whundo–Yannery area apparently had been found by 1911 with the opening of the Trouble copper mine, later known as the Whundo mine. Two years later, mining commenced at the Yannery Hills copper mine (Colman, 1973; Marston, 1979). The deposits were mined intermittently until 1968 and again in 1976 with total production of 12 006 t of high-grade secondary copper ore averaging 22.3% Cu and a small amount of silver and gold. As an indication of the grade of the supergene ore, independent assays for several parcels of direct-shipping chalcocite ore from the 1976 mining indicate 23–25% Cu, 48–61 g/t Ag and 1.1–1.6 g/t Au. There is no recorded production of zinc or lead from these deposits, nor of silver from the early mining, but there is a small stockpile of zinc-rich oxide and sulfide ore from the most recent mining operation at Whundo.

Exploration of the Whundo–Yannery area during the 1960s initially was directed at supergene copper mineralization, especially in the Whundo area where several small high-grade shoots were outlined, including one that was mined in 1976. Later exploration focused on the potential for larger primary sulfide deposits beneath the supergene zone. Westfield Minerals (WA) NL, later Whim Creek Consolidated NL, conducted the first systematic exploration of the area with a number of geological, regolith geochemical, and geophysical programs. About 100 percussion holes were drilled in 1969 and a further 30 holes completed in 1970–71. This work established considerable tonnages of primary Zn–Cu sulfide mineralization in the Whundo and Whundo West ore shoots with a combined indicated resource of 2.0 Mt at 1.3% Zn, 2% Cu and 11 g/t Ag (Marston, 1979; Davies and Blockley, 1990b) and very low levels of gold. A further 15 diamond cored holes and additional percussion holes were drilled by Consolidated Gold Fields Australia in 1972 but failed to establish additional resources. Exploration continued in the early 1980s following a joint venture agreement with Noranda Australia, but most subsequent work has been on reassessment of reserves and investigation of the feasibility of mining leachable copper ore at Whundo and Whundo West.

Sholl Volcanic Belt

The Sholl Belt (Hickman, 1983) consists of a 4 km-thick sequence of well exposed mafic and felsic metavolcanic and metasedimentary rocks occurring in a triangular area

[1] Main accepted Mine, Deposit or Occurrence name is in upper case. Names of other minor workings of occurrences in the immediate vicinity, or alternative names used in publications, maps or open-file reports are in brackets.
[2] Elements are in approximate order of importance as defined by resources, grades, intersections or visual estimate.
[3] School of Applied Geology, Curtin University of Technology, GPO Box U1987, Perth, W.A. 6001
[4] Qestore Pty Ltd, 21 Viewway, Nedlands, W.A. 6009

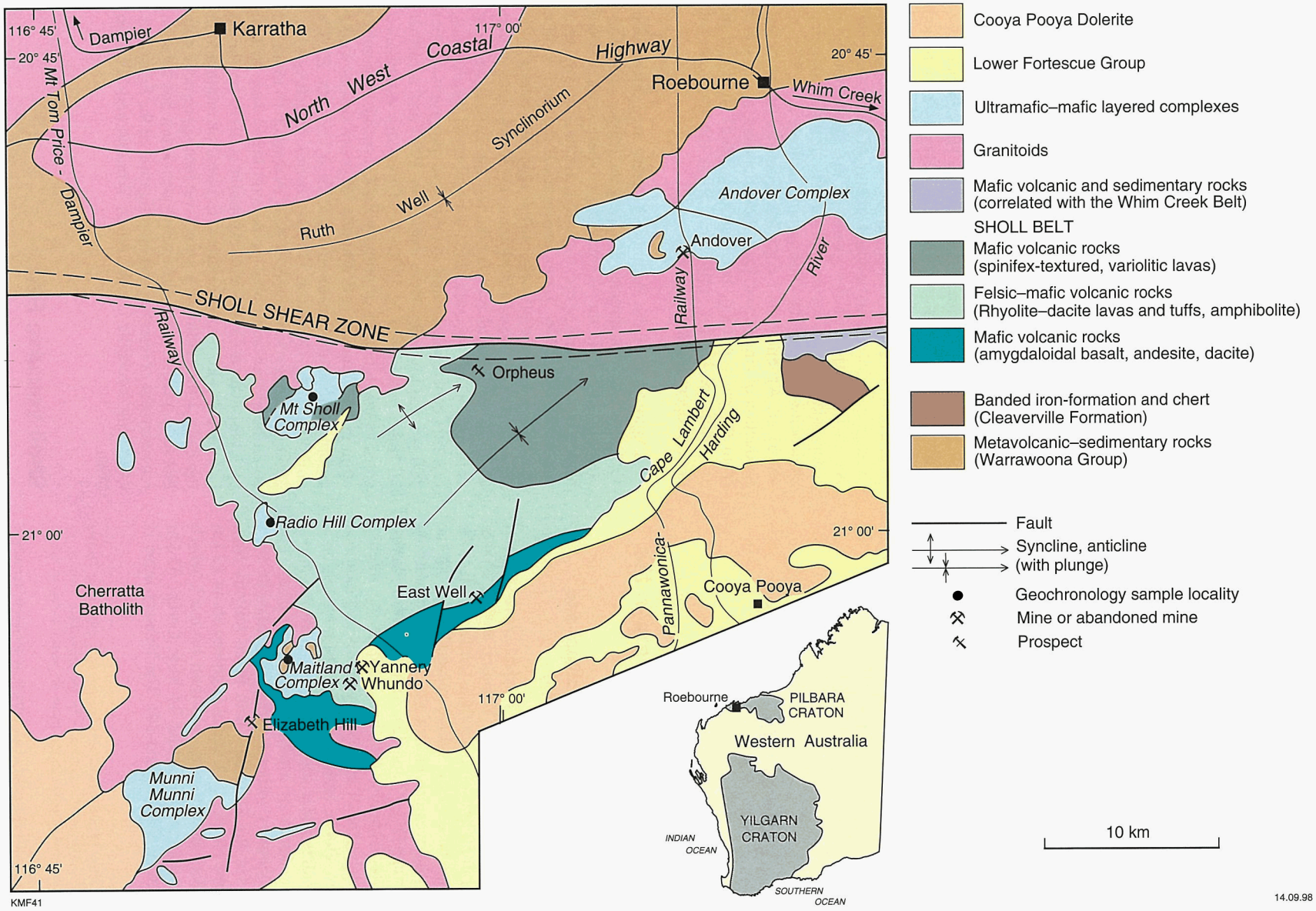


Figure 23. Geology of the Sholl Belt in the west Pilbara, with the Whundo–Yannery deposits located in the southern corner of the belt (regional geology *after* Hickman, 1983; Horwitz, 1988; Barnes et al., 1991)

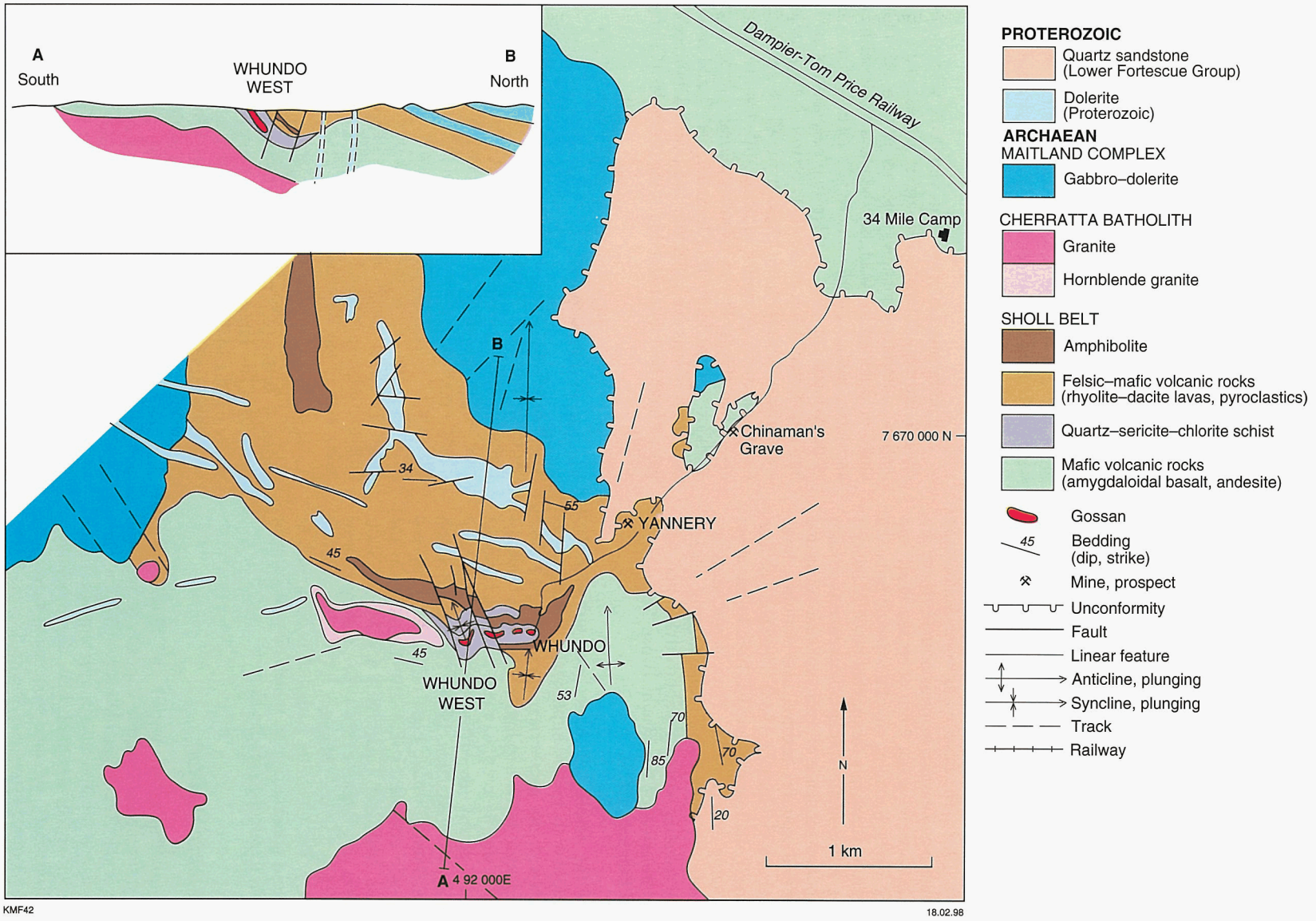


Figure 24. Geology of the Whundo–Yannery area (*based on* unpublished mapping *by* J. W. Schupp, 1969; Noranda Australia). The Whundo and Whundo West deposits are in the axis of a northerly plunging syncline and Yannery possibly is at a higher stratigraphic level. The north–south cross section passes through the Whundo West deposit

confined by the Sholl Fault to the north, granitoids of the Cherratta Batholith to the west, and overlying rocks of the Mount Bruce Supergroup to the east (Fig. 23). The eastern extent of the Sholl volcanic belt beneath the Mount Bruce Supergroup is not known, though Horwitz and Pidgeon (1993) show correlates of the Whim Creek Belt encroaching on the northeast corner of the belt. The bimodal volcanic sequence is similar to the Whim Creek Belt with which it has previously been correlated (Miller, 1975; Horwitz, 1988, 1990b). However, recent zircon U–Pb dating indicates that the Sholl Belt has an age of about 3.11 Ga (Horwitz and Pidgeon, 1993) and is therefore slightly older than the Whim Creek Belt for which there is a zircon U–Pb age of 2.95 Ga (Barley et al., 1994).

A regional stratigraphic succession (Hickman, 1983; Horwitz, 1988) for the northerly younging sequence has a basal pile, about 300 m thick, of mafic volcanics that include andesite and amygdaloidal basalt (Reynolds et al., 1975; Horwitz, 1988). The basal mafic volcanics outcrop along the southern and eastern margins of the belt and are overlain to the north by about 2 km of mixed felsic and mafic volcanic rocks, including rhyolitic–dacitic tuffs and lavas that outcrop extensively throughout much of the belt (Fig. 23). The felsic–mafic volcanic sequence is in turn overlain by another sequence of mafic volcanic rocks that includes pillowed, spinifex-textured and variolitic lavas (Reynolds et al., 1975; Horwitz, 1988). The Sholl volcanic pile has relatively shallow dips and has been folded about northeast-plunging axes (Fig. 23). The volcanic sequence has been intruded by a number of predominantly easterly and northerly trending dolerite–gabbro dykes and sills prior to accumulation of the Mount Bruce Supergroup (Horwitz and Pidgeon, 1993).

Rocks of the Sholl Belt have been subjected to upper greenschist to lower amphibolite facies metamorphism, though the southern parts of the belt have been overprinted by hornblende hornfels contact metamorphism during emplacement of post-regional metamorphism granitoids of the Cherratta Batholith (Reynolds et al., 1975; Marston, 1979). The Sholl Belt and the Cherratta Batholith have been intruded by layered mafic–ultramafic complexes (2.8–2.95 Ga) such as the Munni Munni, Maitland, Radio Hill and Mount Sholl Complexes (Fig. 23; Barnes et al., 1991), and by swarms of younger dolerite dykes (Marston, 1979; Horwitz and Pidgeon, 1993). The Cherratta Batholith is composed of several granitoid masses some of which may be younger than the mafic–ultramafic complexes.

Base-metal mineralization

Base-metal mineralization within the Sholl belt is dominated by stratabound sulfide deposits of probable volcanogenic origin. The largest deposits at Whundo and Whundo West are located at a major change in the volcanic stratigraphy of the Sholl belt, at the boundary between the basal mafic volcanic sequence and overlying felsic volcanic dominant sequence (Reynolds et al., 1975). A smaller deposit at Yannery, about 1 km northeast of Whundo (Fig. 24), apparently is within the felsic volcanic sequence, possibly at a slightly higher stratigraphic level than the Whundo deposits.

Base-metal grades of primary sulfide mineralization at Whundo and Whundo West are typical of Archaean massive-sulfide deposits, being essentially Zn–Cu(–Ag) deposits similar to the sediment-hosted Whim Creek deposit (Table 6); however, they are depleted in gold. The Whundo–Yannery deposits are characterized by a lack of lead minerals, with limited assay data indicating an average of less than 100 ppm Pb (Colman, 1973), which is atypical of the lead-enriched volcanogenic sulfide deposits elsewhere in the Pilbara Craton (Table 6).

In addition to the main deposits at Whundo, Whundo West and Yannery, percussion and diamond core drilling has intersected several pods of disseminated to massive pyrite and minor pyrrhotite with traces of sphalerite and chalcopyrite within the volcanic rocks to the south and west of Whundo (Colman, 1973). This mineralization outcrops as small gossans with anomalous zinc and copper values (e.g. Nicks gossan, Fig. 25).

Sphalerite also occurs in veins within the volcanic pile close to the main deposits. The largest of these is the 'zinc gossan', a northerly trending siliceous gossan, 38 m long and 7 m wide, on the boundary between the basal mafic and felsic–mafic volcanic sequences, about 200 m south of the Whundo pit (Fig. 25). Drilling beneath this gossan has intersected 0.3 m thick veins of massive pyrite and sphalerite with only minor chalcopyrite (21% Zn, 0.12% Cu in one vein). A similar structure filled with coarsely crystalline sphalerite was exposed during mining of the Whundo deposit in 1976 (Alexander, 1977) and several thin veins of massive sphalerite and pyrite with traces of galena have been intersected in some drillholes (Colman, 1973).

Whundo and Whundo West

The Whundo mine (21°04'50"S, 116°55'30"E) is 3.4 km southwest of the 34 Mile Camp on the Tom Price–Dampier railway and Whundo West is a further 350 m west of the Whundo pit (Figs 24 and 25). A description of the deposits is given by Reynolds et al. (1975) and Marston (1979), with detailed accounts of the host-rock petrology and ore mineralogy by Colman (1973) and Roberts (1974), though all of these studies are based on surface exposures and drilling data and preceded excavation of the Whundo pit.

The deposits have been explored and mined from a series of shafts (≤27 m deep) and many small pits and opencuts. The largest opencut was excavated in 1976, when 6746 t of 27.4% Cu ore was produced from a supergene-oxidized ore shoot at the Whundo deposit (Alexander, 1977). Production prior to this was 2214 t averaging 15.3% Cu (Marston, 1979), and there is an additional measured resource in situ of 49 000 t at 7.4% Cu at Whundo West. If the copper grades of the sulfide resource (Table 6) are indicative of that from which the supergene ore was derived, then the total original resource at Whundo and Whundo West is estimated to be of the order of 2.3 Mt of Zn–Cu sulfide mineralization.

The host rocks comprise a basal sequence of massive and foliated amygdaloidal and feldspar-phyric basalt and minor quartz-phyric dacite–rhyodacite which

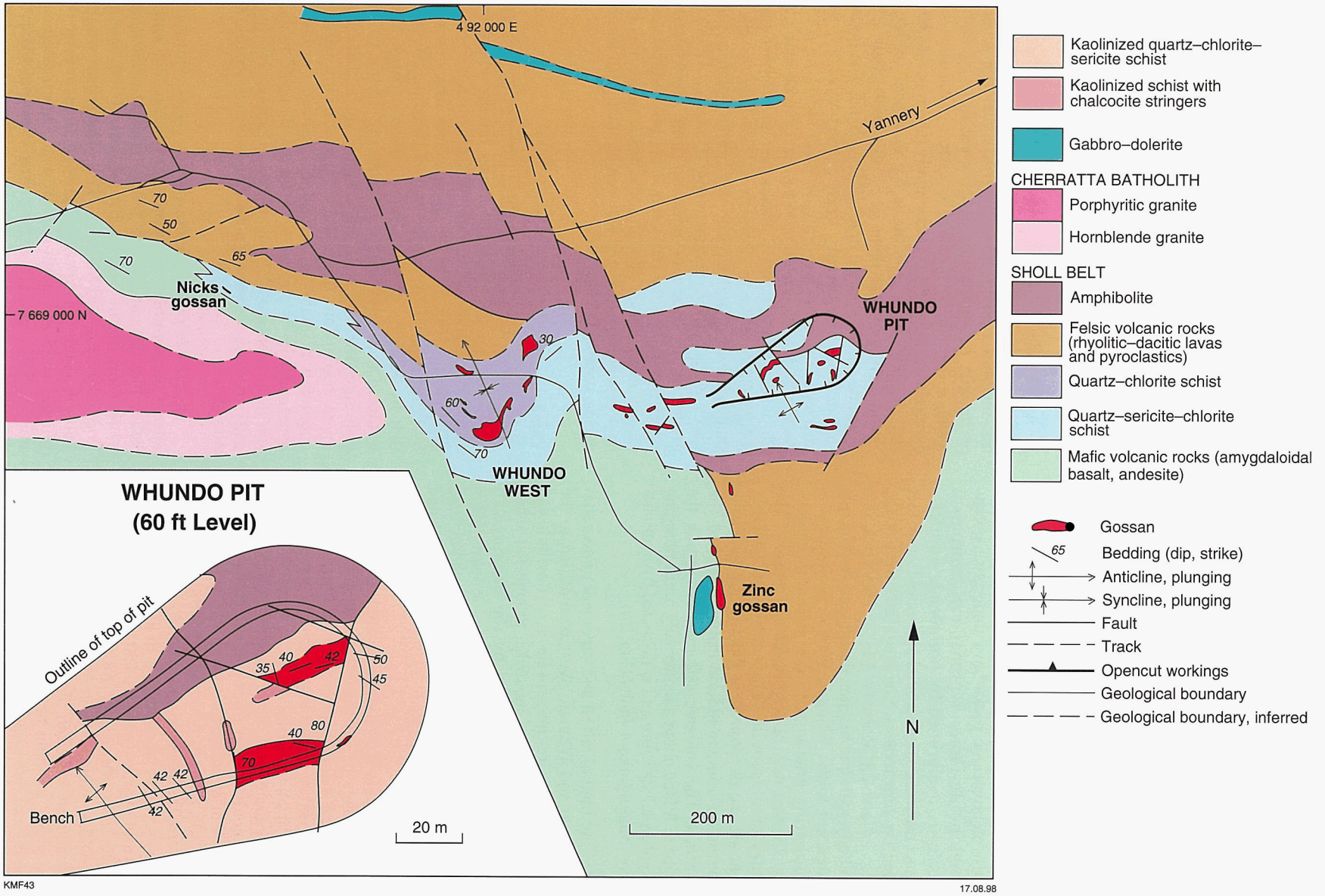


Figure 25. Geology of the Whundo and Whundo West deposits (unpublished mapping *by* J.W. Schupp, 1969; Noranda Australia). The geology of the Whundo pit is based on the 30 ft level plan (Alexander, 1977). Inset: Geology of the 60 ft level, Whundo pit (Alexander, 1977), showing disruption of the ore horizon by faulting

is overlain by a sequence of massive rhyolitic–dacitic volcanics and minor andesite (Roberts, 1974; Alexander, 1977). In the upper parts of the basal basaltic sequence at the boundary with the overlying felsic sequence is a prominently spotted quartz–chlorite–muscovite schist with variable concentrations of chlorite and muscovite and localized concentrations of porphyroblastic andalusite and pyrite (Figs 24 and 25). The schist probably represents a metamorphosed alteration zone (Roberts, 1974) with andalusite porphyroblasts formed during later metamorphism. The schist and overlying felsic volcanics are transgressed by an irregular but subconcordant body of amphibolite that forms the hangingwall to the ore body in the Whundo pit (Fig. 25). This amphibolite is older than, and unrelated to, later gabbro–dolerite dykes and sills that traverse the Sholl Belt.

The host metavolcanic rocks have undergone greenschist–amphibolite-facies regional metamorphism which locally is overprinted by hornblende hornfels-facies contact metamorphism around a granitoid stock that has intruded the host rocks to the south and west of the mines (Figs 24 and 25; Roberts, 1974). The stock is a composite body with biotite granodiorite and hornblende granite. Adjacent to the Whundo West deposit, there is also a porphyritic granite with disseminated chalcopyrite (Fig. 25) that may be a synvolcanic intrusive. The quartz–chlorite–muscovite schist has been variably metamorphosed and the prominent spotting and andalusite are attributed to contact metamorphism around the granitoid stock. The volcanic sequence, including the schist, has been folded about a moderately north-plunging complex synformal structure and is dissected by a number of northerly trending major faults (Fig. 24).

Most sulfide (and oxidized and supergene) mineralization at Whundo and Whundo West is confined to the spotted quartz–chlorite–muscovite schist which can be traced for about 1 km along strike, though the schist is truncated at the eastern end by the hangingwall amphibolite (Fig. 25). The schist extends at least 400 m downdip to the north where it has been intersected in three diamond-cored holes that were drilled by Consolidated Gold Fields Australia in 1972.

The ore apparently is confined to a single stratigraphic horizon as a series of northwesterly to north-northwesterly plunging shoots that outcrop as a sinuous line of discontinuous goethite–hematite gossans that can be traced for some 500 m along strike (Fig. 25; Reynolds et al., 1975). Individual ore shoots have a restricted strike length and are commonly 1–5 m thick but reach a maximum thickness of 20 m in the hinge zone of two small upright synclines in the axis of the major synclinal structure, where they form the Whundo and Whundo West deposits. The ore shoots plunge at about 40° to the northwest and extend down plunge as much as 150 m. The three deep drillholes to the north of the mine did not intersect significant sulfide mineralization. The ore horizon exposed in the Whundo pit has been disrupted by northwesterly and northeasterly trending faults (Fig. 25) which would explain the discontinuous nature of the gossans.

Primary sulfides, mostly pyrrhotite, pyrite, sphalerite and chalcopyrite, are preserved only below the weathering profile (at depths in excess of about 30 m) but neither galena nor any other lead minerals have been reported from the Whundo or Whundo West deposits. Magnetite is disseminated throughout the sulfide mineralization.

Three types of primary sulfide mineralization have been recognized at the Whundo deposit (Roberts, 1974): fine- to medium-grained layered pyrite, sphalerite and chalcopyrite; massive medium- to coarse-grained pyrite and pyrrhotite with minor sphalerite and chalcopyrite; and pyrite with chalcopyrite and sphalerite in thin veins, layers and stringers which may be a narrow stockwork zone in the upper parts of the host chloritic schist beneath the main ore horizon.

At Whundo West, there are two main types of primary sulfide mineralization (Colman, 1973; Marston, 1979): fine-medium grained, layered pyrite–sphalerite–chalcopyrite with disseminated magnetite but little pyrrhotite, which is overlain by medium- to coarse-grained massive pyrrhotite and pyrite that is essentially barren of sphalerite and chalcopyrite. Pyrrhotite is the dominant sulfide at Whundo West where there is a coincident small aeromagnetic anomaly of the order of 80–120 nT. The layered sulfides have relatively high grades with a 7.9 m intersection in diamond drillhole WG6 averaging 6.15% Zn and 2.95% Cu, including 4.6 m at 9.7% Zn and 3.8% Cu, whereas in hole WG5 grades average 3.19% Zn and 0.70% Cu over 4.6 m (Colman, 1973). There is also a small zone of granular pyrite with minor sphalerite and traces of chalcopyrite and magnetite (Colman, 1973). Zinc grades in this zone are similar to those elsewhere but copper is markedly depleted. Sulfide minerals and magnetite are coeval, though some of the pyrite may be a later generation associated with remobilization of sulfides during supergene alteration.

Yannery

The Yannery mine (21°04'30"S, 116°55'50"E) is 2.6 km southwest of the 34 Mile Camp on the Dampier–Tom Price railway line and 900 m northeast of the Whundo pit (Fig. 24). The deposit was first described by Blatchford (1913) but the only detailed description is that by Marston (1979). Some 3045 t of high-grade oxidized and supergene ore averaging 15.9% Cu has been mined from a series of adits and shafts that extend up to 100 m into the hillside. The workings did not encounter primary sulfide mineralization but, as the supergene ore is similar to Whundo, then the primary sulfide assemblage is also likely to be dominated by pyrite and pyrrhotite with minor sphalerite and chalcopyrite, and no galena.

Quartz–sericite(–chlorite–pyrite) schist with minor altered porphyroblasts of andalusite outcrops in a narrow valley that has cut through gently flexured white quartz sandstone of the Lower Proterozoic Cliff Springs Formation (Fig. 24; Marston 1979). The schist is tightly folded about an upright synformal structure that plunges at 25–40° north-northwest and has a steep east-northeasterly dipping axial planar cleavage (Marston 1979). The main mine workings are in the axis of this synform less than 10 m vertically below the Proterozoic unconformity.

A single stratabound ore horizon is confined to, and about 50 m above, the structural base of a zone of chlorite(–pyrite) schist which itself is underlain by quartz–chlorite–sericite schist (Marston, 1979). Several narrow ore shoots commonly less than 1 m thick (but up to 2–3 m) have developed in the axes of minor upright folds in the axial zone of the major synform. The shoots parallel the plunge of this synform but are not continuous along strike as tectonic thinning of the primary sulfide mineralization in the limbs of minor folds has resulted in discontinuity of the ore horizon.

Quartz–chlorite schist in hard siliceous acid–intermediate volcanic rock has been intersected in three vertical percussion holes drilled by Consolidated Gold Fields Australia in 1972 to test the down-plunge continuation of the ore horizon beneath the Proterozoic sandstone (Marston, 1979). The schist is anomalous in copper (≤6600 ppm Cu over a drilled width of 65 m) but only one hole (P81) intersected massive sulfide mineralization, including a 2 m sulfide intersection which assayed 13.0% Zn and 2.3% Cu in a hand-picked sample (Marston, 1979). These grades are comparable with those in the more massive sulfides at Whundo and Whundo West.

Weathering and supergene enrichment

A large gossan caps the more massive pyrrhotite at the Whundo West deposit, but not at Whundo, and a number of smaller gossans have formed on zones of pyritic alteration (Reynolds et al., 1975). The Whundo West gossan has elevated copper, zinc and silver values (0.06–1.7% Cu, 200–700 ppm Zn, 5–165 g/t Ag; Reynolds et al., 1975) but, in comparison with the contiguous primary sulfide mineralization, the gossan is markedly depleted in zinc and enriched in silver (Table 6). The gossan caps an extensive zone of supergene enrichment that extends to a depth of 50–60 m. Supergene-enriched ore consists mostly of massive chalcocite and goethite–limonite, with minor malachite, cuprite and native copper. Remnants of sphalerite, pyrite, pyrrhotite and magnetite are preserved in the lower sections where the ore grades into primary sulfides (Colman, 1973). Grades in the supergene zone commonly are of the order of 10–20% Cu (Reynolds et al., 1975) but there is no enrichment in zinc with grades of the order of 0.01–1.25% Zn (Colman, 1973). The quartz–chlorite–muscovite(–pyrite) schist which hosts the sulfide mineralization has been intensely kaolinized and ferruginized in the oxidized zone adjacent to the ore horizon.

A series of discontinuous ironstones with anomalous zinc and copper values (each ≤1000 ppm) are localized along the boundary between the Archaean sequence and the overlying Proterozoic sandstone (Colman, 1973). At Chinamans Grave, about 0.5 km northeast of Yannery, a shaft and several pits have been sunk on some of these apparent gossans where they contained several per cent zinc and copper. The limonitic gossans probably represent oxidation of lenses of matrix and replacement sulfides, mostly pyrite, within the basal Proterozoic sandstone. Their proximity to the unconformity indicates that they may have resulted from movement of groundwater on the Archaean–Proterozoic contact, though some possibly are remnants of fossil gossans that developed on small sulfide lenses at the Proterozoic palaeosurface (Colman, 1973).

Genesis

Previous workers (Colman, 1973; Roberts, 1974; Reynolds et al., 1975; Marston, 1979) have concluded that the Whundo–Yannery deposits are of volcanogenic origin and subsequently modified by metamorphism and deformation. The zinc–copper sulfide-dominant mineralization and its stratigraphic position at a major change from mafic to more felsic volcanism within a bimodal volcanic sequence is typical of Archaean volcanogenic sulfide deposits (Franklin et al., 1981).

The stratabound sulfide mineralization at Whundo–Whundo West and Yannery is within zones of spotted quartz–sericite–chlorite(–andalusite) schist which most likely represents relatively extensive but shallow footwall alteration of the mafic and felsic volcanic host rocks. Relationships between sulfide mineralization and this alteration are clearest at Whundo West and Yannery where the stratabound ore is within quartz–chlorite schist that is enveloped by a zone of quartz–sericite chlorite schist (Fig. 25; Marston, 1979). This zonation from chlorite to sericite(–chlorite) assemblages is typical of footwall alteration in most volcanogenic sulfide deposits. Prominent spotting of the quartz–sericite–chlorite alteration is attributed to contact metamorphism and is similar to spotted hornfels, known locally as dalmatianite, that has developed as a result of contact metamorphism of the alteration zone at the Millenbach deposit and some other Canadian Archaean volcanogenic sulfide deposits (Franklin et al., 1981; Knuckey et al., 1982).

There do not appear to be any structural controls on the primary sulfide mineralization, though the present morphology of the ore shoots is controlled by folding, with mineralization thickest in hinge zones. The distribution of the ore shoots is controlled by faulting. The lack of primary sulfide mineralization in drillholes designed to test downdip extensions of the deposits may be a reflection of the structural complexity of the area rather than of an absence of massive zinc–copper sulfide mineralization.

Acknowledgments

The authors thank Dominion Mining Ltd for access to unpublished reports and maps of a number of geologists who have worked in the Sholl Belt, particularly T. B. Colman, T. Koehler, and J. W. Schupp.

PILGANGOORA

Occurrence: Cu; Pb; Ag; Zn
Location: 21°04'S, 118°20'E; 90 km south-southwest of Port Hedland

There is a small copper occurrence with appreciable lead and zinc in a mineralized ?limestone bed, probably within

the Gorge Creek Group. A surface sample assayed 3.74% Cu, 1.38% Pb, 0.24% Zn and 258.1 g/t Ag.

Reference: Blockley (1971).

Croydon Road (Stranger)

Prospect: Cu; Zn; Pb
Location: 20°50'24"S, 117°50'50"E; 2 km east of Whim Creek mine.

Malachite-stained limonite quartz veins and lenses lie subparallel to vertical layering and cleavage in marginally silicified phyllite of the Whim Creek Group. Some 10 t of copper ore (25% Cu) were extracted in 1899. Drilling by Australian Inland beneath pits and shallow shafts in 1973 intersected 2.8 m of 0.67% Cu, 0.83% Pb and 9% Zn in 'siliceous rhyolite'.

References: Marston (1979), GSWA-WAMEX - I 2097.

East Pilbara

Strelley Domain — Panorama group

Panorama VMS zinc–copper prospects

Contribution by R. Buick and M. G. Doepel[1]

The Panorama VHMS zinc–copper prospects are situated in the east Pilbara region of Western Australia about 100 km southeast of Port Hedland and 50 km west of Marble Bar. Eight significant occurrences of base-metal mineralization have so far been identified: Sulphur Springs, Kangaroo Caves, Breakers, Anomaly 45, Man O' War, Jamesons, Bernts, and Roadmaster (Fig. 26). Sulphur Springs was the first of these to be discovered, in 1984 by Horatius Wilhelmij. He noticed abundant secondary magnesium-rich sulfate precipitation along several hundred metres of a creek bed in which anomalous base-metal values had been obtained in earlier stream-sediment sampling programs. The area was subsequently pegged by Wilhelmij and others, who vended the tenement into the float of Miralga Mining NL (Miralga). Follow-up exploration by that company resulted in the discovery of a large gossan near the top of a felsic volcanic pile. The gossan, which returned sporadic high gold values (≤6 g/t), was tested by shallow drilling by Miralga and Homestake Australia Ltd. Sipa Resources Limited and Ashling Resources NL (the Sipa–Ashling Joint Venture) farmed into the tenements covering Sulphur Springs and its immediate environs in late 1989 and consolidated a larger landholding (Fig. 27) to cover about 60 km of strike of the felsic volcanic sequence that hosted the Sulphur Springs prospect.

Regional exploration commenced in 1990. A GEOTEM airborne electromagnetic and magnetic survey was flown and followed-up by geological reconnaissance. This regional approach to exploration was expanded in 1992 and 1993 to mapping at 1:25 000 scale the 3000 km² of tenements which by then constituted the project. These programs resulted in seven further base-metal gossan discoveries (listed above) within the same felsic volcanic succession that hosts Sulphur Springs, and several base-metal and gold targets in other stratigraphic successions.

The Outokumpu Group became involved in the project in early 1993. Resource figures (as at March, 1997) for the major prospects are detailed in Table 11 and outlined below.

Sulphur Springs – 2.8 Mt at 10.7% Zn and 0.6% Cu, and 2.5 Mt at 4.0% Cu and 1.1% Zn

Kangaroo Caves – 1.7 Mt at 9.8% Zn and 0.6% Cu

Bernts – 0.6 Mt at 7.8 % Zn and 0.3% Cu.

At Roadmaster, Breakers, Anomaly 45, Man O'War and Jamesons, intersections of lesser grade or thickness have been obtained, albeit from preliminary drilling only.

Regional geology

The Panorama prospects occur in early Archaean rocks of the Pilbara Craton. They are apparently restricted to one particular tectonostratigraphic domain within the granitoid–greenstone terrane, here termed the Strelley Domain (Fig. 26). This domain is bounded by major regional faults and has an internally coherent stratigraphy unlike that of adjacent domains. Rocks of the Strelley Domain are unconformably overlain by early, middle and late Archaean cover successions of the Gorge Creek, De Grey and Fortescue Groups. No basement is anywhere observed. The Strelley Granite forms a laccolith in the middle of the domain, intruding bedded rocks that young to the east to southeast, both below and above it. Other intrusions, of ultramafic to felsic composition, occur mostly as sills and tend to be concentrated along the upper contact of the Strelley Granite. The most obvious deformation event has produced a set of broad upright folds trending northeast, though more complexity is evident around the extremities of the granite body. Several large sinistral faults (displacement >1 km) transect both the granite and the surrounding supracrustal rocks and in some instances merge with the domain-bounding structures of the Shaw Lineament and the Pincunah Fault Zone (Fig. 26). Block faults of smaller displacement radiate from the upper contact of the Strelley Granite, mostly dying out a short distance into the Gorge Creek Group cover succession. Metamorphic grade is generally very low (sub-greenschist facies), though assemblages representative of greenschist to amphibolite facies are developed in the southwestern part of the domain near the contact with the Yule Batholith. Pb-model ages of about 3260 Ma have been obtained from the Strelley Granite and from the mineralization at Sulphur Springs and Kangaroo Caves (McNaughton, N. J., and Vearncombe, S. E., unpublished data).

The greenstone succession within the Strelley Domain, the Strelley Succession, is laterally variable in thickness

[1] Sipa Resources Limited, 87 Colin Street, West Perth, W.A., 6005.

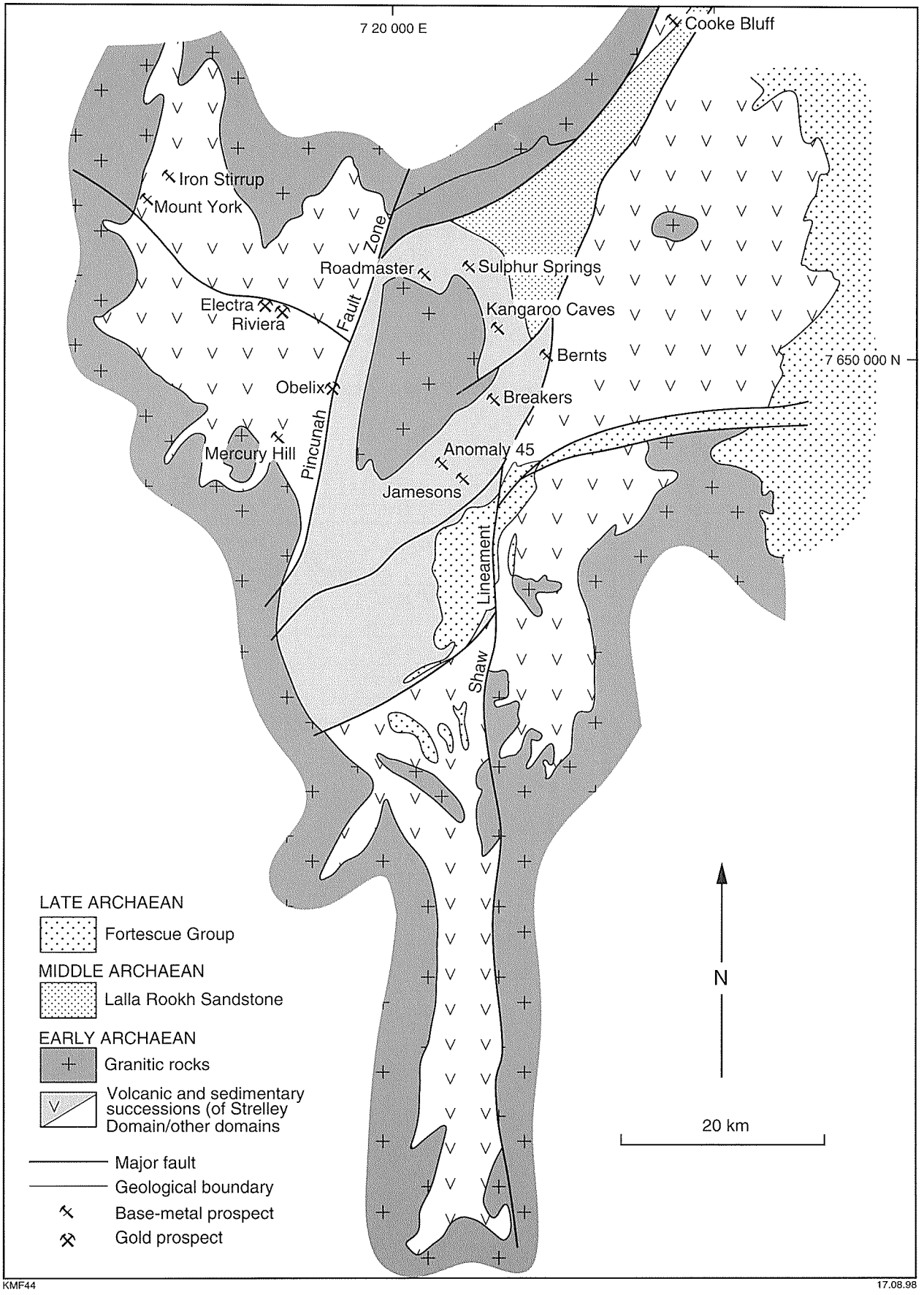


Figure 26. Panorama Project: regional geology and prospect locations (*after* Sipa Resources Ltd)

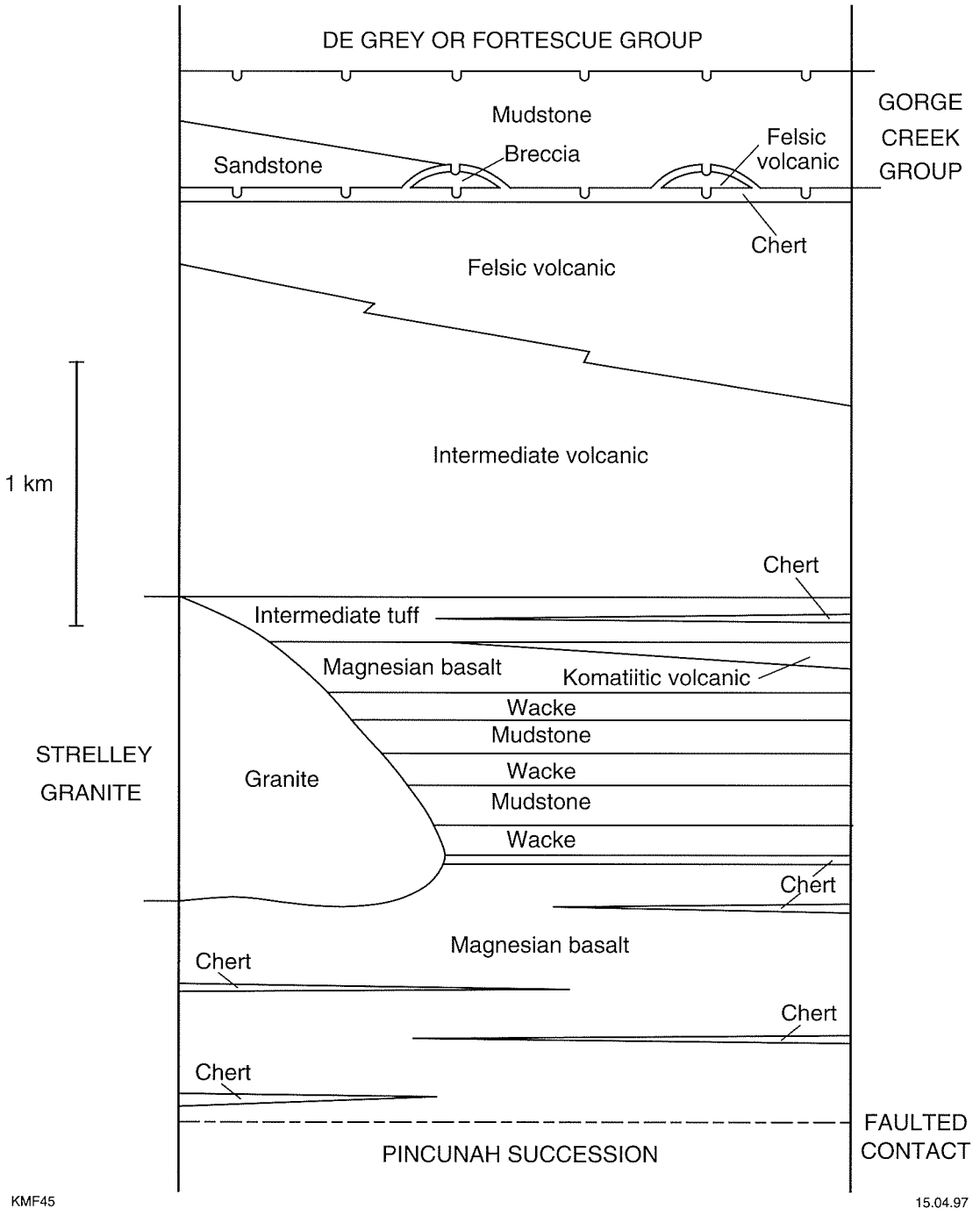


Figure 27. Strelley succession: around Strelley Granite (schematic) (*after* Sipa Resources Ltd)

and lithology, though a consistent stratigraphy of five fundamental units can be identified everywhere (Fig. 27). The lowermost unit consists predominantly of pillowed magnesian basalt with some interbedded plane-laminated cherts and komatiitic volcanic rocks towards the top. Overlying this is a sedimentary unit containing immature turbiditic sandstones, wackes and siltstones. Above the sedimentary rocks lies another, thinner unit of magnesian and komatiitic volcanic rocks, in some places with a distinctive bed of vitric-lithic-crystal tuffaceous arenite or diamictite containing mafic scoria, felsic-derived quartz clasts and pebbles or cobbles of kerogenous chert, magnesian basalt and quartz sandstone. A unit of intermediate to felsic volcanic rocks follows. This contains pillowed and amygdaloidal andesite with interflow hyaloclastite that passes up into amygdaloidal, plagioclase-phyric dacite with perlitic and high temperature devitrification textures. Quartz-phyric rhyolite and pumice-rich volcaniclastic deposits are locally abundant within this unit, especially

Table 11. Panorama Project — identified mineral resources (March 1997)

Locality/ Category	*Tonnes*	*ZnEq %*	*Cu %*	*Zn %*	*Pb %*	*Ag ppm*	*Au ppm*
SULPHUR SPRINGS MINERAL RESOURCE ESTIMATE							
Zinc resource estimate at 6% zinc cut-off							
Indicated	2 400 000	–	0.57	10.74	0.41	35	0.18
Inferred	400 000	–	0.8	10.1	0.4	34	0.2
Total	**2 800 000**	**–**	**0.6**	**10.7**	**0.4**	**35**	**0.2**
Copper resource estimate at 2% copper cut-off							
Indicated	2 420 000	–	4.1	1.1	0.1	16	0.05
Inferred	100 000	–	3.5	0.5	0.0	8	<0.1
Total	**2 500 000**	**–**	**4.0**	**1.1**	**0.1**	**15**	**0.1**
Zinc equivalent estimate							
Estimate at 6% zinc equivalent cut-off							
(ZnEq = Zn% + 3.0 * Cu% + 0.45 * Pb% + 1.35 * Au ppm + 0.02 * Ag ppm)							
Inferred	7 500 000	12.0	1.9	5.5	0.2	25	0.1
KANGAROO CAVES MINERAL RESOURCE ESTIMATE							
Estimate at 6% zinc or 2% copper cut-off							
Indicated	970 000	–	0.73	9.90	0.64	18.6	0.05
Inferred	700 000	–	0.4	9.6	0.5	18	0.1
Total	**1 700 000**	**–**	**0.6**	**9.8**	**0.6**	**18**	**0.1**
BERNTS MINERAL RESOURCE ESTIMATE							
Zinc resource estimate at 6% zinc cut-off							
Inferred	600 000	–	0.3	7.8	1.7	69	0.3

towards the south. The top of the succession is generally marked by a chert horizon composed of plane-laminated volcanogenic mud and fissure-filling secondary silica (locally absent at Breakers and Anomaly 45). At Kangaroo Caves, felsic volcanism continued after silicification of the chert horizon in the form of rhyodacitic lavas and breccias that overlie an erosive disconformity; these are in turn capped by chert. At Sulphur Springs, a lens of unsilicified polymictic megabreccia containing large clasts of altered dacite disconformably overlies the chert, possibly forming the basal unit of the Gorge Creek Group.

Structurally isolated blocks displaying a similar stratigraphic succession to that described above are found in the Jamesons and Soansville areas within the Strelley Domain, though the individual units, especially the intermediate-to-felsic unit, are markedly thinner than elsewhere.

The Panorama VMS deposits are concentrated along the upper contact of the intermediate-to-felsic unit with most presently known mineralization (including surface gossans and drillhole sulfide intersections) occurring immediately below or within the overlying chert horizon. Only the Roadmaster mineralization (and that at the Cardinal prospect, which has been excised from the project) occurs elsewhere, at the base of the intermediate-to-felsic unit. Prospects appear to be located where there is a concentration of faults cross-cutting the stratigraphy, where there are irregularities in the relationships between the intermediate-to-felsic unit and the capping chert, and where comagmatic intrusive rocks are most abundant. Proximal to mineralization, haloes of intense chloritic, silicic, sericitic and dolomitic alteration are developed, in some areas up to 2 km wide and 1 km deep. Of relevance to the formation of VMS deposits is that the entire succession was apparently deposited in at least moderately deep water, indicated by the presence of turbidities and highly amygdaloidal felsic lavas (the relative scarcity of brecciation suggesting considerable confining pressure).

Prospect geology

SULPHUR SPRINGS, KANGAROO CAVES, BERNTS, BREAKERS

The following description will concentrate on Sulphur Springs, but it should be noted that the other prospects show similarities in the basic style of mineralization, albeit with considerable differences in detail.

The mineralization at the Sulphur Springs prospect outcrops as spongy, cellular siliceous and ferruginous gossan up to 100 m thick and is traceable over 300 m of strike. Sixty diamond drillholes to date show that the deposit occurs in two distinct panels: a smaller upper zone contained within the uppermost chert units, and a larger contact zone between the footwall dacitic volcanics and the chert (Fig. 28). The upper zone is generally zinc-rich,

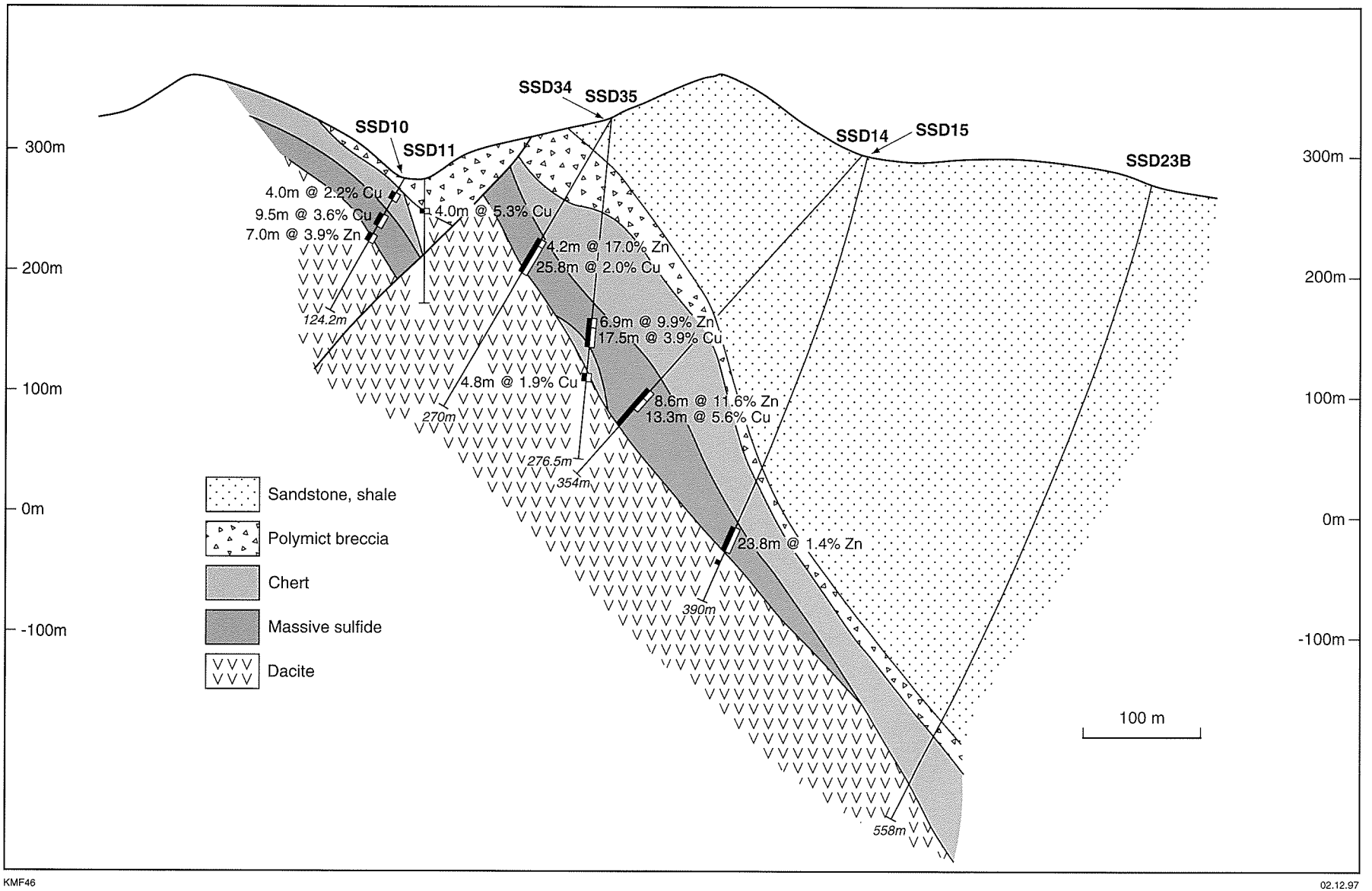


Figure 28. Sulphur Springs prospect: cross section near centre of deposit (*after* Sipa Resources Ltd)

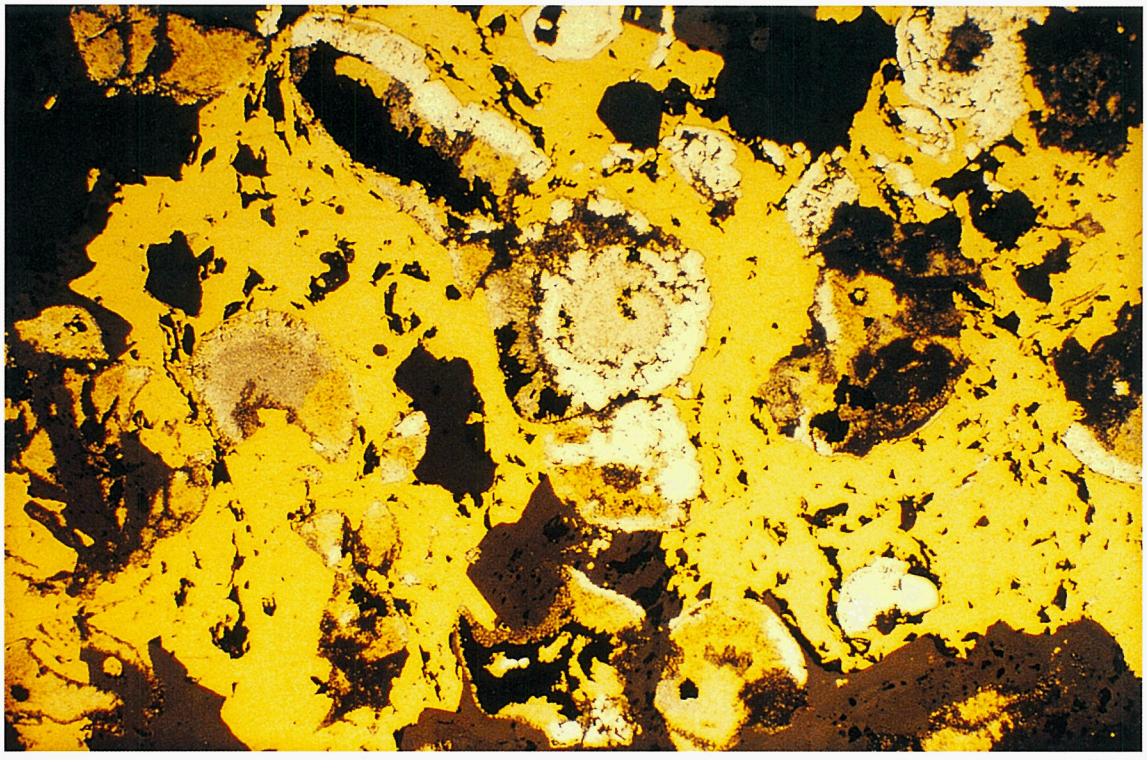


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Figure 29. Photograph showing free-space precipitation textures in Sulphur Springs mineralization (*after* Sipa Resources Ltd)

whereas the contact zone has a massive zinc-rich cap, a massive copper-rich middle and, towards the west, a stringer-style copper-bearing base. The main sulfide minerals are sphalerite, chalcopyrite and pyrite with sporadic and minor galena, tennantite and arsenopyrite in some, but not all, intersections. Gangue minerals include quartz, dolomite, chlorite, sericite and barite. The footwall rocks, amygdaloidal dacites with interflow layers of hyaloclastite and jigsaw breccia, have undergone intense chlorite, sericite and dolomite alteration, whereas the hangingwall chert (originally plane-laminated tuffaceous mudstone with secondary fissures filled with black kerogenous chert) has undergone silicification and carbonatization. Textures in the mineralization (Fig. 29) indicate both free-space precipitation (colloform, botryoidal and dendritic) and replacement of glassy volcanic rock (hyaloclastic and perlitic textures preserved). Colloform and euhedral quartz (commonly microcrystalline chert) and barite fill cavities in precipitated mineralization and cement fragments in replacement mineralization, thus representing the last stage of mineralizing activity. The mineralized shoot has been dissected by a cross-cutting fault and its splays. It is not yet clear whether cross-cutting faults acted as conduits for mineralizing fluids, whether there is lateral zonation within the body of mineralization, or whether other shoots are associated with the two so far identified.

At Kangaroo Caves, mineralization exists within and beneath the lower of two chert horizons that enclose a lens of geochemically distinct rhyodacite lava and breccia. Free-space precipitation textures are abundantly developed in the pyrite–sphalerite–chalcopyrite intersections.

Genesis

It is clear that the mineralization at the Sulphur Springs prospect, and indeed at all of the other Panorama prospects, is of volcanic-hosted massive-sulfide style. The situation of the mineralization within, and generally at the top of, a felsic volcanic pile, its association with intense haloes of hydrothermal alteration, its vertical metal zonation and its partial replacement of and precipitation between fragments of felsic volcanic rock are all consistent with such an origin. Very little post-depositional remobilization or recrystallization of the sulfides has occurred, features attributable to the low-strain, low-grade environment. The mineralizing system evidently varied in temperature with time, indicated by the zonation from copper-rich to zinc-rich (with minor lead) to quartz–barite precipitation. It is currently uncertain whether the system was capped by impermeable sediment during sulfide precipitation or whether the mineralizing fluids debouched onto the seafloor, but the abundance of replacement textures suggests that a large portion of mineralization occurred subsurface. The heat source and fluid foci are also moot subjects, but several reasonable alternatives exist for both. Hydrothermally enriched seawater was evidently the mineralizing solution, as indicated by the moderately deep subaqueous depositional environment and the style and

distribution of alteration. The relative impacts of mixing with cold seawater and of microbiological activity in situ are unknown. Thus, although the regional setting of the Panorama VMS prospects is now fairly well defined, much remains to be done before the detailed genetic histories of the individual prospects can be elucidated.

Acknowledgements

Sipa Resources Limited and Outokumpu Zinc Australia (OZA) have given permission for these results of exploration at Panorama to be published. The regional geological mapping was a team effort between Roger Buick, John Maniw, Peter Morant and Jim Thornett, under the overall guidance of Nick Archibald. Drilling and overall exploration responsibilities were handled by Bruce Uren (1991–1993), Urpo Kuronen (1994–1995) and Adrian Black (1996).

Comment

The above contribution on the Panorama deposits and prospects may be augmented by reference to further recent publications.

Vearncombe et al. (1994) have reported unusually well-preserved sulfide textures, strikingly similar to those of the sulfide chimneys formed by black smokers at present-day submarine hydrothermal vents, at Sulphur Springs and Kangaroo Caves. The mineralization also shows an abundance of sulfates, largely in the form of barite, as part of the original hydrothermal deposition system, further indicating a close similarity to modern VMS deposits. The textures of the effusive volcanics indicate deposition under hydrostatic pressure in water depths of at least 1000 m. Structural and geochemical features suggest mineralization has taken place in zones of extensive fluid flow in elevated grabens within a back-arc basin developed on a continental infrastructure. Mineralization shows an association with synvolcanic growth faults and splays. Extensive alteration of the volcanics in association with the mineralization indicates widespread interaction with seawater.

The strong similarities of the Panorama mineralization with Phanerozoic deposits, particularly the abundance of barite, are interpreted as suggesting an oxygenated biosphere in the early Archaean, in contrast with the anoxic conditions of the late Archaean.

Morant (1995), in describing the Panorama deposits, mentioned early exploration by several companies in the area of the Cardinal gossan (*see* Abydos 1). His description of the setting of the Panorama mineralization adds some important details and differs in some respects from the above account. Regional facies variations are described in the felsic upper part of the Strelley Succession (Fig. 30), with rhyodacitic sills dominating the sequence between Roadmaster and Sulphur Springs while dacitic sills predominate south towards Man O'War. The dacitic sills are up to 250 m thick and continuous along strike for up to 10 km. They host much of the mineralization and footwall alteration at Sulphur Springs and Kangaroo Caves (Fig. 31). Morant (1995) characterizes the rhyodacitic breccia overlying the mineralization at Kangaroo Caves as an extrusive dome, chemically different from the rest of the succession by virtue of calc-alkaline magmatic affinity. The Bernts mineralization is described as being hosted by pumiceous rhyolitic breccias of the Gorge Creek Group and lying about 1 km stratigraphically above the base of the group in the core of a syncline. He also argues against a major time break before the onlapping of the Gorge Creek Group mudstones and sandstones.

The massive to semi-massive mineralization is interpreted as indicating replacement of volcanic and volcaniclastic deposits in a sub-seafloor environment and Morant (1995) throws some doubt on the interpretation of colloform, botryoidal and dendritic textures in the mineralization as indicating sulfide chimneys. The mineralization shows typical downward zonation from Zn(–Pb) rich to Cu rich and is low in gold, silver and lead compared with most other Australian deposits. Footwall alteration extends away from the mineralization in chlorite–pyrite, sericite–pyrite, sericite–dolomite and albite–dolomite zones and there is no hangingwall alteration in the Gorge Creek sedimentary rocks.

Big Stubby (Marble Bar, Kurts Prospect, Duffer Creek)

Deposit: Zn; Pb; Ag; Cu; Ba
Location: 21°12'59"S, 119°45'10"E; 6 km south of Marble Bar.

This deposit was referred to as Duffer Creek in Blockley (1971). Seven massive subvertical sulfide lenses occur within acid to intermediate (andesitic–rhyolitic) volcanic and volcaniclastic rocks near the top of the Duffer Formation, on the southwest margin of the Mount Edgar Batholith. Mineralization is associated with chert bands, interlayered with turbiditic tuff and overlying a sequence of tuff breccias with minor intercalated volcaniclastic conglomerate and turbiditic tuff. Barley (1992) considers the intrusive rhyolite domes, described by Reynolds et al. (1975) as being in association with the mineralization, to be lenses of subaqueous pyroclastics. Zinc–lead mineralization, which includes barite, is stratigraphically above the copper-rich zone. Barite and gypsum are also located in the lateral extensions of the lenses. Sphalerite, galena, pyrite and barite are the principal ore minerals. Silver occurs as acanthite. No pyrrhotite or magnetite are present. The mineralized zones are thin and inconsistent, with some chlorite and carbonate alteration.

Reynolds et al. (1975) and Barley (1992) consider the zinc-rich mineralization to have more in common with the Miocene Kuroko deposits in Japan than with typical Archaean VMS deposits. Lead ages of 3.5 Ga obtained by Sangster and Brook (1977) and Richards et al. (1981) are consistent with the zircon U–Pb age for the Duffer Formation obtained by Thorpe et al. (1992a): between 3.471 ± 5 and 3.465 ± 3 Ga. Brook (1974) has estimated

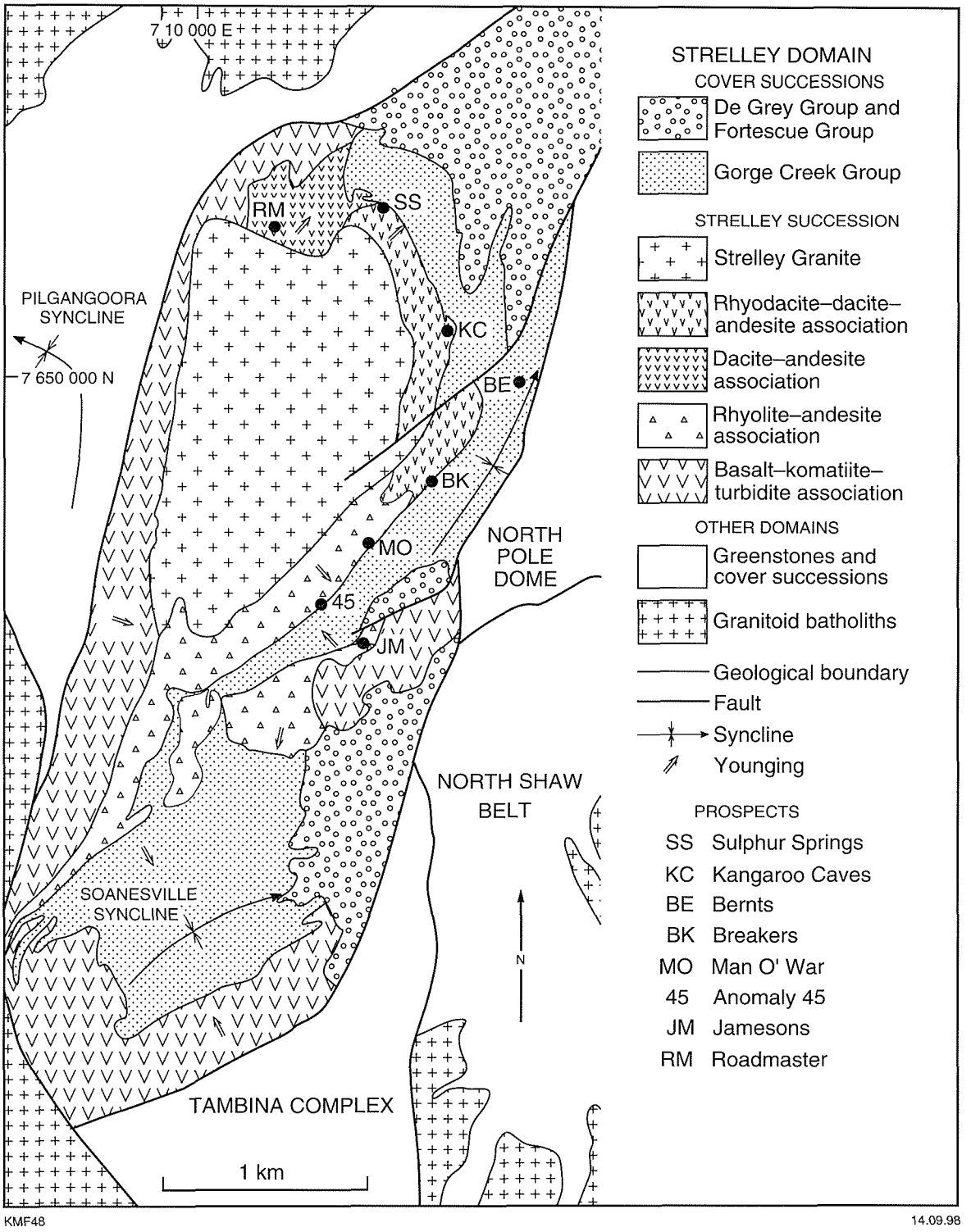


Figure 30. Geology of the Strelley tectono-stratigraphic domain (*after* Morant, 1995)

reserves of 0.1 to 0.2 Mt at 13.8% Zn, 4.5% Pb, 305 g/t Ag and 20% barite.

Gossans were known in the area from the turn of the century but only a minor trench was excavated before 1968 when Newmont with Narla Minerals undertook exploration. Drilling on the main gossan in 1971 intersected sulfide mineralization. Subsequent exploration through to the mid-1980s, involving Aquitaine, BP, Alcoa, Sanidine and Australian Anglo American, established a deposit of limited size. Drillhole results include a 4.27 m intersection with 14.1% Zn, 3.2% Pb, 840 g/t Ag and 0.3% Cu. Australian Anglo American dropped their interest in Big Stubby in 1987.

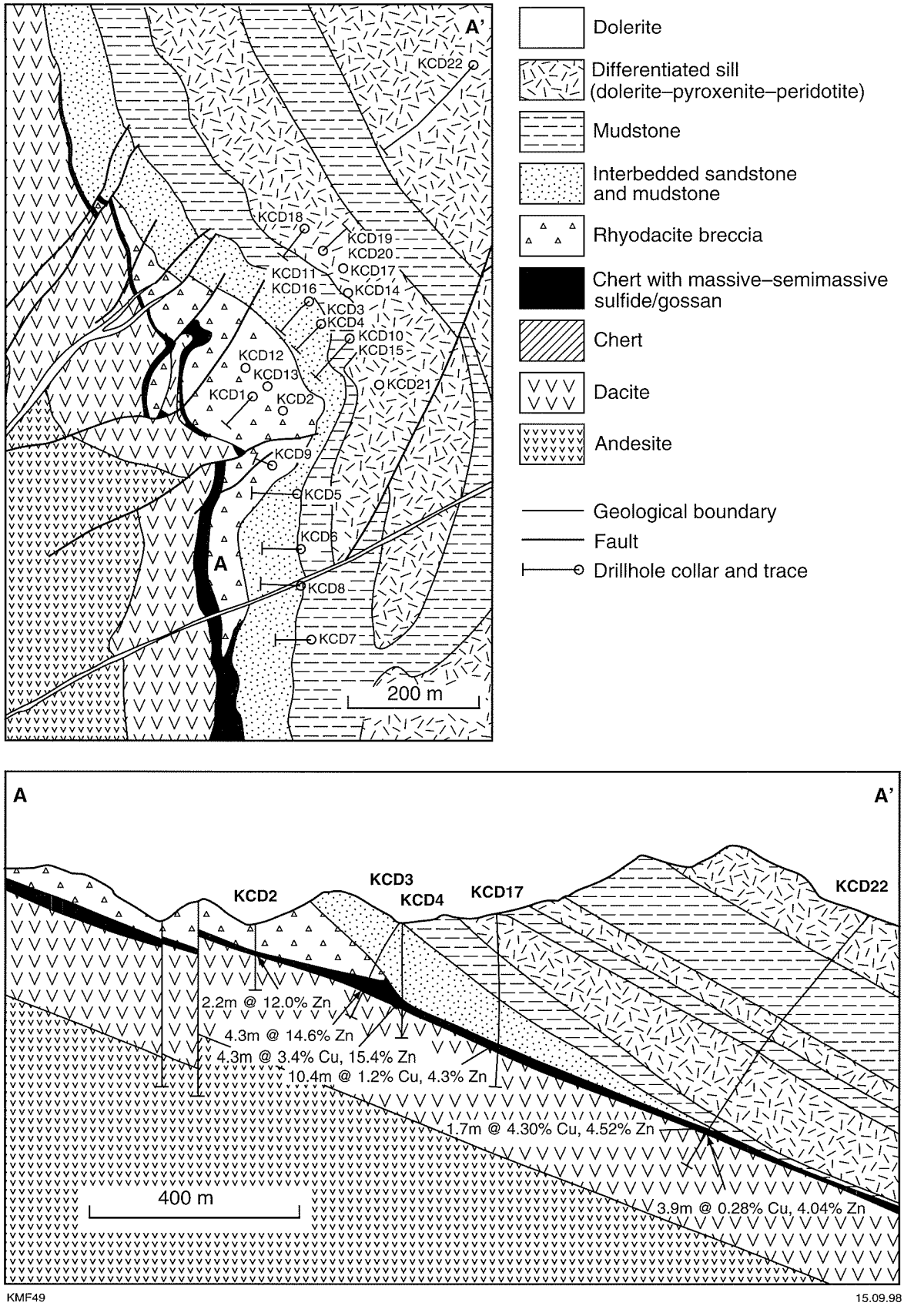


Figure 31. Geological plan and section of the Kangaroo Caves prospect (*after* Morant, 1995)

References: Davies and Blockley (1990), Marston (1979), Reynolds et al. (1975), Barley (1992), Thorpe et al. (1992a), Brook (1974), Sangster and Brook (1977), Richards et al. (1981).

Miralga

Prospect: Pb
Location: 21°10'S, 119°44'E; 28 km south-southwest of Marble Bar.

Exploration was carried out by Placer (1970–72) for VMS lead–zinc–copper–silver mineralization in Warrawoona Group basic to intermediate volcanic rocks of the Coongan Syncline, between the Shaw and Corunna Downs Batholiths, similar to that located at Kurts Prospect (Big Stubby). Only minor felsics were found but no gossans were seen. However, grades up to 950 ppm Cu, 5.8% Pb, 790 ppm Zn, and 124 ppm Ag were obtained in chip samples. No samples were baritic.

Reference: GSWA-WAMEX - I 1134/2.

Lennons Find (Lennon Find, Yandicoogina)

Deposit: Zn; Pb; Cu; Ag; Ba
Location: 21°21'30"S, 120°14'E (Fig. 30); 55 km south-east of Marble Bar

Stratiform, lenticular sulfide bodies occur in sheared sericite schists and calc-silicate rocks of the upper part of the Duffer Formation, near the southeast margin of the Mount Edgar Batholith. The host rocks, locally named the Sharks Formation, are felsic pyroclastic and pelitic to psammitic sedimentary rocks overprinted by amphibolite-grade metamorphism (Fig. 32). They are conformably overlain by basic volcanic and minor ultramafic rocks of the locally named Miralga Formation. The main ore horizon extends about 4.3 km along strike, trending at about 055° and dipping at 40–60° southeast. Surface gossans contain malachite, chrysocolla, anglesite, cerussite and hemimorphite. A chert horizon beneath this zone is a useful marker. Mineralization is massive (≤4.4 m thick), thinly banded and disseminated and contains cobaltiferous pyrite, sphalerite, galena and minor chalcopyrite with silver (≤180 g/t) and barium. Chlorite and carbonate alteration have been noted. The bodies are typically zinc, lead and barium rich at the top and zinc, copper rich at the base; the main Hammerhead orebody is 400 by 300 by 2 m. A further five gossan anomalies have been defined along strike. Another three gossans occur in the stratigraphically lower Grey Nurse Zone.

Model ages of between 3.4 and 3.5 Ga (Richards et al., 1981; Barley, 1992), are similar to the zircon U–Pb age for the Duffer Formation obtained by Thorpe et al. (1992a) of between 3.471 ± 5 and 3.465 ± 3 Ga.

Lennons Find was discovered in 1907 and worked in a small way at that time. Minor copper production was recorded in the 1950s. Following prospecting and poorly controlled percussion drilling in the mid-1960s, Westfield and later Cominco conducted IP surveys and diamond drilling of the main gossan in the latter 1960s. Some results from this work are reported in Blockley (1971) and Marston (1979). The best intersection was 1.22 m at 1.37% Cu, 2.8% Pb and 8.3% Zn. In 1973 Project Mining and Jennings Mining carried out grid mapping and geochemistry leading to a major diamond-drilling program by Serem Australia in 1976–77. This work established a demonstrated resource of 1.2 Mt at 7.76% Zn, 0.43% Cu, 1.94% Pb, 100.42 g/t Ag and 0.3 g/t Au in the Hammerhead deposit, calculated by Centenary Mining who took over management of the project in 1983. They further defined an inferred resource of 4.2 Mt in extensions of Hammerhead and in other, on-strike mineralized zones. With ore widths too thin to support an economic underground operation attempts were made to establish an open-pittable resource in the oxidized zone. In the late 1980s SIROTEM surveys gave some encouragement for the location of 'hidden' lodes, and possible 'stringer' zones to the stratiform mineralization were also being sought.

References: Blockley (1971), Marston (1979), Hickman (1983), Louthean (1993), Barley (1992), Thorpe et al. (1992a), Richards et al. (1981), GSWA-WAMEX - I 6230.

Copper Gorge (Mickles)

Deposit: Zn; Cu; Ag
Location: 21°36'20"S, 120°20'50"E; 39 km northeast of Nullagine

Sulfide mineralization is present in the Duffer Formation (cyclic mafic to felsic metavolcanics) at the eastern end of the McPhee Dome. Three cycles of basalt, andesite, and felsic volcanic material capped by black chert, dipping northwest at 20 to 25°, are recognized. The mineralization is in the top 30 m of the felsic volcanic unit in the lowermost cycle, within rhyolite and rhyodacite and coarse rhyolite breccia, between two growth faults that may have acted as synvolcanic conduits. Mineralization occurs as pyrite, chalcopyrite, sphalerite and quartz disseminations with minor galena, is erratic and localized in detail, and is accompanied by sericite, carbonate and silica alteration.

The prospect was discovered by W. Mickle in 1964 and a small amount of copper ore was extracted in the following year. Cominco carried out 415 m of percussion drilling in 1966 and inferred a resource of 0.5 Mt at 0.5% Cu. Australian Ores and Minerals followed between 1969 and 1983 undertaking ground magnetic, IP, EM and resistivity surveys, percussion and diamond drilling. The best intersection was 4.5 m at 2.25% Zn, 0.16% Cu and 8 g/t Ag: the mineralization was considered subeconomic. The Broken Hill Proprietary Co. Ltd included the prospect in a regional study carried out between 1977 and 1984 and considered the potential to be low.

References: Marston (1979), Hickman (1983), GSWA-WAMEX - I 288 and I 2431.

Middle Creek

Prospect: Cu; Zn; Pb; Ag; Au; Sb; Cd; W; Hg; Te
Location: 21°52'40"S, 120°17'E; 20 km east of Nullagine

Exploration by Aquitaine (1976–77) involving mapping and sampling of a known zone of base-metal mineraliz-

Grey Nurse Zone – drill intersections

Drillhole no.	Intersection (m)	True width (m)	Mineralization Cu%	Pb%	Zn%	Ag g/t
LF14	105.70–109.70	3.46	0.009	0.03	0.59	1.3
	109.70–110.70	0.87	0.10	0.003	6.10	3.0
	110.70–117.70	6.06	0.07	0.02	0.72	2.6

Tiger West Zone — gossan samples

Sample no.	Width (m)	Values in % Cu	Pb	Zn
3999	0.71	0.008	1.5	0.02
4000	0.76	0.008	0.12	0.04

Grey Nurse East Zone – drill intersections

Drillhole no.	Intersection (m)	True width (m)	Mineralization Cu%	Pb%	Zn%
BH5	4.57–21.34	14.50 approx.	0.05	0.03	2.27
	4.57–10.67	5.30 approx.	0.04	0.04	3.30

Tiger Zone — gossan samples

Sample no.	Width (m)	Values in % Cu	Pb	Zn
3995	0.30	0.02	0.11	0.02
3996	0.15	0.12	1.30	0.60
3997	0.36	0.11	6.20	14.40
3998	0.15	0.69	0.31	1.90

Tiger Zone – drill intersections

Drillhole no.	Intersection (m)	True width (m)	Mineralization Cu%	Pb%	Zn%	Ag g/t
LF7	58.30–59.30	0.87	0.03	1.92	3.40	105.0
	62.30–63.30	0.87	0.06	0.01	2.10	6.0
LF8	51.88–52.88	0.91	0.03	2.35	6.40	86.0
	52.88–53.88	0.91	0.14	0.19	2.55	9.0
	51.88–53.88	1.82	0.09	1.27	4.48	47.5
LF13	60.8–61.8	0.90	0.36	0.46	4.90	43.0
	61.8–63.8	1.80	0.21	0.003	1.39	6.5

Hammerhead Zone — gossan samples

Sample no.	Width (m)	Values in % Cu	Pb	Zn
3982	0.33	0.23	3.60	27.50
3983	0.91	0.65	1.10	0.78
3984	1.52	0.25	1.10	4.40
3985	0.76	1.90	0.92	8.30
3986	1.83	0.27	1.40	16.50
3987	0.30	0.09	.70	0.76
3988	0.51	0.07	3.20	0.31
3989	0.51	0.21	0.28	7.90
3990	0.76	0.33	0.62	3.30
3991	0.51	0.19	0.85	17.50
3992	0.30	6.50	0.20	2.90
3993	0.23	0.39	1.20	11.80
3994	0.46	12.30	0.24	1.80

Hammerhead Zone – drill intersections

Drillhole no.	Intersection (m)	True width (m)	Rec (%)	Mineralization Cu%	Pb%	Zn%	Ag g/t
Y601	57.91–59.43	1.40	56.0	0.08	1.40	5.60	45.9
Y701	50.75–52.43	1.40	34.5	0.02	2.00	4.90	79.6
	52.43–53.65	1.10	88.8	1.37	2.80	8.30	180.7
LF1	96.55–97.90	1.26	–	0.12	0.57	2.56	44.3
	99.73–101.73	1.88	–	0.48	1.83	8.75	107.5
	96.55–101.73	4.87	–	0.23	0.86	4.09	53.8
LF2	81.18–81.78	0.52	–	0.02	0.37	0.50	160.0
	84.02–86.08	1.78	–	0.28	2.82	6.00	94.9
	81.18–88.08	5.98	–	0.14	0.89	1.92	48.7
LF3	93.30–94.51	1.23	–	0.03	2.08	4.20	180.5
	105.58–106.25	0.63	–	1.45	0.68	3.50	75.0
LF4	No significant base-metal mineralization Highest values: Cu (1800 ppm); Pb (40 ppm); Zn (2875 ppm); Ag (8 g/t)						
LF9	204.10–207.10	2.95	–	0.56	0.85	10.83	81.0
	207.10–209.10	1.97	–	0.48	0.09	0.41	32.5
LF10	299.30–300.30	0.97	–	0.04	5.70	18.00	142.0
LF11	105.00–106.00	0.93	–	0.21	0.08	0.33	14.0
LF12	194.70–195.70	0.96	–	0.34	0.25	0.57	38.0
LF15	193.55–195.55	1.80	–	0.09	0.15	0.40	39.5
	197.23–199.23	1.80	–	0.15	0.49	1.28	52.5

Bronze Whaler Zone — gossan samples

Sample no.	Width (m)	Values in % Cu	Pb	Zn
3974	0.25	0.03	0.59	0.05
3975	0.38	0.42	0.35	0.09
3976	0.30	0.64	13.50	17.00
3977	0.23	1.30	6.20	8.40
3978	0.38	1.20	0.55	0.09
3979	0.25	0.11	0.13	0.05
3980	0.25	0.03	0.12	0.02
3981	0.15	0.04	0.13	0.08

Bronze Whaler Zone – drill intersections

Drillhole no.	Intersection (m)	True width (m)	Rec (%)	Mineralization Cu%	Pb%	Zn%	Ag g/t
Y1201	49.53–51.51	1.80	65.0	0.05	0.60	1.50	1.5
LF5	No significant base-metal mineralization Highest values: Zn 1.73% and Ag 18.0 g/t						
LF6	80.47–81.97	1.06	–	0.25	1.16	4.77	88.0
	84.47–85.47	0.71	–	0.05	0.05	5.00	7.0
	80.47–85.47	3.53	–	0.13	0.45	2.94	33.9

Mako-East Zone — gossan samples

Sample no.	Width (m)	Values in % Cu	Pb	Zn
3956	0.16	0.78	1.40	18.0

Mako Zone — gossan samples

Sample no.	Width (m)	Values in % Cu	Pb	Zn
3957	0.10	0.05	0.005	138.0

Mako Zone – drill intersections

Drillhole no.	Intersection (m)	True width (m)	Rec (%)	Mineralization Cu%	Pb%	Zn%	Ag g/t
Y831	39.78–41.45	1.50	80	0.50	0.10	0.46	30.5

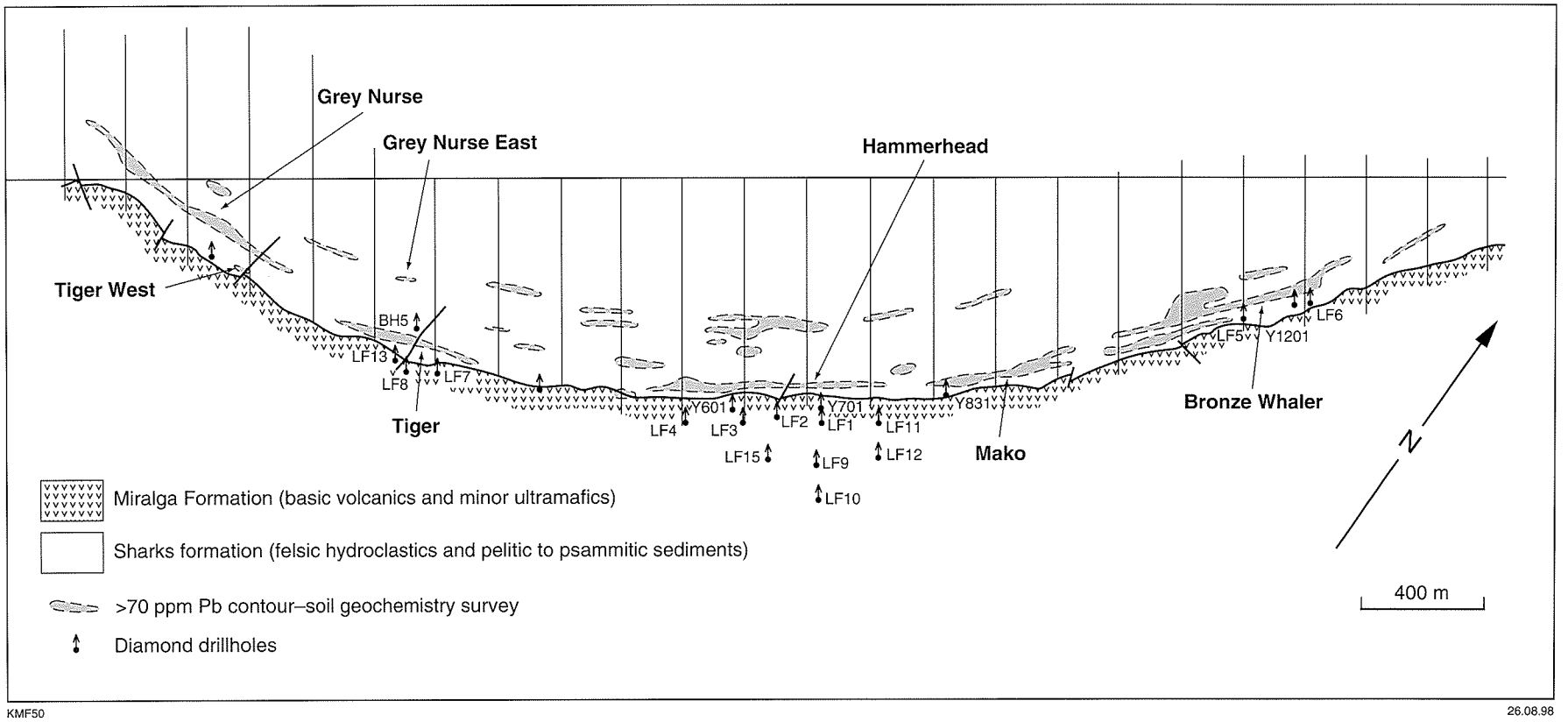


Figure 32. Lennons Find: geology, soil geochemistry and drilling (*after* Centenary International Mining Ltd)

ation located small high-grade polymetallic gossans in volcaniclastic rocks and cherts of the Mosquito Creek Formation of the De Grey Group. The sequence has been extensively tectonized with upright isoclinal folding and axial-plane cleavage parallel to bedding. The gossans represent stratiform massive-sulfide mineralization in exhalative chert and contain up to 21.5% Cu, 3.3% Pb, 7.25% Zn, 6.8% Sb, 35.5 g/t Au and 380 g/t Ag. They occur in the lower of two stratigraphic units representing distal volcanism. The zones of mineralization are very restricted, however. Small stringers, pods and lenses up to 10 m long and 1.2 m wide occur over 200 m of strike. Other pods are found farther away. Extensive supergene magnesite alteration may be related to the high base-metal values in the gossans. Broader prospecting encountered only minor, but high-grade, occurrences in ironstone float. Two drillholes indicated that the mineralization reflected in the gossans has very limited persistence with depth, though Aquitaine do not suggest a supergene origin.

Production of 7.5 t of oxide containing 5.3% Cu has been recorded for this prospect.

References: Marston (1979), GSWA-WAMEX - I 1964.

Copper Hills–Emu Creek (Gilbert)

Prospects: Cu; Pb; Zn
Location: 21°40'S, 119°57'E; 30 km north-northwest of Nullagine

Layered felsic volcanic and volcaniclastic rocks and cherts of the Duffer Formation strike north-northeast in the Kelly Belt in the vicinity of the Copper Hills, Copper Hills West and Kellys Copper Mines, on the eastern margin of the Corunna Batholith. In this zone they are intermittently intruded by the felsic Boobina porphyry. Three types of base-metal and minor precious-metal mineralization have been described in association with this major felsic volcanic centre, related to west to northwest faulting on the northern margin of a caldera collapse structure:

1. Fault-controlled copper mineralization associated with chloritic alteration (Copper Hills West and Copper Hills South).

2. Copper–zinc–iron in chert horizons, probably syngenetic/exhalative.

3. Fault-controlled lenses of lead–zinc and minor copper plus barium, gold and silver related to cauldron-collapse structures north of the main Copper Hills airstrip and in the south at Donkey Flats. Rock-chip levels up to 8.52% Zn, 4.53% Pb, and 15.4% Cu were encountered in separate samples. Both chloritization and carbonation are reported in association with the mineralization.

Pickands Mather International briefly examined the porphyry copper potential of the Emu Creek area in 1969. Hawkstone explored the Copper Hills–Kelly Belt (1969–71) for stratiform copper–zinc beneath chert horizons. Diamond and percussion drilling produced a best result of 1.22 m of 0.73% Cu with minor zinc. Broken Hill explored for VMS targets in the Kelly Belt between 1977 and 1984, encountering only minor veins and disseminations. Kalgoorlie Southern Goldmines explored the area between 1982 and 1990, combining surface geochemistry and geological mapping in a regional synthesis. Recognition of volcanic vents, caldera collapse structures and zones of alteration led to the identification of the mineralization styles described above. Drilling was recommended but does not appear to have been carried out.

References: Marston (1979), GSWA-WAMEX - I 1947, I 2602, I 4385.

Fielding Gully (Fieldings Gully)

Prospect: Pb; Cu
Location: 21°18'20"S, 119°45'E; 16 km south of Marble Bar

Exploration by Alcoa between 1978 and 1986 for base metals and gold in the Fieldings Gully area, in interfingering of mafic and felsic volcanic and volcaniclastic rocks, encountered lead–copper–silver anomalism in rock chips (up to 4.2% Cu, 4.9% Pb and 3800 g/t Ag). An inconclusive single percussion hole intersected malachite- and azurite-bearing stringers in siliceous sedimentary rocks with anomalous arsenic, antimony and silver, but low base metals. This suggested that the base-metal anomalism might be due to surface enrichment. Drilling of a gold anomaly 500m to the west intersected quartzite, gossanous chert, sericite and carbonate rich rocks with zinc levels up to 0.56%.

Reference: GSWA-WAMEX - I 5172.

Coongan River (Corboys)

Prospects: Cu; Zn; Pb
Location: 21°54'S, 119°44'E; about 40 km northwest of Bamboo Springs Homestead

Exploration in mixed mafic and felsic volcanic, volcaniclastic and sedimentary rocks and cherts of the Warrawoona and Gorge Creek Groups was undertaken by Kennecott in 1968–73. Following regional stream-sediment sampling and airborne EM, geological traversing and extensive chip sampling were carried out. No base-metal anomalism was associated with the EM targets but some copper anomalism (12.5–21.7%) was found in three separate spot samples, two of them in quartz stockwork in metabasalt, associated with >1% Pb.

Reference: GSWA-WAMEX - I 964.

Abydos 1

Prospects: Zn (Cu; Pb; Ag)
Location: 21°25'30"S, 119°05'E; 15 km east of Abydos

Exploration by Mount Newman (1978–82) of base-metal gossans for stratabound VMS located a subeconomic deposit in volcanic rocks of the Warrawoona Group. Three diamond drillholes intersected chalcopyrite, sphalerite and galena with pyrite, pyrrhotite, minor barite and rutile in acid (andesitic/dacitic) fragmental rocks in contact with

intrusive pyroxenite in a possible south-plunging, complex ore zone. A very approximate resource of 2700 t Zn, 600 t Cu, 180 t Pb and 2.4 t Ag is based on an average intersection of 4.5% Zn, 1.00% Cu, 0.3% Pb and 40 g/t Ag, in a 200 m profile, 100 m deep. The best intersection was 1.35 m at 6.51% Zn, 0.56% Pb and 0.99% Cu. Macdonald (1984–88) recommended follow-up of Newman's drilling on the assumption that their results could lie in the marginal zone of a higher grade body.

Reference: GSWA-WAMEX - I 1974, I 3701.

Potential

Some variation in host rock and mineralization styles between VMS deposits and prospects in the east and west Pilbara, may have some bearing on the potential of the three main felsic volcanic/volcaniclastic sequences (the Duffer Formation of the Warrawoona Group, the Wyman Formation, and the Mons Cupri Volcanics of the Whim Creek Group) to host further deposits of economic size and grade.

Barley (1992) and Barley and Groves (1984) suggest that the shallower water setting of the east Pilbara deposits, associated with extensively reworked pyroclastic material, is less prospective than the increasingly deeper water settings seen progressively through Big Stubby, Panorama, Mons Cupri and Salt Creek to the west. Cas et al. (1993) confirm the prospective association of deeper water environments and graben-like basins, with coherent lavas and autoclastic rocks, by comparison with modern analogues and the setting of the Scuddles deposit.

In relation to the Whim Creek Belt, Collins and Marshall(a) (this volume), while acknowledging the relatively small size of the Whim Creek, Mons Cupri and Salt Creek deposits, draw attention to the tendency for these types of deposits to form in clusters and suggest that there is still potential for further discoveries of similar sized, or larger deposits in the belt. Mons Cupri-type deposits would be expected in fragmental volcanic rocks on the flanks of domal felsic volcanic piles, whereas Whim Creek – Salt Creek-type deposits would be expected in marginal sedimentary sub-basins. In the Sholl Belt, the apparent structural complexity of the area may have limited the success of attempts to find downdip extensions of the known mineralization.

Yilgarn Craton

Geological framework

On the basis of various structural, geochronological and stratigraphic considerations, the Yilgarn Craton is subdivided into a Western Gneiss Terrane and three granite–greenstone provinces, the Murchison, Southern Cross, and Eastern Goldfields Provinces (Trendall, 1990a).

As detailed by Myers (1990a, 1992), Barley et al. (1992), Swager et al. (1990, 1992) and Goleby et al. (1993a), recent mapping and interpretation of high-definition geophysical surveys by GSWA and AGSO have allowed more emphasis to be placed on comparing the tectonic evolution of the Yilgarn Craton with that of younger orogens. A number of fault-bounded tectono-stratigraphic terranes have been proposed, which amount only to a partial reworking of the broader subdivision. Myers (1992) proposes, from west to east, the Narryer, Murchison, Yellowdine, Barlee, and Kalgoorlie Terranes.

In the relatively poorly known Western Gneiss Terrane and in the Southern Cross Province (or Murchison, Yellowdine and Barlee Terranes), Barley et al. (1992) suggested that the 3.0 to 2.9 Ga greenstone belts formed in broad zones of foreland and/or hinterland deformation, and involved widely spaced systems of strike-slip faults with associated thrusts and fold belts located farther from a late Archaean craton margin than the greenstone belts of the eastern Yilgarn Craton.

In the eastern part of the craton the north-northwest trending strike-slip faults that divide the area into structural terranes and/or domains are closely spaced. The understanding of this complex and poorly exposed area has been greatly improved by the recent interpretation of a regional seismic crustal reflection transect over the western margin of the eastern goldfields (Goleby et al., 1993a,b). The implications of this work, still in the process of being applied to tectono-stratigraphic models, are reviewed below. Barley (1992) proposed that volcanism and sedimentation between 2.72 and 2.69 Ga in the eastern Yilgarn had occurred in craton-marginal, volcanic-arc and marginal-basin settings reflecting westward-dipping subduction. Other models, however, give emphasis to a continental setting and production of the volcanic suite in the greenstone belts by partial melting of continental crust above a deep-sourced mantle plume (Hill et al., 1992).

Murchison Province

The Murchison Province (Fig. 33; Watkins and Hickman, 1990; Myers, 1992) contains two major greenstone sequences, the Luke Creek and Mount Farmer Groups, about 10 km and 5 km thick respectively (Fig. 34). The Luke Creek Group (~3.0 Ga) forms a layered stratigraphy of four formations that is continuous throughout most greenstone belts in the terrane. Its lower part comprises two sequences of submarine tholeiitic and high-Mg basalt, massive lava-plain flows overlain by banded iron-formation. The upper part consists of interlayered basalt and felsic volcanic and volcaniclastic rocks. The Luke Creek Group was intruded by sheets of granite and deformed in a subhorizontal tectonic regime (2.9 Ga) prior to the accumulation of the Mount Farmer Group (2.8–2.7 Ga) in nine separate, local, predominantly basaltic volcanic centres, and one epiclastic sedimentary basin. These formed in shallow-water to subaerial environments. Felsic volcanic and volcaniclastic rocks are present in six of the centres (Fig. 35).

The Luke Creek Group greenstones are considered to represent volcanism associated with ensialic rifting following thrusting and crustal thickening (Watkins and Hickman, 1990). The Mount Farmer Group reflects island-

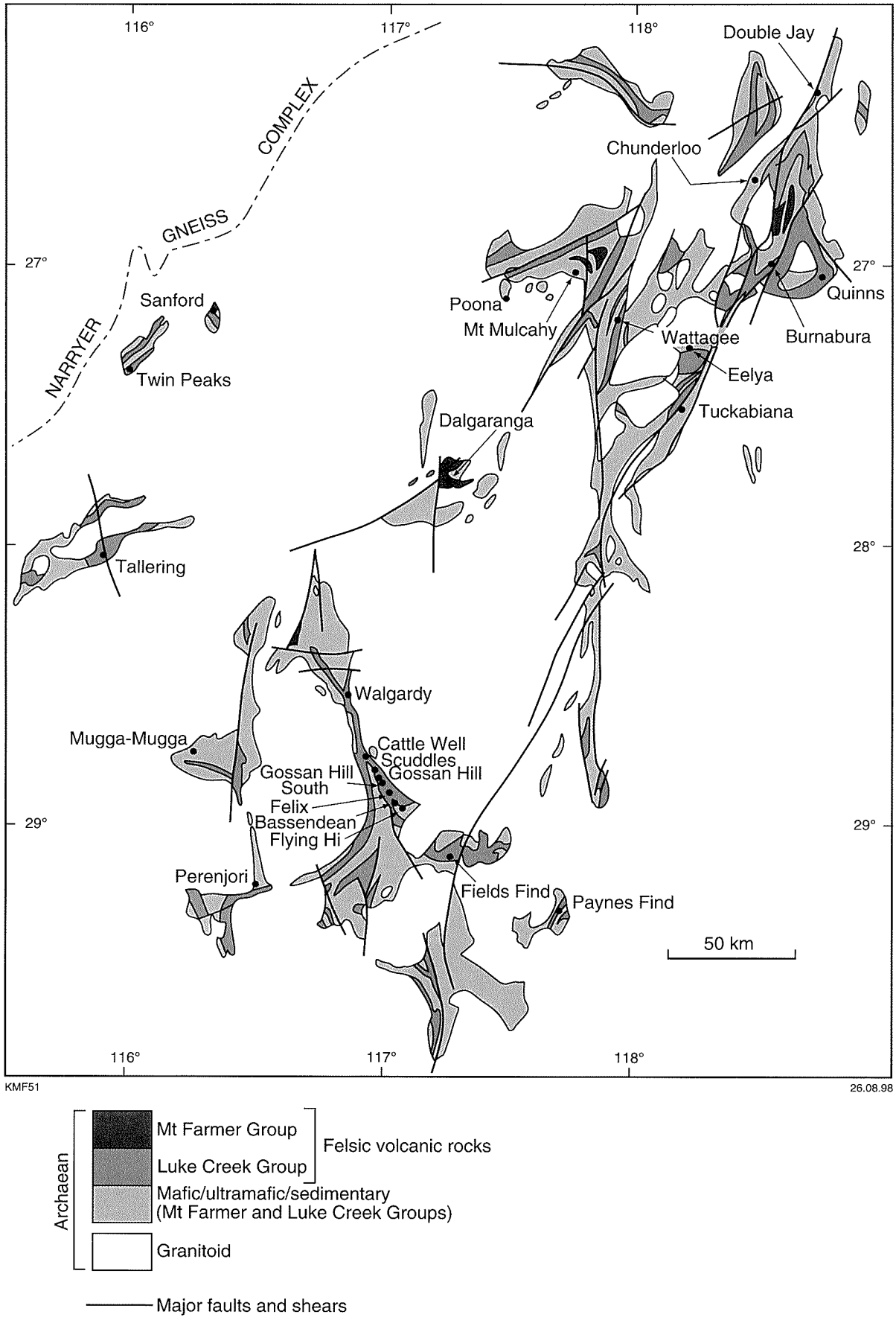


Figure 33. Distribution of lead–zinc–silver occurrences and lithological and tectonic framework in the Murchison Province

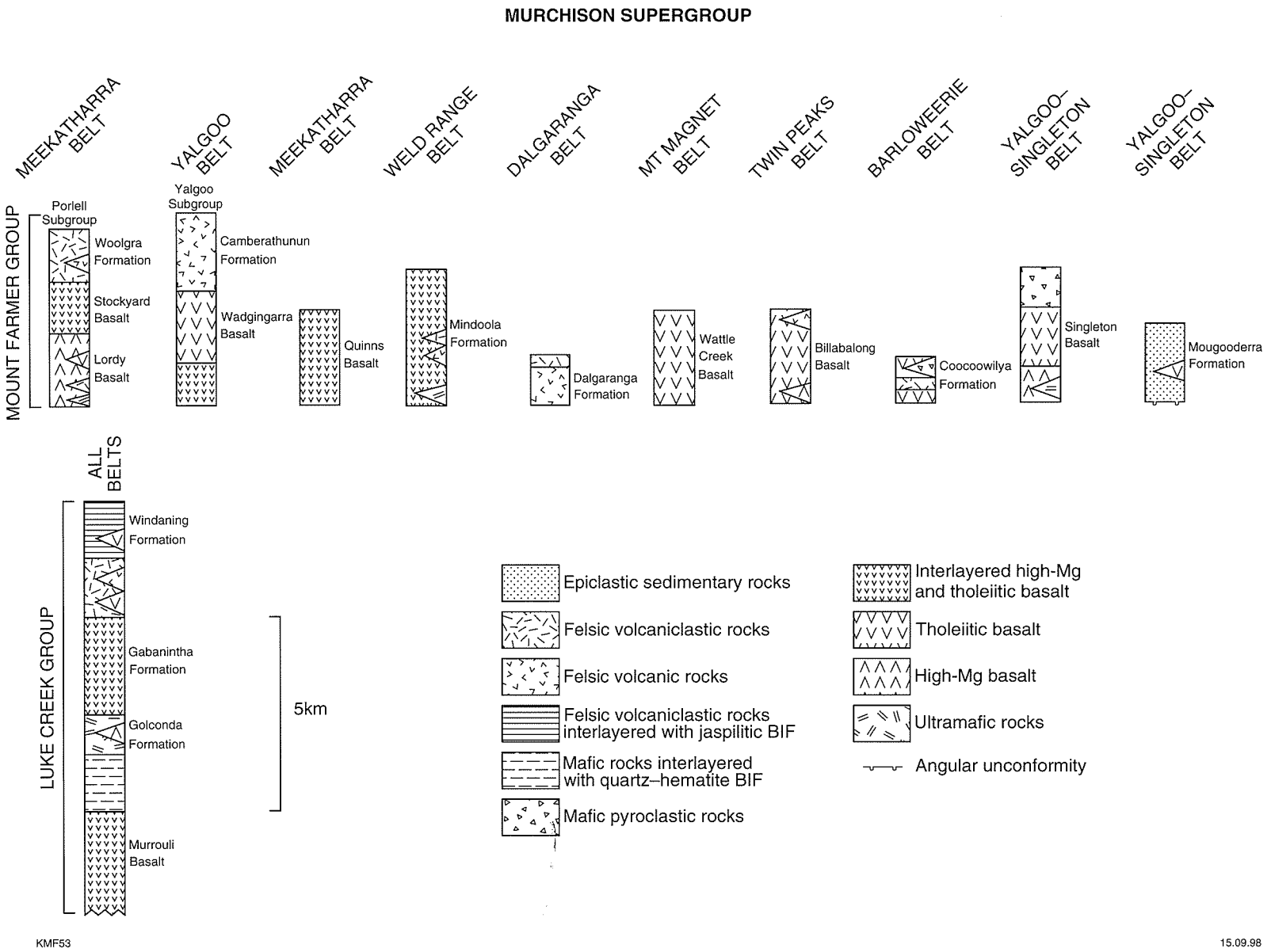


Figure 34. The Murchison Supergroup: stratigraphic groups, subgroups, formations, and rock types (*after* Watkins and Hickman, 1990)

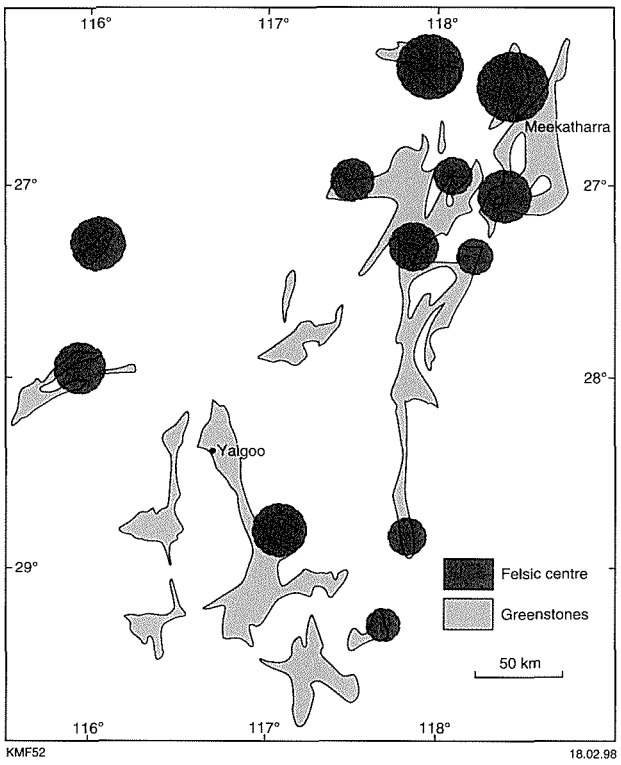


Figure 35. Felsic volcanic centres of the Gabanintha Formation (3.0 Ga), Murchison Province (*after* Watkins and Hickman, 1990)

arc and continental-margin volcanism associated with subduction zones (Myers, 1992).

The greenstones and granites were subsequently intruded by thick sheets of monzogranite (2.69–2.68 Ga), further deformed (2.68–2.64 Ga) in east–west and north–south upright folds and finally metamorphosed to greenschist or lower amphibolite facies and intruded by granitoid plutons (2.63 Ga). In the final phase of deformation, crustal shortening in response to east–west compression produced a craton-scale network of north-northeasterly trending shear zones and fold belts.

Southern Cross Province

The Yellowdine and Barlee Terranes (Myers, 1990a), which lie within the previous Southern Cross Province (Fig. 36), have not yet been covered by comprehensive recent GSWA mapping, but are considered, on available evidence, to have undergone a tectono-stratigraphic evolution similar to that of the Murchison Province (Barley, 1992). Two major periods of greenstone volcanism are recognized. The lower sequence is also dominated by high-Mg basalts and komatiites with restricted felsic volcanic and volcaniclastic rocks towards the top (Griffin, 1990). The upper sequence, which includes the thick conglomerate, sandstone, siltstone and argillite sequence of the Diemals Formation and the extrusive calc-alkaline andesite to rhyolite of the Marda Complex, is separated from the lower sequence by a major unconformity. At least three phases of deformation are recognized, with D_3 producing the dominant north-northwest isoclinal folding with major, parallel strike-slip faulting reflecting crustal shortening.

Some doubt is thrown on the idea of parallel evolution with that of the Murchison Province by the zircon U–Pb dating of Pidgeon and Wilde (1990). They note no evidence for ~3.0 Ga greenstones in the Southern Cross Province but find dates resolving into a 2.71–2.74 Ga granite–greenstone event in that area. Comparing this with a 2.68–2.70 Ga spread for granite–greenstones in the eastern Yilgarn Craton they suggest an overall eastward younging that would support progressive eastward cratonization.

Eastern Goldfields Province

A considerable proportion of the Eastern Goldfields Province (Fig. 37) has recently been mapped at 1:100 000 scale by GSWA and AGSO. The 2.7–2.69 Ga greenstones in this area have been interpreted as forming a number of tectono-stratigraphic terranes, separated by an anastomosing network of north-northwesterly trending strike- to oblique-slip shear zones (Myers, 1990a; Swager et al., 1990; Swager, 1997). The terranes can be identified by distinctive stratigraphies and/or structural histories and, possibly, ages. Of these, the best studied is the Kalgoorlie Terrane, and Figure 38 shows its relationship to the neighbouring Norseman, Gindalbie, Jubilee, Steeple Hill, Mulgabbie, Yabboo and Pinjan Terranes.

The Kalgoorlie Terrane has a distinctive greenstone stratigraphy with a lower basalt which passes upwards from high-Mg to tholeiitic composition and includes minor acid volcanics and volcaniclastics. An overlying komatiite unit is followed by an upper basalt which, in turn, is overlain by predominantly dacitic felsic volcanic and volcaniclastic rocks of the Black Flag Group. The top of the sequence derives from the volcanic centres and is predominantly sedimentary. The major structural features are early recumbent folding and thrusting followed by north-northwesterly trending upright folding and subparallel transcurrent faulting. The major faults and shears within the terrane have subdivided it into tectonic domains which contain various parts of the regional stratigraphy (Swager et al., 1990)(Fig. 38). Earlier interpretations of Eastern Goldfields stratigraphy, prior to the recognition of structural repetition of a single sequence in the early 1980s, invoked repeating mafic–felsic volcanic cycles to explain the surface distribution of lithologies.

Preliminary results from recent mapping in the northeastern part of the east Yilgarn Craton (Rattenbury, 1993; Williams et al., 1993) suggest, in some contradiction with the terrane concept, that the stratigraphy can be correlated across apparent major structures, such as the Keith–Kilkenny Tectonic Zone, and may link with the scheme erected in the Kalgoorlie Terrane. Figure 39 shows the proposed correlation and includes the various domains now defined in the northeast Yilgarn Craton. The correlation is based on the recognition of a proposed regional ultramafic marker horizon corresponding with the komatiite horizon in the Kalgoorlie area. This is supported by the recognition (Hill et al., 1988) of very low

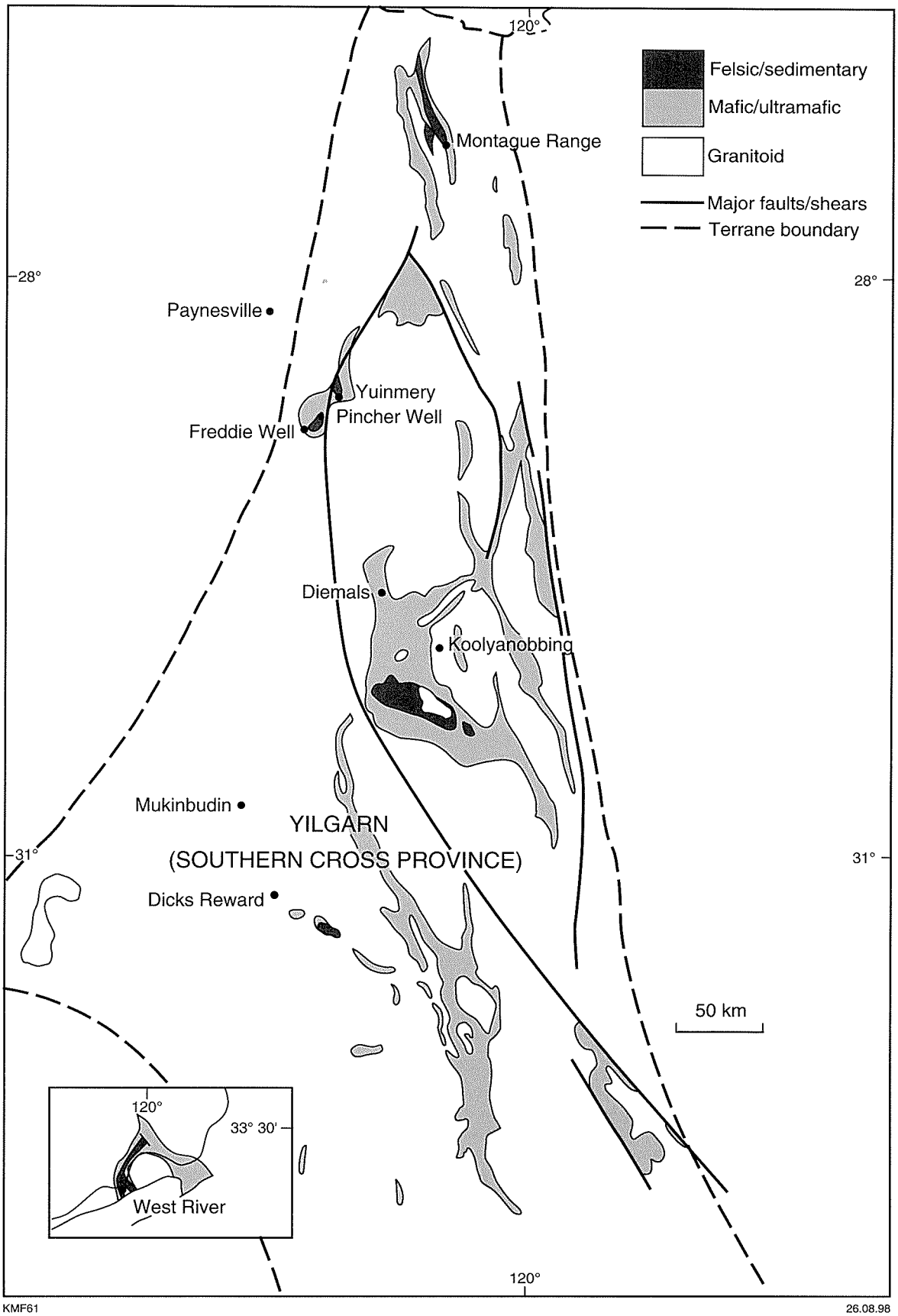


Figure 36. Distribution of lead–zinc–silver occurrences and lithological and tectonic framework in the Southern Cross Province

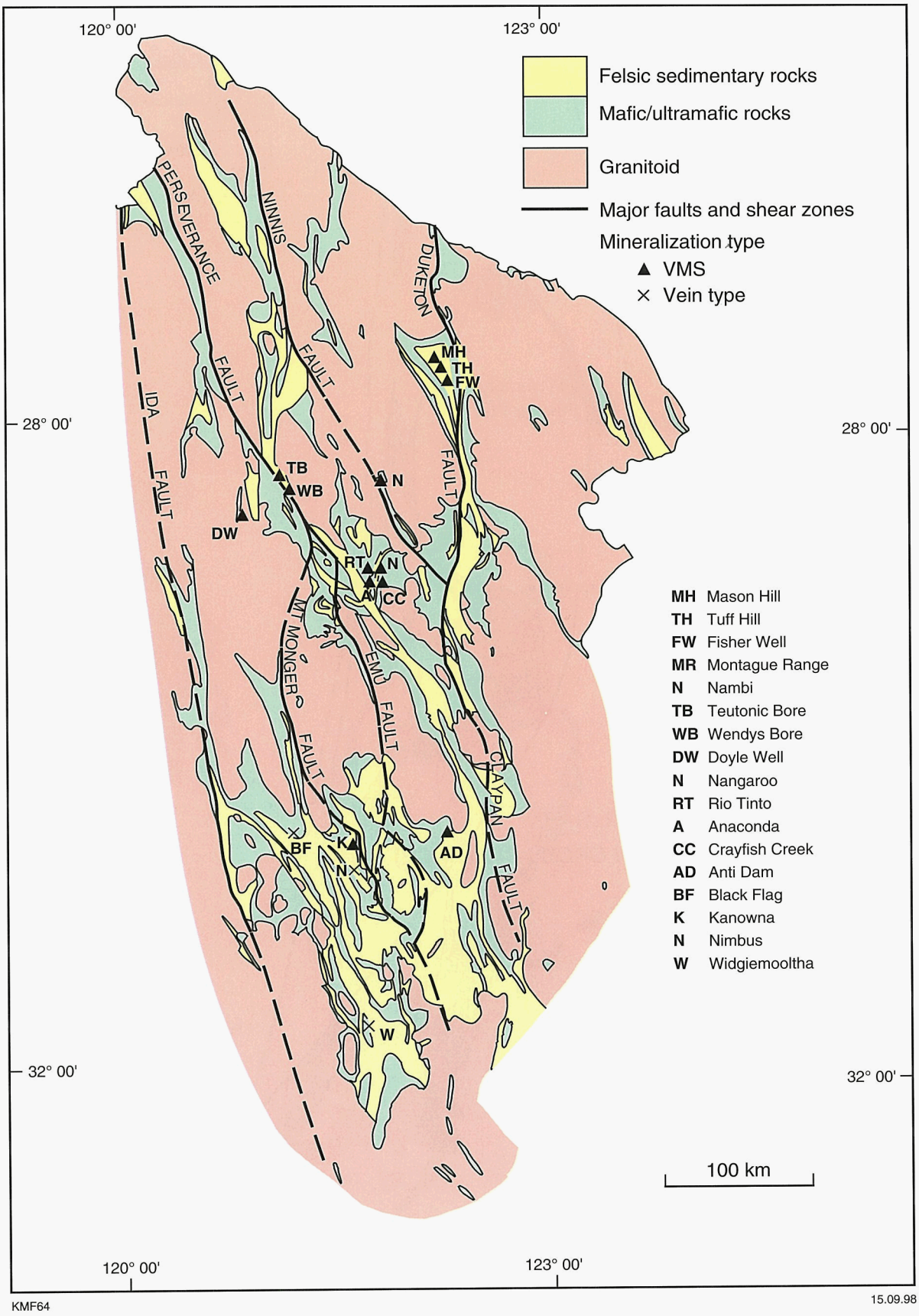


Figure 37. Distribution of lead–zinc–silver occurrences and lithological and tectonic framework in the Eastern Goldfields Province

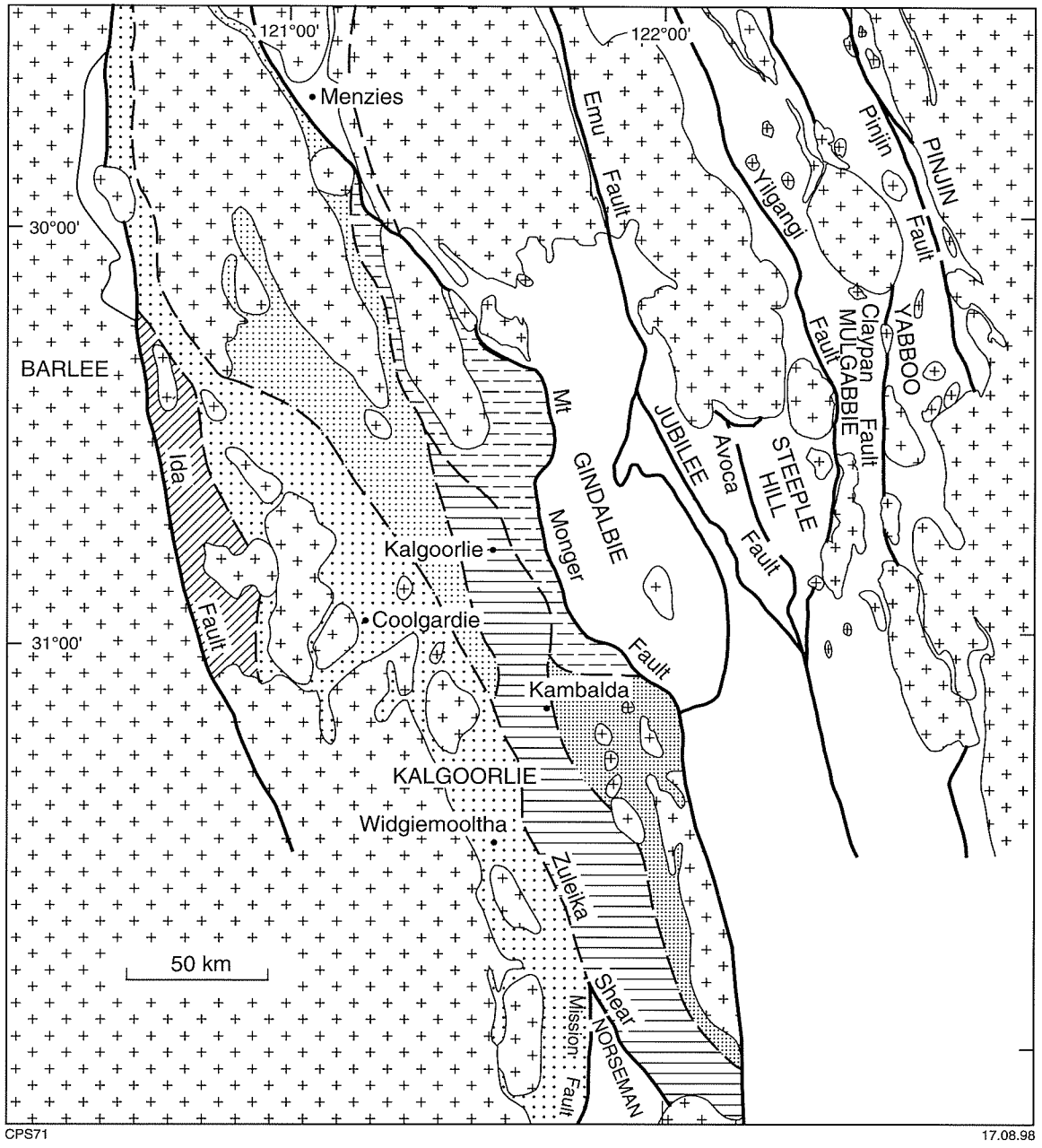


Figure 38. Terrane map of the Kalgoorlie region highlighting the Kalgoorlie Terrane and its six constituent structural–stratigraphic domains (*after* Swager et al., 1992)

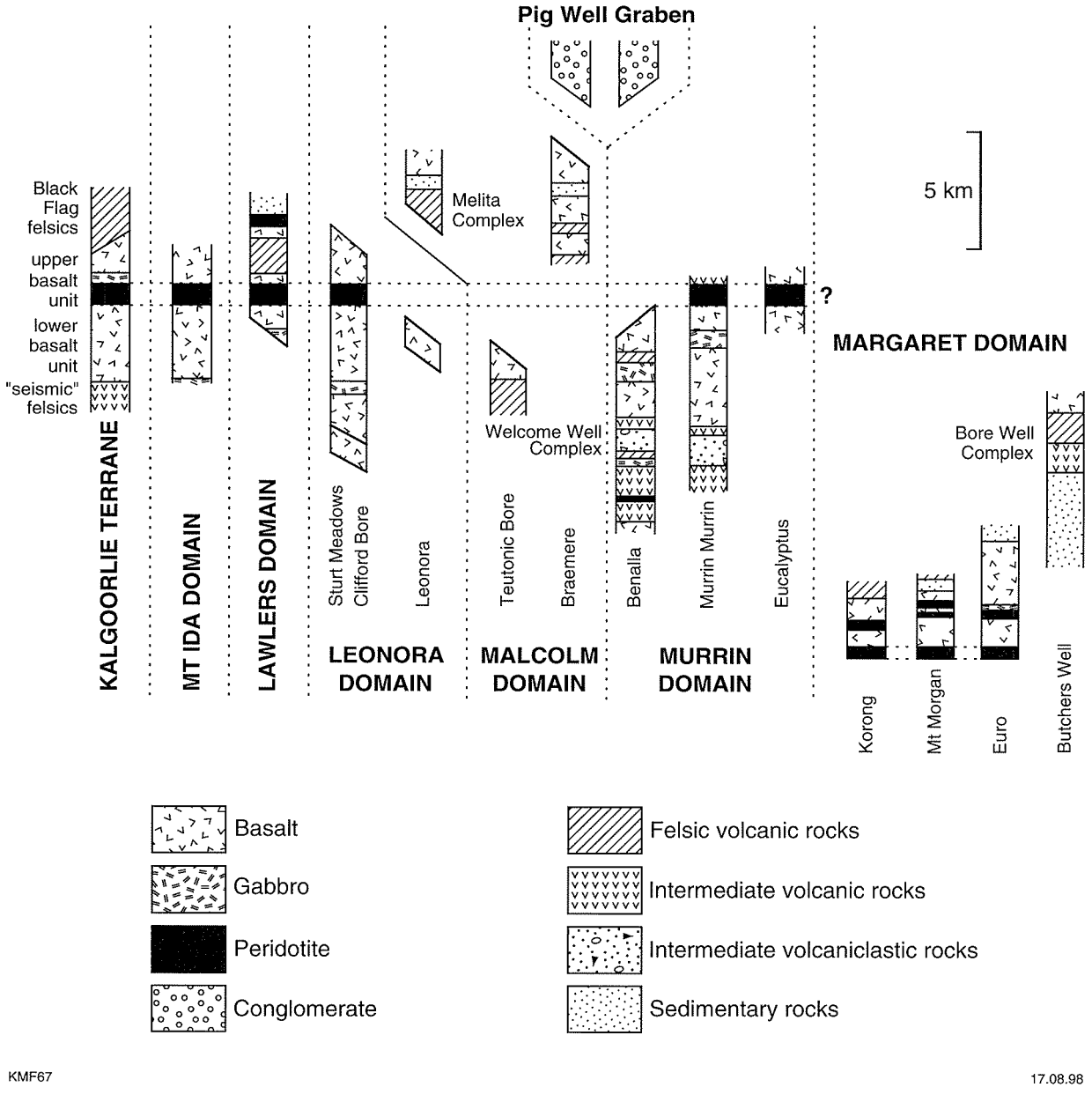


Figure 39. Schematic stratigraphic columns from greenstone belts in the Eastern Goldfields Province (*after* Rattenbury, 1993)

viscosities in komatiite lavas allowing widespread areal distribution (≤150 km^2 for individual flows), and by zircon U–Pb dating in the Kalgoorlie and Murrin areas.

Of particular importance in relation to the potential for VMS mineralization in the east Yilgarn Craton is the nature, distribution and correlation of felsic volcanic and volcaniclastic sequences within this framework. Figure 39 indicates that felsic and intermediate volcanic centres occupy at least two stratigraphic levels, above and below the ultramafic marker horizon. Felsic and intermediate volcanic rocks in the Welcome Well volcanic centre and at Murrin Murrin in the Murrin Domain are present below the marker horizon and may correlate with possible felsic volcanic rocks below the lower basalt unit in the Kalgoorlie area interpreted from gravity data (Williams et al., 1993). Figure 39 indicates that the felsic material of the Melita Complex is younger than the marker horizon, roughly correlating with the Black Flag Group. The position of the Teutonic Bore sequence is less clearly defined.

Hallberg et al. (1993) have summarized and updated the features of felsic volcanism in the Eastern Goldfields in the light of recent mapping by GSWA and by Hallberg Mapping Services Pty Ltd (HMS). This study separates the felsic volcanic rocks of the Kalgoorlie Terrane (the Black Flag Group) from the two main suites occurring in the northern and eastern part (Figs 40 and 41). The Black Flag Group contains soda-rich andesitic to dacitic lavas

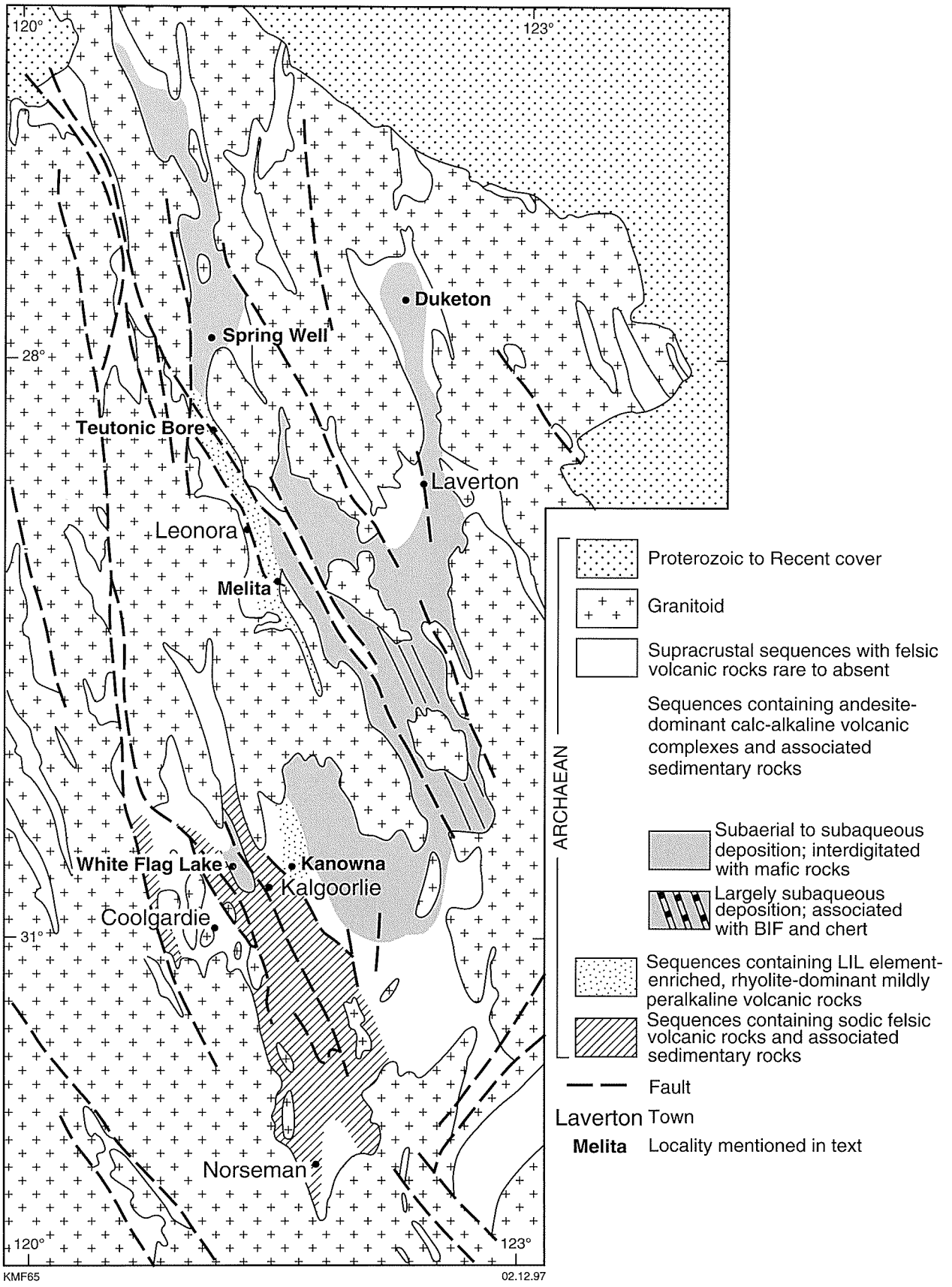


Figure 40. Distribution of major felsic volcanic rock types in the greenstone belts of the Eastern Goldfields Province (*after* Hallberg et al., 1993)

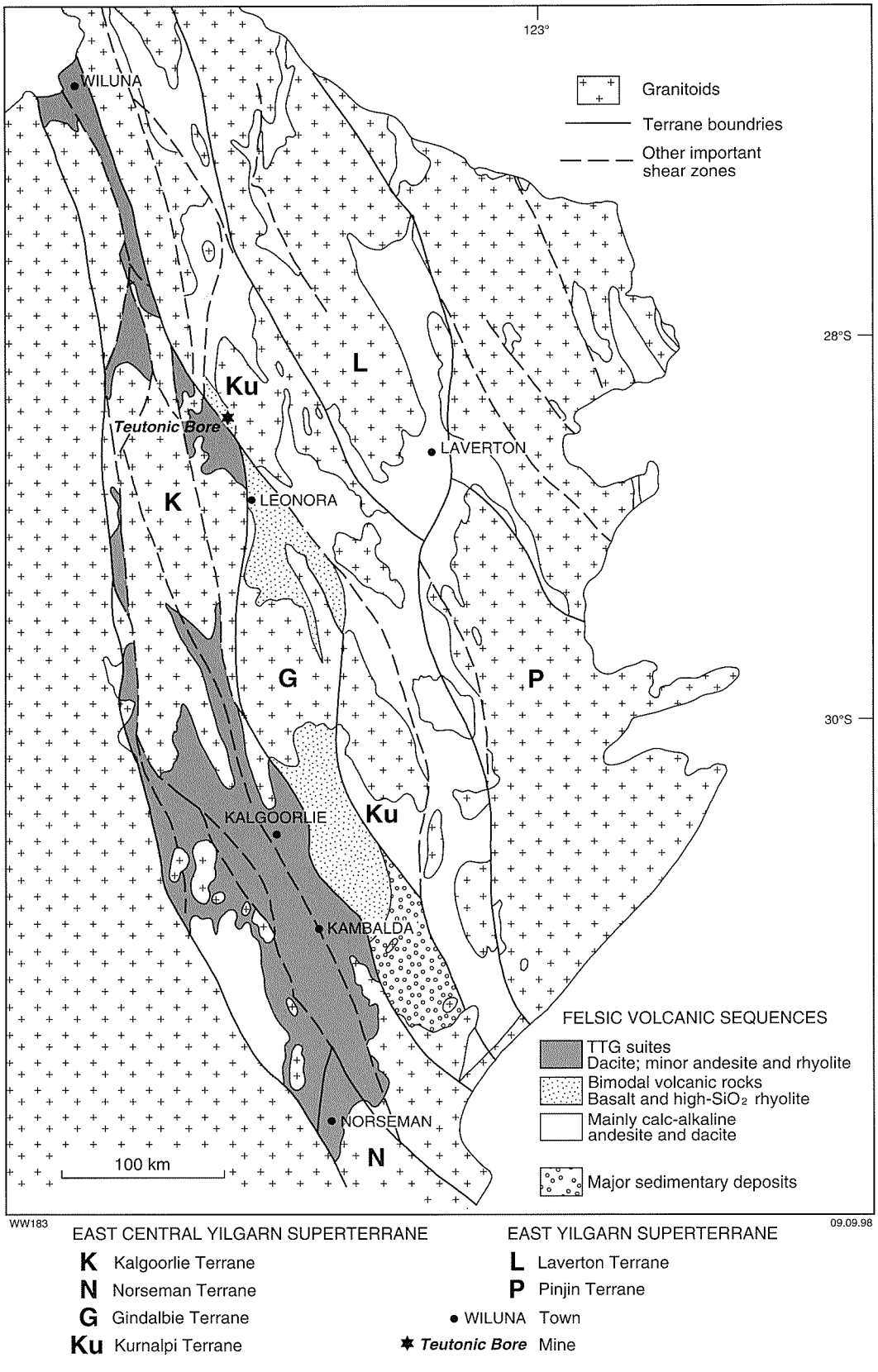


Figure 41. Felsic volcanic associations in the Eastern Goldfields Province related to terrane distribution (*modified after* Witt et al., 1996)

and rhyolitic fragmental rocks closely associated with quartz-rich clastic sedimentary rocks. Chemically, the volcanic rocks are distinct with Nb, Y and heavy REE lower, and Sr and Ti higher, than felsic volcanic rocks of the Gindalbie Terrane (Fig. 41).

The Gindalbie Terrane volcanic rocks form a bimodal basalt-high SiO_2 rhyolite association coeval with the Black Flag group, but with LIL element-enriched, flat REE patterns, and a distinct negative Eu anomaly suggesting a higher degree of fractionation (Witt et al., 1996). Mafic volcanic rocks occur above and below, and interdigitate with, the felsic material. Individual felsic centres are separated by aquagene tuffs and fine-grained sedimentary rocks. These rocks can be traced from Kanowna in the south to Teutonic Bore in the north. The mildly peralkaline melts of this group are considered by Hallberg et al. (1993) to relate to increased levels of crustal extension at the margin of an ensialic basin to the west.

The most widespread felsic rocks in the eastern and northeastern Goldfields, east of the Gindalbie Terrane, are calc-alkaline, andesite-dominated volcanic rocks with minor dacite and rhyolite. These formed in emergent centres with interbedded andesite flows and immature, chaotic mass-flow deposits. The centres were dominantly subaerial with the distal equivalents being subaqueous interbedded turbidites and tholeiitic pillow basalt. More subaqueous equivalents, associated with banded iron-formation and chert, are located southeast of Melita (Fig. 40).

The sequence of structural events indicated in the Kalgoorlie Terrane identified by Swager et al. (1992) has some parallels in other parts of the east Yilgarn Craton. Schemes proposed by Williams et al. (1993) in relation to the regional seismic line, by Hammond and Nisbet (1992) in the northern part, and by Williams and Currie (1993) in the Leonora area, are compared with the Kalgoorlie Terrane in Table 5. All recognize an early phase of low-angle, bedding-parallel deformation followed by upright folding and later strike-slip faulting. There are differences in details and interpretation, but most of the above studies agree that at least one stage of extensional, rather than compressional, deformation has been a major factor in the tectonic regime.

This contradicts the conclusions of Witt et al. (1989), Witt (1994), Swager et al. (1990, 1992) and Barley et al. (1993), who have suggested an accretionary, crustal-aggregation tectonic model for the east Yilgarn Craton to explain stratigraphic and tectonic variations between the terranes. Barley (1992) has suggested a subdivision separating the tholeiitic, calc-alkaline volcanic successions of the eastern part of the Norseman–Wiluna belt from the tholeiite–komatiite association of the western part, including the Kalgoorlie Terrane. The latter association is interpreted as representing a marginal basin, and the former a volcanic arc forming in response to westward-dipping subduction. These associations are depicted in Figure 42, incorporating information derived from recent mapping of the MELITA 1:100 000 sheet and interpreting the positions of the Teutonic Bore/Melita LIL element-enriched felsic rocks and the eastern andesite-dominated volcanic rocks of Hallberg et al. (1993) in the subduction-related arc and back-arc tectonic scheme.

Mineralization

Only the three broad granite–greenstone terranes host significant VMS deposits and occurrences. In the relatively poorly known Western Gneiss Terrane the high grade of metamorphism and the limited occurrence of greenstones probably reduce the VMS potential.

In the Murchison Province, VMS mineralization is predominantly associated with the deep-water intermediate to silicic volcanic rocks in the upper part of the older Luke Creek Group, particularly the Gabanintha and Windanning Formations. At Golden Grove in the Warriedar Greenstone Belt a number of significant VMS deposits, including the Scuddles zinc–copper mine, have been discovered and detailed volcanological and sedimentological studies carried out on the host Gabanintha Formation. In the Gabanintha Formation a lower sequence of tholeiitic basalt and komatiite is overlain by intermediate to silicic, calc-alkaline lavas (andesite to rhyolite), autoclastics and intrusives, minor basaltic lavas, and resedimented pyroclastic debris and volcaniclastic sediments. The succession is interpreted by Cas et al. (1993) as being relatively deep water (>1 km), having erupted in a graben-like basin with the lavas and autoclastics being proximal, and with the pyroclastic and epiclastic material being distal sediments in the form of mass flows. Barley (1992) has reported two chemical suites based on low or high Zr. The low-Zr suite has fractionated REE patterns, with no negative Eu anomaly, and variable depletion in heavy REE. The high-Zr suite has less extreme REE fractionation and a negative Eu anomaly. Both suites are low in Pb (<20 ppm). Table 12 compares the chemical and physical features of the major Archaean VMS deposits in Western Australia.

In the Yellowdine and Barlee Terranes, VMS mineralization is confined to relatively minor prospects. Only the stratiform lenses in meta-banded iron-formation and felsic schists at Freddie Well have yielded a resource figure. At West River, near Ravensthorpe, an altered tuff horizon with sporadic zinc values associated with copper-dominant sulfide lenses may be volcanogenic.

In the Eastern Goldfields Province, most VMS deposits and occurrences are located within the central eastern part of the Norseman–Wiluna Belt characterized by the bimodal basalt-rhyolite and calc-alkaline andesitic volcanic associations (Figs 37 and 41) outlined by Barley et al. (1992a) and Barley (1992). This part of the belt is considered by Barley (1992) to represent a subduction-related volcanic-arc setting. The volcanic rocks in this zone, east of the Gindalbie Terrane are mostly in the andesite-dominated group of Hallberg and Thompson (1985). Small copper–zinc deposits and occurrences in the Murrin area (Anaconda, Nangaroo, Rio Tinto and Crayfish Creek) lie within, and towards the top of, a sequence of epiclastic sedimentary rocks considered to be distal subaqueous deposits related to the andesitic Wellcome Well Complex (Hallberg, 1985). These deposits show

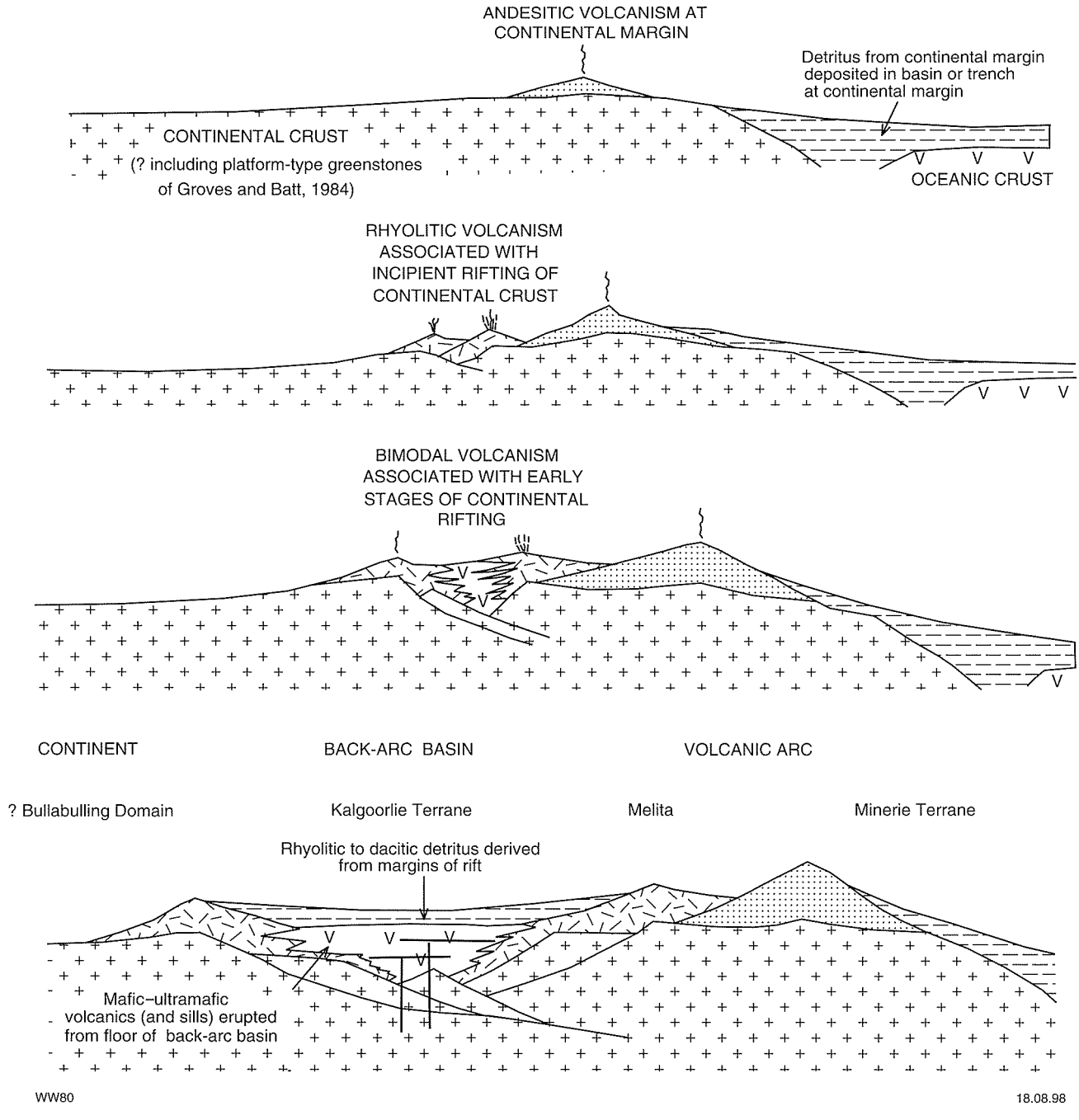


Figure 42. Proposed tectonic settings of felsic volcanism in the Eastern Goldfields Province (*after* Witt, 1994)

evidence of submarine mass flows and turbidity currents indicating a deep-water basinal setting. Prospects in the Duketon Greenstone Belt (Tuff Hill, Mason Hill and Fisher Well) also occur in epiclastic sedimentary rocks within a rhyolite–andesite volcanic sequence.

The only major VMS deposit in the Eastern Goldfields Province, Teutonic Bore, is, however, located within the Gindalbie Terrane, in a tectonically transposed slice east of the Keith–Kilkenny Fault. Teutonic Bore and the nearby Wendys Bore and Doyle Well prospects are, uniquely for Western Australia, associated with bimodal volcanism of the LIL-enriched group of Hallberg and Thompson (1985) described above. A deep-water environment is again indicated at Teutonic Bore and active growth faults seem to have controlled the formation of, and access of exhalative fluids to, a sediment-filled sub-basin. Further mineralization at Wendys Bore is at the same stratigraphic position as the Teutonic Bore deposit. Witt (1994), considering the lack of success in exploration for VMS mineralization in the Melita area in rhyolites comparable with those at Teutonic Bore, has suggested

Table 12. Comparison of Archaean VMS deposits and host felsic volcanic sequences

Location	*Chemical association*	*Lithology*	*Size (mt)*	*Zinc ratio*	*REE*	*LIL*	*Pb (ppm)*	*Eu*	*Depth*
Warrawoona	Calc-alkaline (modern)	Dacite–rhyolite	<0.5	75	Fractionated	–	>20	No anomaly	Shallow–deeper
West Pilbara	Calc-alkaline to tholeiitic	–	0.5–1.0	60–74	Fractionated	Enriched	>20	-ve anomaly	Deep
Murchison/Golden Grove 1	Calc-alkaline, intermediate to silicic	Andesite–rhyolite	>10	94–100	Fractionated	–	<20	No anomaly	Deep
Murchison/Golden Grove 2	Calc-alkaline	–	–	–	Less fractionated	–	<20	–	Deep
Kalgoorlie	–	Dacite–rhyolite	–	–	–	–	–	No anomaly	Deep
Teutonic	Bimodal/mildly per-alkaline	Basalt–dacite/ dacite–rhyolite	~1	93	–	Enriched	<20	-ve anomaly	Deep
Murrin	Calc-alkaline to tholeiitic	Andesite + dacite–rhyolite	0.5–1	–	–	Minor enrichment	–	–	Subaerial

NOTES: REE: rare earth elements; LIL: large ion lithophile; Eu: Europium; zinc ratio: 100Zn/(Zn+Pb)

SOURCES: Barley (1992), Hallberg et. al (1993)

that a combination of shallow-water conditions and the explosive nature of the volcanism in this area that may have dispersed the ore components, are negative factors. He also notes the lack of extensive alteration haloes that would indicate large-scale hydrothermal systems. He has also suggested that intermediate-facies volcanic rocks and proximal epiclastic sedimentary rocks may offer more potential for exploration, particularly the epiclastic component of the Jeedamya Rhyodacite. Witt et al. (1996) have suggested that the central vent area of the Melita volcanic centre may have been deeper, due to caldera collapse, and may therefore remain prospective.

Table 12 compares the setting, style and chemical affinities of the various VMS deposits and occurrences in the Yilgarn Craton. The favourable combination of deeper water environments, which prevent sub-seafloor boiling of hydrothermal fluids, with coherent lavas, hyaloclastite and resedimented volcaniclastic material is consistent with the environment indicated at Golden Grove. Cas et al. (1993) have examined the Black Flag Group volcanic rocks in the Kalgoorlie Terrane from a perspective of close knowledge of the Golden Grove environment, and find them to consist of rhyolitic lavas, hyaloclastites, resedimented volcaniclastic rocks, ambient black/dark grey mudstones and siltstones and resedimented polymictic sedimentary rocks. They concluded this environmental–sedimentological association to be prospective for VMS mineralization despite the lack of exploration success in this group to date.

Exploration history

Murchison Province

Exploration for volcanogenic targets in the Murchison began only in the late 1960s with the main concentrated phase commencing in the early to middle 1970s following the discovery of Gossan Hill in 1971. Of a total of 190 exploration projects indexed in GSWA's WAMEX system specifically targeting copper–zinc mineralization in the Murchison, 7% began in the 1960s, 55% in the 1970s, and 38% in the 1980s. This falling off reflects the shift to gold exploration in the second half of the 1980s and, to some extent, the lack of major discoveries apart from the Golden Grove project.

Among the earliest explorers for this target type between 1969 and 1972 were Union Oil, Homestake and Australian Hanna (I 1454), who followed up gossans in cherty metasedimentary and silicic volcanic rocks, close to a contact with overlying basalts, at Mount Mulcahy in the Weld Greenstone Belt. These had been worked for copper on a small scale between 1954 and 1965. Exploration along the prospective contact established a small, stratabound copper–zinc resource. Concurrently, in the Wattagee area, Eastmet discovered copper- and zinc-rich gossans in felsic volcanic and metasedimentary rocks during exploration for nickel in ultramafic bodies (I 1733).

Also, in 1970, Aztec began exploration specifically for Canadian-type VMS mineralization in the Yalgoo–Singleton Greenstone Belt. Gossans in acid volcanogenic sequences were sought and evaluated (Pitt, 1990). By early 1971 a significant discovery of copper-rich massive sulfides had been made, centred on the prominent gossans at Gossan Hill. Pitt (1990) suggested that geologists in Western Australia were unfamiliar with felsic volcanogenic copper–zinc at this time but it is also likely that they were preoccupied with nickel as a priority target for exploration in mafic and ultramafic sequences. The high magnetite content which gave the gossan an outcrop pattern resembling banded iron-formation, and the lack of malachite staining, made potential partners reluctant to drill. The recognition of boxworks after chalcopyrite and sphalerite in polished section studies of the gossan, however, and the confirmation of the felsic volcanic association, led to the involvement of Amax in a diamond drilling program.

A burgeoning of VMS exploration followed these results during the 1970s and the first half of the 1980s. Projects generated in the latter part of the 1980s tended to reflect the boom market for gold, with base metals as a second string in the program. All the greenstone belts in the Murchison were explored with the Warriedar, Meekatharra and Wattagee centres and Narndee receiving most attention. The major companies involved include those associated with the Golden Grove Joint Venture (Aztec, Amax, Esso and EZ), CRA and WMC.

The major success of this concerted activity was the discovery of the blind zinc-rich deposit at Scuddles in 1979. The recognition that VMS deposits in Canada typically cluster along certain stratigraphic horizons representing quiescent periods during the formation of the volcanic terrain was a critical element leading to the location of Scuddles (Mill, 1990). Detailed geological mapping by Amax, EZ and Esso between 1970 and 1978 led to the delineation of a mineralized horizon extending for 40 km along the eastern margin of the greenstone belt. A RAB drilling program was important to the continuity of this mapping in areas of poor outcrop and helped recognition of intense chlorite alteration at Scuddles. This, in combination with a subtle aeromagnetic anomaly, led to the location of geochemical anomalism in weathered bedrock at 40 m. Shallow RAB drilling showed no anomalism. Follow-up diamond drillholes intersected massive sulfides at greater than 140 m below surface. Numerous smaller mineralized bodies have been located by similar methods along this zone.

The magnetic nature of the mineralization, with high contents of magnetite and pyrrhotite, was a useful tool in exploration. Various types of ground-based EM survey were tested over Scuddles and Gossan Hill with Sirotem and EM-37 proving effective. Gradient-array IP proved ineffective but dipole–dipole IP showed some potential. Deep RAB geochemistry is required to detect base-metal anomalism but testing of trace-element geochemistry in pisolitic laterite indicated some positive results for copper, bismuth, arsenic and tin. Clifford and Sheppy (1991) indicated that in this area geochemical strategies relied heavily on the use of Au and Pb tracers within the supergene zone, as these two elements reliably characterize the primary mineralization at all known occurrences.

In the extension of the Yalgoo–Singleton Belt north from Gossan Hill, exploration by Mines Ex (I 131),

Unimin (I 2907), EZ (I 1001, 685 470), Esso, Dalrymple (I 6086) and Aztec, at Walgardy (I 5607, 6817), has so far not revealed further major prospects, though minor sulfide mineralization has been located at Lambshaft Well and at Strongs Gossan.

In the Meekatharra–Wydgee Greenstone Belt some minor mineralization has been explored by a number of companies in the Wattagee Well area. Zinc-rich intersections in graphitic shales and tuffs may indicate a more distal mineralization environment of the type which produced the more poddy and stringer-related mineralization at Scuddles. Limited mineralization, with stratiform and stockwork components, was located by Pennzoil in the Tuckabianna area of the belt.

In the Gullewa Greenstone Belt AAR/Aztec/Esso (I 1721) defined two areas of subeconomic stratiform mineralization associated with chert horizons in the Gabanintha Formation. Sons of Gwalia is still active in the belt, though with a gold focus. In the northeastern part of the belt at Whiskey Hills, Dalrymple, following up work by CRA in the 1970s, is exploring Golden Grove-style targets over 3 km of strike in the Grants Prospect. A potential resource has been identified below 250 m.

In the Dalgaranga Greenstone Belt the lead-rich Seivwright Gossan was located by CEC in the 1970s (I 1368) on a basalt–rhyolite contact in the Gabanintha Formation. CRA (I 3922) has been active in the area, using SIROTEM and INPUT surveys in areas of deep surficial cover: CRA/Outokumpu are following up these results.

Some encouragement has been found in other, smaller belts. At Twin Peaks Amoco/Cyprus obtained high lead and zinc grades in association with stratiform and feeder mineralization. Poseidon/Jilbadgi are following up four EM conductors in the northern part of the belt. In the Tallering Belt, EZ located only weak grades in distal tuffs and sedimentary rocks. In the Perenjori Belt, Sipa/Ashling have been exploring an environment similar to that at Golden Grove and have reported encouraging grades of lead and zinc in massive-banded and breccia-fill sulfides. In the Narndee area, INCO located stratabound disseminated sulfides in 1970–71 in a sequence of felsic volcanic rocks, cherts and BIF intruded by the Narndee layered mafic–ultramafic complex where the company was exploring for nickel (Ruddock, I., 1995, pers. comm.; I 1735); since then other companies have followed up the VMS search.

Southern Cross Province and Eastern Goldfields Province

In the Yilgarn, as in the Pilbara Craton, small stratabound sulfide bodies in greenstones produced copper from secondary ore in the 1890s and early 1900s. In the Murrin area of the east Yilgarn Craton, the Anaconda and Nangaroo mines produced oxidized and supergene copper between 1899 and 1908, and copper from primary sulfides between 1911 and 1922. Cupreous ores were also mined between 1950 and 1967. The Last Venture and Copper King mines in the West River area, southwest of Ravensthorpe, also produced copper from stratabound sulfides in the early 1900s. There was also minor production from Last Venture in 1962–63.

As in the Murchison Province, exploration for volcanogenic copper–zinc in the rest of the Yilgarn began in the 1960s. As early as 1964, Australian Selection (I 5998)and WMC were examining VMS potential in the Murrin area. It is interesting to note that of a total of some 340 exploration projects in the GSWA WAMEX open-file system that specifically targeted copper–zinc mineralization in the Eastern Goldfields Province, only 7% commenced in the 1960s. The great bulk (64%) commenced in the 1970s, presumably reflecting the growing awareness of the potential of the Canadian model and the discoveries at Golden Grove and, in 1974, Teutonic Bore. Only 29% commenced in the 1980s, partially reflecting the very low success rates in the 1970s and the move to gold exploration. This is a more pronounced falling off than in the Murchison, where the Scuddles discovery helped to sustain exploration momentum. The much larger overall number of projects relative to the Murchison probably reflects the much larger area of target greenstones in the Eastern Goldfields Province. A total of 82 projects was initiated in the Southern Cross Province, many fewer than in the Murchison despite roughly similar areas of greenstones. This is probably due to the lack of major discoveries.

In the Murrin project area in the 1960s, exploration was initially based on INPUT airborne EM and magnetic surveys followed up with ground geophysics, geochemistry and diamond drilling. EM tended to reflect graphitic shales and magnetite-rich ultrabasic material whereas sample results were subdued and element mobility poorly understood. After 1970, exploration was concentrated largely around former workings; geomorphological mapping aided interpretation of geochemistry, and IP proved successful. Drilling of the main prospects, however, failed to establish economic size or grades.

From 1970, exploration in the Melita–Kookynie area was undertaken by several companies, including CRA (I 158), Shell (I 206), Chevron (I 1443) and Dechow (I 5028). Despite an apparently favourable cyclical bimodal, calc-alkaline volcanic suite with many similarities to the Kirkland Lake–Timmins area in Canada, only minor anomalism (≤0.36% Zn over 0.9 m) was encountered. Dechow suggested that the lack of intermediate volcanics in the suite may be a negative factor.

In the Anti Dam–Jurangie Hill area of the Kurnalpi Greenstone Belt exploration by a number of companies including Amax (I 1073), Aquitaine (I 144, 575, 851), Newmont (I 644), Esso (I 2764) and CSR (I 4475) began in 1971 and continued with a base-metal focus until 1985. Despite multi-phase exploration to diamond-drilling level around gossanous surface indications, anomalism was limited (≤1.9% Zn) and interpretation ambiguous. Despite the lack of exploration success, CSR in 1985 considered the sequence to have geological and geochemical similarities to known base-metal deposits. This seems to have been a common finding in the eastern and central Yilgarn Craton.

The most successful program in the east Yilgarn Craton was that of Australian Selection and partners (BP, CEC, and Chevron, I 4029), who discovered the Teutonic Bore deposit in 1974 in the Yandal Greenstone Belt. CEC initially discovered gossanous stringer mineralization during reconnaissance sampling and mapping in felsic volcanic rocks. Subsequent sampling and shallow drilling revealed a massive gossan, beneath which an economic lens of massive sulfides was proved by early 1977. Exploration since has largely been directed at finding extensions and repetitions of the deposit in the bimodal sequence. BP/Chevron/Esso/Aquitaine and Aztec (I 3273, 5832) had moderate success to the south at Wendys Bore following the prospective basalt–felsic contact zone with extensive EM, EM-37 and SIROTEM surveys with follow-up drilling.

Another area of moderate success was in the Duketon Greenstone Belt between Tuff Hill and Fisher Well, involving CEC/Esso and Homestake between 1973 and 1988 (I 5573, 5998). A wedge of felsic volcanic and sedimentary material within basalts and ultramafic rocks contains anomalous gossans. The follow-up strategy included bedrock auger geochemistry, IP, TEM and percussion drilling. TEM was most effective and helped to define mineralization over 400 m of strike at Mason Hill.

In the Southern Cross Province exploration has been underway since 1971 in the Freddie Well and Pincher Well areas of the Youanmi Greenstone Belt. Metafelsics, meta-banded iron-formation, chert and argillite, occupying the contact between the Youanmi Gabbro and granite, are associated with stratiform sulfide lenses in zones of hydrothermal alteration. Conwest/CRA (I 3406) defined a zinc-rich body with grades up to 22.5% Zn. Aeromagnetic and gravity surveys were used to aid stratigraphic and lithological interpretation and TEM proved able to distinguish sulfides. Attempts to locate extensions of the felsic sequence met with limited success. However, in the Pincher Well area to the northeast of Freddie Well, WMC (I 2102), CEC, and more recently BHP explored an apparent extension of the felsic horizon around a domal structure with some success.

In the Montague Range–Mount Townsend area of the Gum Well Greenstone Belt, Amax/Amoco (I 564) in the late 1960s located copper gossans in a felsic volcano-sedimentary sequence while searching for nickel–copper targets. At about the same time, INCO (I 572) recognized an anomalous black shale–chert unit traceable over 75 km. Follow-up in the 1980s by CRA (I 4682) using aerial EM with soil and RAB geochemistry outlined additional targets. Downhole and surface SIROTEM was used successfully to define conductors at depth. Surface INPUT surveys were only partially successful due to high surface conductivity in some areas. The mineralization appears to have been of relatively low grade. Exploration by Pancon and CRA is continuing in this area.

In the Ravensthorpe area, copper–gold dominant, structurally controlled mineralization has been mined since 1899. In the West River area, at the southwestern extremity of the greenstone belt, stratiform massive sphalerite is present at the Last Venture mine. CRA and Amax (I 1615), were among the first to explore stratiform targets in this area, in the mid-1970s, using IP and magnetic surveys, mapping, sampling and drilling. They identified thin horizons of moderate-grade mineralization. Follow-up by Pancon (I 6420) in the early 1990s identified two horizons representing sea-floor tuffs hosting, or adjacent to, mineralization at the Last Venture and Copper King mines.

Deposits, prospects and occurrences

Murchison Province

Golden Grove group

Two major base-metal deposits and a number of prospects in the form of massive-sulfide accumulations are present within the upper part of the Gabanintha Formation in the Warriedar Greenstone Belt, about 50 km south-southeast of Yalgoo. The lower part of the Gabanintha Formation is absent in this area, having been intruded by monzo-granite before and after regional metamorphism (Watkins and Hickman, 1990). The mineralization lies within a sequence of felsic lavas and volcaniclastic sedimentary rocks, with minor chemical sedimentary rocks, about 400 to 500 m below the base of an upper tholeiitic basalt unit. This is unconformably overlain by felsic volcanic and volcaniclastic rocks of the Windanning Formation. The succession is up to 3 km thick and dips steeply west-southwest on the eastern limb of a major, south-plunging syncline. Mineralization, represented by a number of deposits and prospects and a regional zone of quartz–chlorite–sericite–carbonate alteration, extends over a strike length of at least 30 km.

The stratigraphy of the upper Gabanintha Formation in the Golden Grove area has not yet been formalized. Mill et al. (1990) refer to the mineralized felsic sequence as the Gossan Hill Group and the overlying tholeiitic sequence as the Thundelarra Group. Boyd and Frankcombe (1994) show the Gossan Hill Group subdivided into five formations as a result of detailed mapping and facies analysis by the joint venture partners at Golden Grove in the Warriedar Belt. Figure 43 shows part of the Gossan Hill Group stratigraphy with the stratigraphic level of the major deposits and prospects. Figures 35 and 43 show the regional and more detailed distribution of the formations. Clifford et al. (1991), however, refer to these formations as 'units' and, in the light of the present informal nature of the stratigraphy, this latter term will be used below.

The basal unit is the Shadow Well unit (<850 m thick) which comprises poorly sorted quartz-rich sandstones with minor pelites, lithic sandstones and pebble breccias deposited by turbidity currents in a deep subaqueous setting. A gneissic or granitic provenance is inferred. The overlying Gossan Valley unit (<400 m thick) is the footwall succession and is dominated by turbidites and debris flows of intermediate to basic volcanic provenance with minor mafic and felsic lavas and dacite to rhyolite volcaniclastic sedimentary rocks. This unit represents

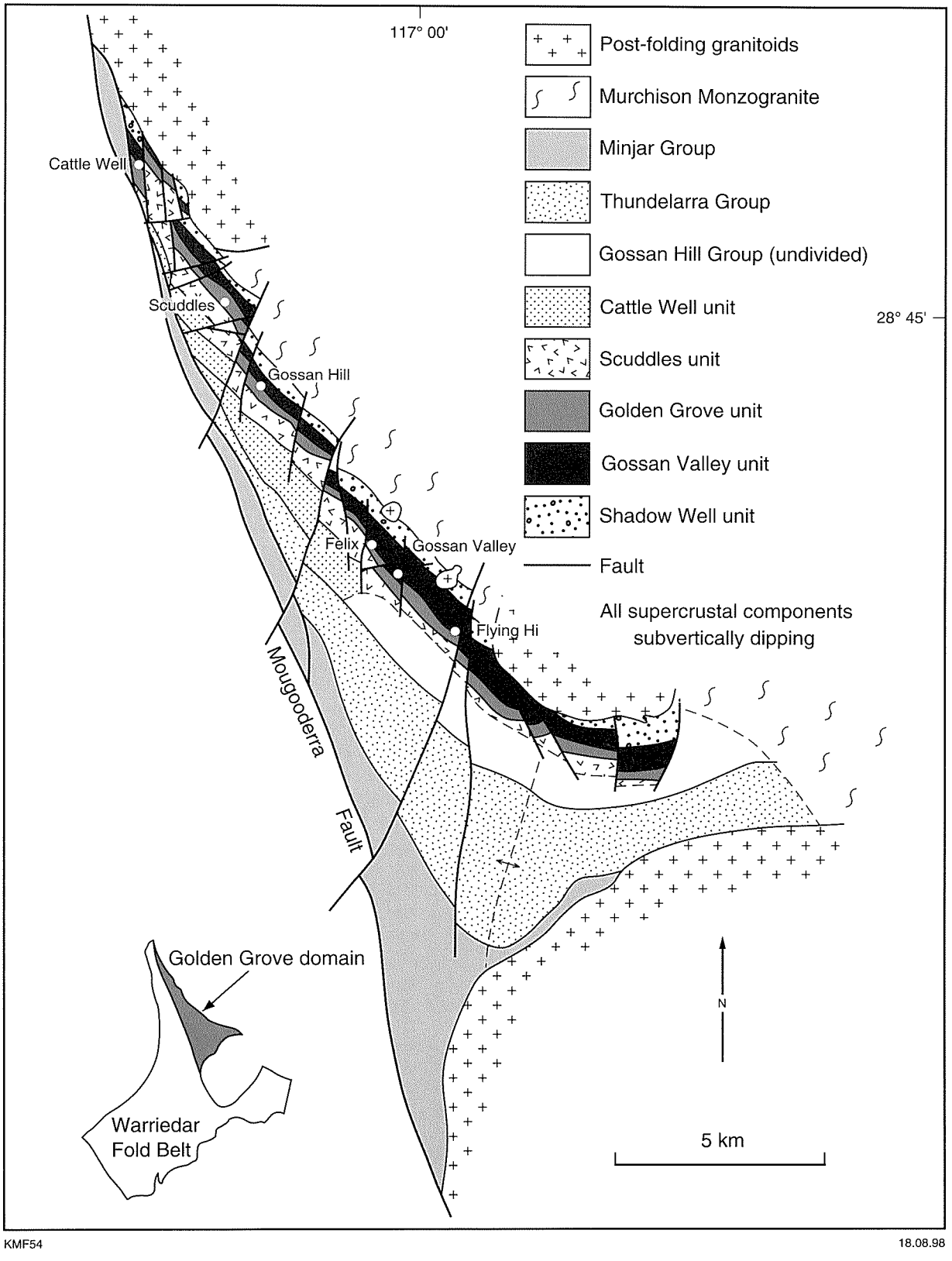


Figure 43. Warriedar Belt–Golden Grove: distribution of stratigraphic components, deposits, and base-metal prospects (*after* Murchison Zinc)

major deep subaqueous, distal, intrabasinal volcanism, with minor effusive proximal volcanism.

The Golden Grove unit (<400 m thick) is the main mineralized succession and consists largely of dacitic to rhyolitic resedimented pyroclastic debris with minor andesitic to rhyolitic lavas, andesitic litharenites and chemical sedimentary rocks. The Golden Grove unit represents the onset of major, intrabasinal, felsic, explosive volcanism. Chemical sediment deposition and proximal hydrothermal-fluid activity has produced massive-sulfide deposition towards the top of the unit. Further subdivision of the unit into six subunits can be seen in Figure 44. The mineralization is associated with thinly bedded sediments and chemical sediments. The surface distribution is shown in Figure 45.

The Golden Grove unit contains a number of minor and major deposits and prospects over a strike length of about 20 km. A U–Pb date of 2.95 Ga has been obtained from zircons in the host sequence (Pidgeon, 1986). More recent detailed U–Pb ages (obtained using conventional single-grain zircon techniques) of two samples separated by a stratigraphic thickness of 550 m give ages ranging between 2.951 and 2.957 Ga (Pidgeon et al., 1994). The probable time difference between the samples (3–6 m.y.) gives a sedimentation rate comparable with modern high rates of extensional marginal basin sedimentation (50–300 m per m.y.) reported by Cary and Sigurdsson (1984).

The Scuddles unit (<850 m thick) is the hangingwall succession and is dominated by rhyodacitic to andesitic lavas and associated autoclastic breccias with some tuffaceous and non-tuffaceous volcaniclastic sedimentary material. Chemical sedimentary rocks are rare. Figure 34 shows four subunits, only the lowest of which is present at Gossan Hill. The Scuddles unit reflects major, proximal effusive volcanism, although some distal and intrabasinal explosive volcanism is indicated towards the base. Some proximal hydrothermal activity and related massive sulfides occur in the lower part of the unit.

The Cattle Well unit (<700 m thick) is composed of poorly sorted volcaniclastic sedimentary rocks, mainly fine sandstones and pebble breccia. These indicate a provenance of felsic and mafic volcanic debris, with felsic predominant.

Five groups of post-mineralization intrusive rocks are found within the Gossan Hill sequence. An older group of irregular, high-angle dacite dykes extends throughout the sequence and may represent feeders for extrusive and pyroclastic units higher in the sequence. They are followed by monzogranite, post-tectonic granitoids, tholeiitic dolerite dykes up to 20 m wide, and felsic dykes.

In relation to both the Gossan Hill and Scuddles deposits, Clifford and Sheppy (1991) have pointed out the importance of a detailed understanding of the depositional environment in locating mineralization. They consider that the deposits accumulated in local depressions alongside growth faults that provided access for hydrothermal fluids. The chemogenic cherts, which are closely associated with the hangingwall of the mineralization, are considered to reflect the hydrothermal solutions that were precursors of proximal rhyodacitic to dacitic volcanism. Clifford (1992) has concluded that, in a regional sense, the felsic volcano-sedimentary succession of the Gossan Hill Group was deposited in a setting analogous to a modern subduction-related marginal basin.

Scuddles

Mine: Zn; Pb; Ag; Cu; Au
Location: 28°44'47"S, 116°56'31"E; 50 km south-southwest of Yalgoo

The mineralization at Scuddles takes the form of two stratiform, zinc-rich massive-sulfide lenses (the Main and Central Lenses) developed near the top of the Golden Grove unit in thinly bedded, mixed provenance, volcaniclastic and chemical sedimentary rocks. Each is underlain by a zone of disseminated and stringer copper-rich mineralization. Smaller sulfide bodies occur at a lower stratigraphic level east and north of the Central Lens. These include the poorly known North Lens (Normandy Poseidon Ltd., 1992).

The lenses, which are up to 50 m thick, coincide with a zone of thickening of the enclosing mineralized horizon and grade into cherty and chloritic exhalative sedimentary rocks and chloritic tuffs. Both lenses are capped by an exhalite-dominated marker horizon which is iron-rich (± manganese) and laminated. Clifford and Sheppy (1991) consider the thickening of the mineralized horizon, in association with the lenses, indicates the presence of a depression or small basin at this level in which sulfides accumulated. The upper part of each lens is zinc rich, taking the form of massive coarse-grained recrystallized sphalerite (>50%). This overlies a relatively barren pyritic zone (<50% sphalerite and <5% chalcopyrite). The central parts of each lens contain a zone of copper-rich massive sulfides. Some copper-rich massive ore is also developed above the zinc zone in part of the main zone. Accessory galena, chalcopyrite and pyrrhotite occur in the zinc-rich caps, with lesser arsenopyrite, tetrahedrite and mackinawite, in a gangue of magnetite, quartz, sericite, talc, albite, tourmaline, clinoamphibole, carbonate and cassiterite. The pyrite ore also contains minor sphalerite, chalcopyrite, pyrrhotite and magnetite with quartz, chlorite, carbonate, sericite and talc. In the copper-rich ore, chalcopyrite and pyrrhotite become more prominent.

Disseminated to semi-massive, copper-rich, pyrite–chalcopyrite mineralization extends in stockwork and stringer style as much as 50 m below the two lenses. This is most strongly developed directly beneath the central part of the Main Lens. Pyrite is dominant although there are some chalcopyrite-rich veins and aggregates within these zones. Minor pyrrhotite and magnetite are also present.

Alteration of wall rocks is most intense in the mineralized horizon and lower levels of the Golden Grove unit, and to some degree in the hangingwall. Primary plagioclase has been converted to sericite, carbonate and chlorite in these zones. The geochemical zonation created by the alteration and mineralizing processes shows the addition of water and CO_2 to the hangingwall with some depletion of Na, Ca and Sr. Immediately above the lenses

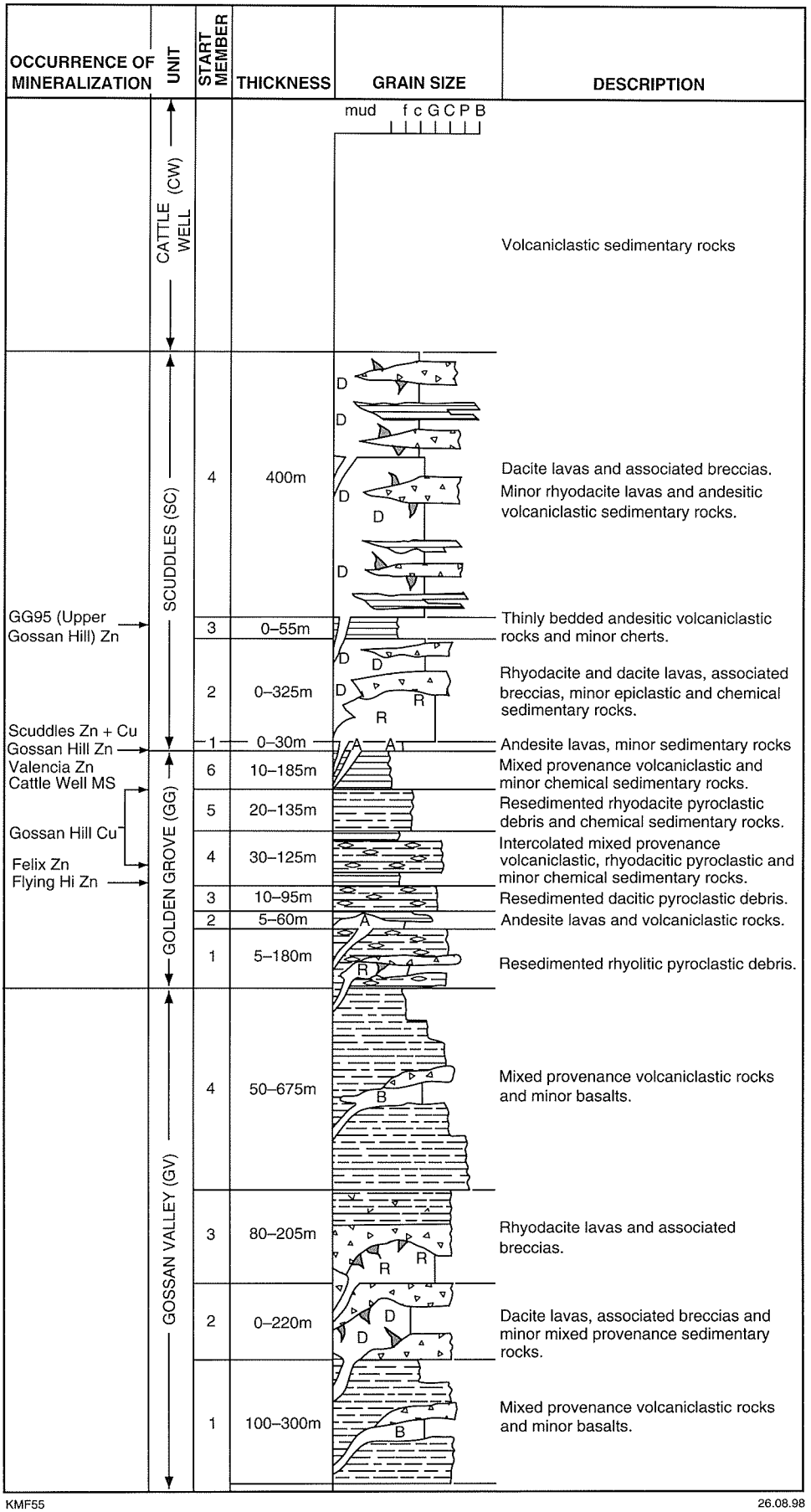


Figure 44. Gossan Hill Group: stratigraphic column (*after* Murchison Zinc)

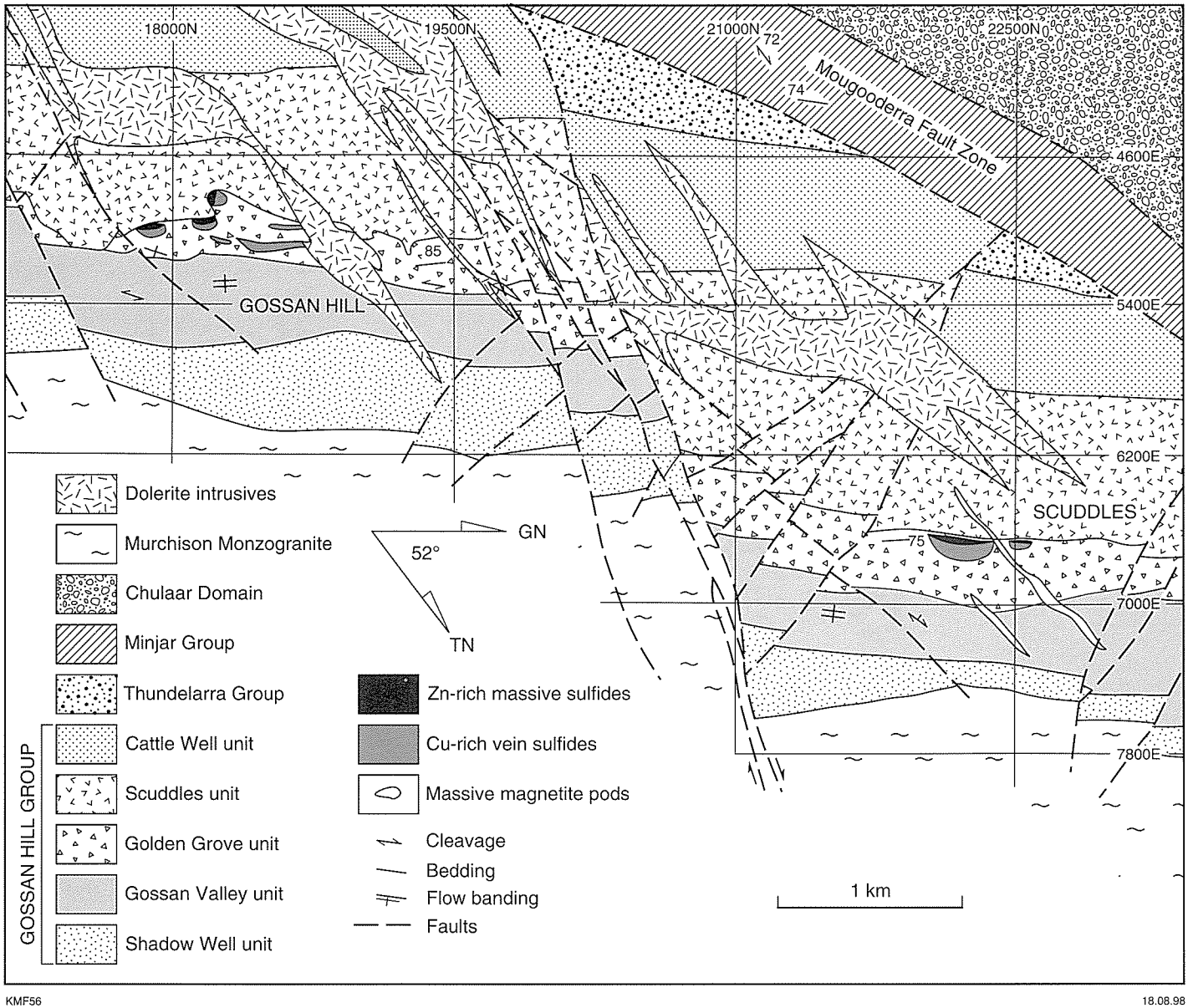


Figure 45. Golden Grove: geological interpretation correlating the Gossan Hill and Scuddles deposits (*after* Murchison Zinc)

Fe, Mn and base metals are enriched, whereas Na is strongly depleted. Iron, base metals and chalcophile elements are strongly enriched in the mineralized zones. In the zinc-rich zone Pb, Ag, Sn, Cu, As, Sb, Co, Au and Mn are prominent. Beneath this zone, Fe and Cu are associated with As, Co, Zn and some Mn and F. Sodium, Ca and Sr are depleted in the lenses. In the footwall rocks Fe, base metals, As, Mg and water increase towards mineralization, whereas Na, Ca and Sr are depleted, as is K to a lesser extent. Footwall alteration extends 3 km along strike to the Gossan Hill mineralization.

An indicated resource of 12 Mt at 8% Zn, 0.6% Pb, 1.8% Cu, 65 g/t Ag and 0.9 g/t Au was reported in 1993 for Scuddles as a whole (Bain and Co., 1994). The total reserve was 6.2 Mt at 10.2% Zn, 0.7% Pb, 1.5% Cu, 78 g/t Ag and 1.1 g/t Au. This was broken down as follows. For the Main Lens, above the 550RL, in the zinc zone, 3.1 Mt at 13% Zn, 0.9% Pb, 0.5% Cu, 91 g/t Ag and 1.1 g/t Au were proven. The Main Lens copper gave 1.4 Mt at 1.1% Zn, 0.1% Pb, 4.6% Cu, 36 g/t Ag and 0.8 g/t Au. The Main Lens (transitional) gave 0.4 Mt at 7.1% Sn, 0.5% Pb, 1.8% Cu, 75g/t Ag and 1.6 g/t Au. The Central Lens zinc gave a probable 1.2 Mt at 15% Zn, 1.1% Pb, 0.4% Cu, 98 g/t Ag and 1 g/t Au, and Central Lens copper gave 0.1 Mt at 2.5% Zn, 0.2% Pb, 2.1% Cu, 57 g/t Ag and 1.7 g/t Au.

Mining of the Main Lens at Scuddles commenced in 1990 and, since 1991, ore processed annually has increased from 640 000 to 900 000 t. At the beginning of 1994 about 535 000 t of zinc concentrate and 47 000 t of copper concentrate had been produced. With changing geological conditions the proportion of copper-rich ore is increasing with depth. Exploration drilling to 900 m has indicated that the Main Lens is open at depth (Bain and Co., 1994).

References: Mill et al. (1990), Ashley et al. (1988), Clifford and Sheppy (1991), Murchison Zinc (1992), Normandy Poseidon Ltd. (1992), Bain and Co. (1994).

Gossan Hill

Deposit: Cu; Zn; Au; Pb
Location: 28°46'41"S, 116°57'46"E; 4 km south-south-east of Scuddles

The Gossan Hill stratabound base-metal mineralization occurs at two levels in the Golden Grove Formation and at a higher level in the Scuddles Formation. Extensive but discontinuous mineralization has been established over a strike length of 1.6 km. Zinc-rich mineralization, with some associated lead, is present in finely bedded volcaniclastic rocks and chert at the top of the Golden Grove Formation, at the same stratigraphic position as the Scuddles lenses. This is the hangingwall group of Frater (1983), equivalent to the unit he refers to as association IIb. Associated minerals are sphalerite, pyrite, galena, chalcopyrite with minor magnetite and pyrrhotite; there are strong associations of Zn–Cd–Pb–Ag–Sn and Cu–Bi. The main copper-rich lensoid body, however, occurs about 100 m below the top of the Golden Grove unit. It has been outlined over 600 m of strike and is up to 30 m thick with broad concentric ore-mineral zonation. The massive central portion of this lens (association I *of* Frater, 1983) features a magnetite–pyrite–chalcopyrite–pyrrhotite mineralogy, with minor sphalerite, which passes upward and outward into a pyrite–magnetite–sphalerite–chalcopyrite–pyrrhotite association (association IIa *of* Frater, 1983). Within this broad pattern of the main copper-rich lensoid body, individual smaller lenses also show a tendency to zinc enrichment towards the top. Within the copper mineralization there are strong associations of Cu–Ag–Se and Co–As.

The mineralized zones contain minor tetrahedrite, arsenopyrite, pentlandite, valleriite, cubanite, tellurobismuthite, cassiterite and ilmenite. Chlorite is the main gangue mineral with quartz, ankerite, siderite, talc and sericite.

An Upper Gossan Hill zinc-rich prospect has been located in thinly bedded andesitic volcaniclastic rocks and minor cherts of the Scuddles unit about 20 to 30 m above the hangingwall zinc–lead zone.

Figures 44, 45 and 46 show the distribution of the copper-rich lens and the hanging wall zinc–lead zone in relation to the internal stratigraphy of the Golden Grove unit. The main lens is predominantly within subunit 4 intercalated volcaniclastic and rhyodacitic pyroclastic rocks and minor chemical sedimentary rocks. Mineralization in the hangingwall zone is in the form of tabular, conformable bodies. In the main lens the bulk of the mineralization is present as massive tabular or lens-shaped pods which coalesce or interfinger and are subparallel to bedding. Some unconformable zones occur near the base of the main lens.

Chloritization is the most widespread alteration, being present within and surrounding the mineralized zones and extending in some cases hundreds of metres beyond the mineralization. Intense silicification is most common in the footwall zone and also adjacent to massive magnetite and sulfides. Textural evidence suggests that it preceded chloritization. Sericitization is absent in mineralized lenses but is present laterally in the unmineralized host rocks. The top and margins of mineralized zones are carbonatized. Chemical changes associated with the hydrothermal mineralizing processes, proposed by Frater (1983) are shown in Figure 47 (*after* Frater, 1983). The main elements are the Fe–Mg enrichment related to chloritization and the depletion of Na and Ca from the system. Iron–magnesium are depleted in the hangingwall rocks. Some carbonatization and redistribution of Na, K, Ca, Al and Si is also related to the lower greenschist regional metamorphism, which postdates the mineralization.

In the copper zone, Gossan Hill contains an indicated resource of 5.8 Mt at 3.8% Cu. In the zinc zone the indicated resource is 0.6 Mt at 16.9% Zn, 1.8% Pb, 0.5% Cu, 147 g/t Ag and 1.5 g/t Au. The inferred resource is 1.8 Mt at 10.7% Zn, 0.8% Pb, 0.1% Cu, 75 g/t Ag and 0.9 g/t Au. Two other lenses of the zinc-rich mineralization contain, respectively, an indicated resource of 0.25 Mt at 10.9% Zn, 1% Pb, 244 g/t Ag and 1.0 g/t Au and an inferred resource of 0.70 Mt at 13% Zn. The oxidized portion of the zinc zone contains an

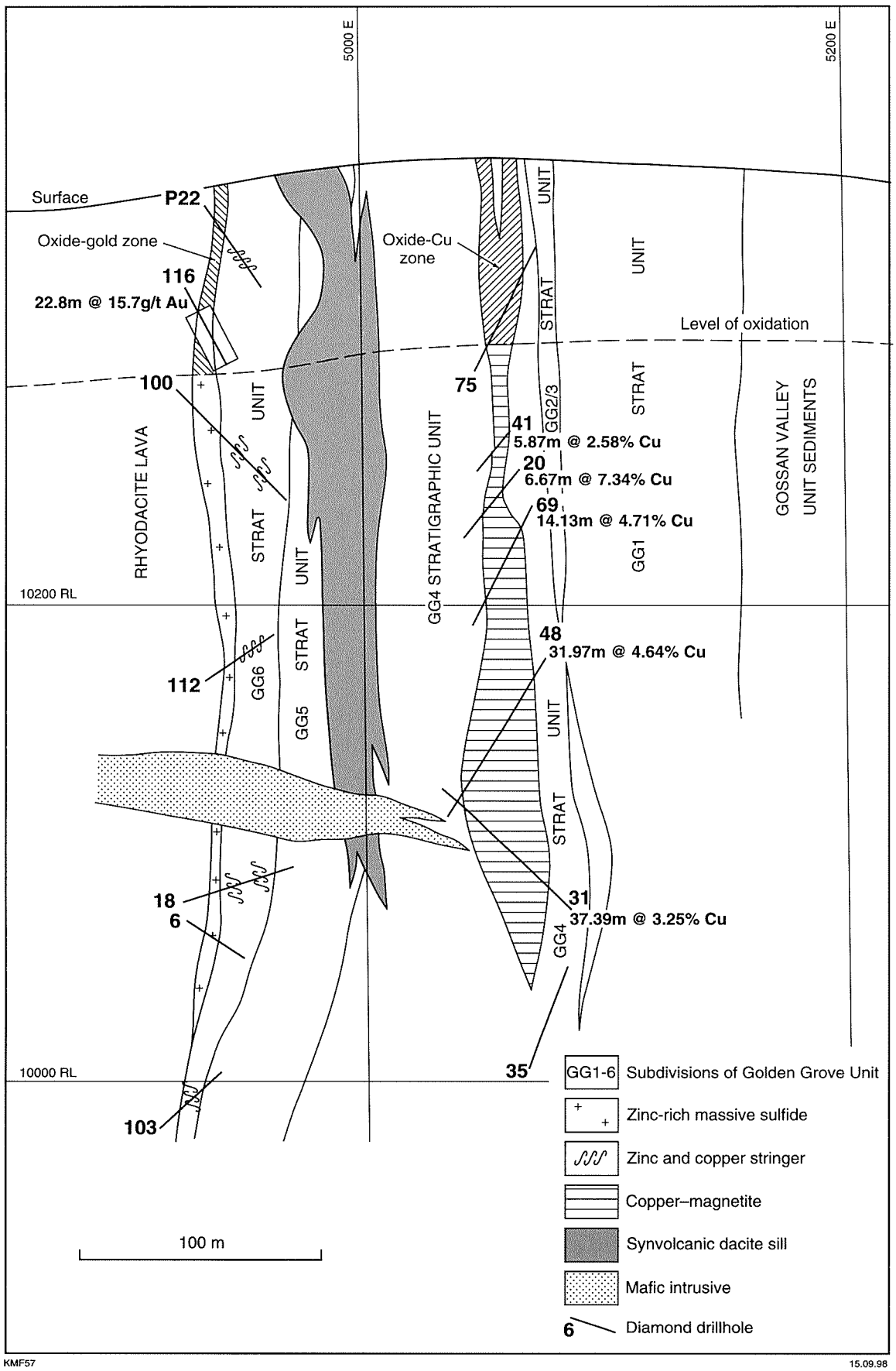


Figure 46. Gossan Hill: schematic cross section (*after* Murchison Zinc)

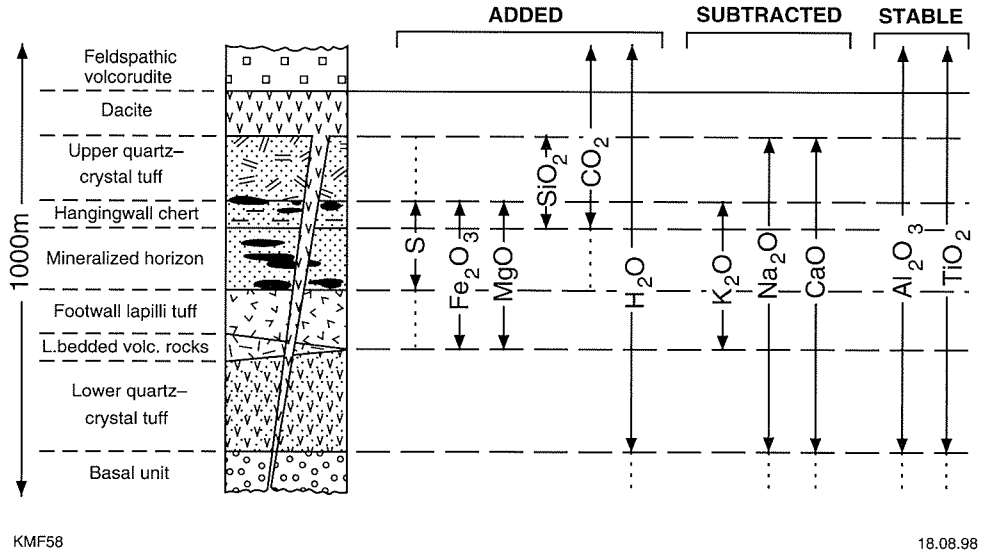


Figure 47. Gossan Hill: major-oxide mobility during mineralization (*after* Frater, 1983)

indicated gold resource of 0.67 Mt at 3.2 g/t Au (Bain and Co., 1994).

In 1993, a decline was proposed by Normandy Poseidon to provide access to the copper lenses for detailed drilling, bulk sampling and metallurgical testwork. This was planned to be completed by early 1995 (Bain and Co, 1994).

References: Frater (1983), Watkins and Hickman (1990), Marston (1979), Ashley et al. (1988), Clifford (1987), Murchison Zinc (1992), Bain and Co. (1994).

Bassendean

Prospect: Cu; Zn; Pb
Location: 28°52'40"S, 117°03'10"E; about 20 km southeast of Scuddles

Sulfide mineralization has been identified in the Golden Grove unit.

References: Ashley et al. (1988).

Cattle Well

Prospect: Cu; Zn; Pb
Location: 28°42'30"S, 116°54'40"E; 5 km northwest of Scuddles

Barren massive sulfides occur at Cattle Well at the top of the Golden Grove unit.

References: Boyd and Frankcombe (1994), Murchison Zinc (1992).

Felix

Prospect: Zn
Location: 28°49'20"S, 117°00'E; 12 km southeast of Scuddles

Stratabound zinc-rich sulfides occur in volcaniclastic rocks in subunit 4 of the Golden Grove unit. A gossan is present at the surface. A drill intersection of 4.5 m at 3% Cu and 22% Zn has been reported by the joint venture partners. Smith and Perdrix (1983) report anomalous Mo, Se and Bi in pisolite sampling at Felix.

References: Smith and Perdrix (1983), Murchison Zinc (1992).

Flying Hi

Prospect: Zn
Location: 28°51'20"S, 117°01'30"E; 15 km southeast of Scuddles

Zinc-rich mineralization occurs at the same stratigraphic level as that at Felix in a small sulfide occurrence.

Reference: Ashley et al. (1988), Murchison Zinc (1992).

Gossan Hill South

Occurrence: Cu; Zn; Pb
Location: 28°47'20"S, 116°58'30"E; 6 km southeast of Scuddles

Sulfide occurrence has been located.

Reference: Ashley et al. (1988).

Gossan Valley

Occurrence: Cu; Zn; Pb
Location: 28°50'S, 117°00'30"E; 14 km southeast of Scuddles

A small base-metal sulfide occurrence has been located.

Reference: Ashley et al. (1988).

Walgardy (Gossan Hill North, Gnows Nest, Lambshaft Well, Wownaminya. Whelock Well)

Prospect: Zn; Pb
Location: Walgardy/Gnows Nest — 28°30'S, 116°50'E Wownaminya/Whelock Well — 118°48'S, 28°28'E

Exploration for repetitions of the Gossan Hill/Scuddles mineralization type has been carried out by a number of companies in the Gabanintha Formation, in the Warriedar Fold Belt north of Golden Grove, from 1971. These companies include Mines Ex (1971–72), Unimin (1973–75), EZ (1976–77), Esso (1982), Aquitaine/A Anglo/Aztec/ Esso/Walgardy/Dalrymple (1974 on).

At Lambshaft Well, Unimin selected exploration targets based on geophysics and gossan sampling, and encountered thin zones of tuff, shale and banded iron-formation containing chalcopyrite, galena and sphalerite in follow up diamond drilling (0.53 m at 4.5% Zn and 0.35 m at 5% Pb and 0.76% Zn).

Exploration by the Walgardy/Dalrymple JV in the Wownaminya and Whelock Well areas, including reappraisal of previous exploration, proved negative. Exploration in the Gnows Nest–Walgardy Well area by the same group located Strongs Gossan over weak sphalerite pyrite mineralization (Dalrymple withdrew in 1991). Twenty-one magnetic targets remain to be tested in this project.

References: Louthean (1992), GSWA-WAMEX - I 2907, I 5607, I 6086.

Meekatharra–Wydgee Greenstone Belt

Double Jay

Prospect: Pb; As; Ag
Location: 26°26'S, 118°36'30"E; 20 km north-northeast of Meekatharra

A number of sulfide gossans strongly anomalous in Pb, As and Ag occur over about 7 km of strike in poorly exposed and deeply weathered Golconda Formation. Individual gossans measure up to 3 m by 600 m. The gossans are in a pyritic black shale and quartz–sericite schist unit 10 to 25 m thick, trending north-northeast within a basalt–komatiite volcanic sequence. Up to 11.6% Pb was obtained in rock chips and a best intersection of 2 m at 2.25% Pb was recorded at 14 m in RC percussion drilling. The pyritic shale was shown to contain minor cerussite and rare galena.

Previous rock-chip sampling by Giralia Resources, who delineated the gossan, gave up to 0.69% Pb and 71 g/t Ag. Rock-chip sampling by MIM (1989–93) delineated a 300 m strike length of greater than 1000 ppm Pb with associated copper (≤1460 ppm), zinc (≤450 ppm), arsenic (≤2.7%) and silver (≤32 g/t). The anomalous drill intersections (>0.5% Pb in two holes) were in weathered slate and considered by MIM to represent preferential mobilization of trace disseminated galena during amphibolite-facies metamorphism.

References: Louthean (1992), GSWA-WAMEX - I 7521.

Burnakura

Prospect: Cu; Zn; Ag
Location: 27°01'10"S, 118°26'30"E; 50 km south of Meekatharra

Since 1974, exploration in north-northeasterly trending mafic and felsic volcanic rocks, chert and clastic metasedimentary rocks of the Windanning Formation in the Burnakura area has included that by Seltrust (1974–76), who encountered anomalous copper, lead, silver, and zinc in seven gossans. Drilling failed to locate significant sulfides and the anomalism was assumed to reflect surface enrichment over black shales. Stratiform sulfides are in two horizons of felsic volcanic rocks, cherts and sedimentary rocks, on the opposite sides of a major north-northeasterly trending syncline. Up to 0.4% Cu, 0.7% Zn and 0.1% Pb were recorded in drill and chip samples. Pyrite, chalcopyrite, sphalerite, malachite and chalcocite were recognized. Esso (1977–78) followed up but the results of an IP survey were negative. Giralia (1983–89) tested gold targets. Rock chips gave low base-metal values.

References: Watkins and Hickman (1990), GSWA-WAMEX - I 940, I 1797.

Chunderloo (Yaloginda)

Mine: Cu
Location: 26°43'30"S, 118°22'50"E; 20 km south of Meekatharra

Stratiform sulfides (malachite, azurite, chrysocolla and cuprite) occur in narrow (≤0.5 m) zones in a northeasterly trending folded and lineated contact zone between amphibolites and intermediate quartz–mica–chlorite–hornblende schists, on the western margin of the northeastern part of the Meekatharra–Wydgee Greenstone Belt. Marston (1979) suggested similarities with the copper-dominant mineralization at Yannery in the west Pilbara, but on a smaller scale.

Exploration was focused on nickel–copper in the early 1970s. WMC (1975–76) found anomalous base-metals at the surface but only pyrite in drilling.

References: Marston (1979), Watkins and Hickman (1990), GSWA-WAMEX - I 640.

Quinns

Prospects: Cu; Zn; Pb
Location: 27°03'30"S, 118°38'30"E; 54 km south-southeast of Meekatharra

Exploration has been carried out since 1976 in complexly folded andesitic, dacitic and felsic volcanic and volcaniclastic rocks (sericitic schists), cherts and banded iron-formations of the Gabanintha and Windanning Formations, overlain by basic sills and the tholeiitic Quinns Basalt. Newmont (1976) found low-grade pyrite, pyrrhotite, and chalcopyrite (2–3% Cu and 0.9% Zn over 0.63 m) beneath gossanous zones thickened in a complex fold hinge.

CRA/Esso (1981 on) have focused on the Quinns sericitic schist and overlying pyritic chert and banded iron-formation for gold and base-metal targets. These units overlie basalts and ultramafics and are exposed in two domes on an easterly trending anticline. Massive gossans, up to 10 m thick and several hundreds of metres strike length, occur at the contact between the pyritic chert and the banded iron-formation. These are associated with intense footwall chloritization, silicification, carbonatization and steatization. Gold is found predominantly in quartz reefs, with the hinge zone between the two domes being most prospective. Base-metal mineralization, comprising pyrite and pyrrhotite with subordinate sphalerite and chalcopyrite, is of volcanogenic origin and occurs below quartz–magnetite banded iron-formation and silica–silicate–carbonate banded iron-formation.

At Laterite Hill an intersection of 10 m at 10% Zn, 629 ppm Pb, 0.17% Cu and 4.9 g/t Ag was obtained in chloritized schist (?felsic volcanic). Subsequent SIROTEM traversing (62 line km) outlined seven conductors between footwall felsic material and banded iron-formation. At the Dalmation prospect, thin continuous semi-massive to massive sulfides occur over 700 m of strike and gave intersections of 1 m at 24.3% Zn, 0.17% Cu, 1.1% Pb and 10.5 g/t Ag, and 3 m at 3.1% Zn, 0.5% Cu, 10 g/t Ag and 578 ppm Pb.

References: Marston (1979), Watkins and Hickman (1990), GSWA-WAMEX - I 937, I 4380, I 7056.

Eelya (Eelya North, Eelya South, Hollandaire)

Prospect: Cu; Zn; Pb
Location: 27°18'20"S, 118°08'30"E; 88 km south-southwest of Meekatharra

Stratiform massive sulfides occur in poorly exposed felsic volcanics and quartz–sericite schist striking east-northeast in a copper-rich gossan 50 m long at Eelya North. Drilling by EZ (1971–83) in the Colonel Gossan intersected up to 1.3 m at 2.4% Cu and 0.22% Zn and 3 m at 2.7% Cu in massive pyrrhotite–pyrite–chalcopyrite. This was considered to be a small steeply plunging body of no economic significance. At Hollandaire an intersection of 17.85 m at 1.5% Cu in massive sulfides, related to a large pipe-like chloritic zone, was downgraded by further drilling. At Eelya South a narrow intersection of 15% pyrite and sphalerite, with minor galena, was obtained in a bedded ash flow, but with no indication of economic deposits.

References: Marston (1979), Watkins and Hickman (1990), GSWA-WAMEX - I 2333.

Wattagee (Gidgee Well, Wattagee Well)

Prospects: Cu; Zn
Location: 27°12'30"S, 117°52'E; 30 km north of Cue

Exploration over a 6 km belt on the east flank of a north-northeasterly trending, isoclinally folded syncline has identified horizons variably rich in copper or zinc, in felsic volcanic and volcanogenic metasedimentary rocks of the Gabanintha Formation. The main companies involved in substantial exploration were Eastmet (1971–72), Esso (1975–81) and Chevron/Aztec (1982–88). Ground and airborne magnetic, IP and EM surveys were followed by extensive gossan and rock-chip sampling, and drilling which included diamond coring.

Sulfide mineralization was identified by Eastmet at A7, A14, Eastmet, Kennecott, Metalsex and Chellews gossans. Copper–zinc mineralization is associated with andesitic porphyry/tuff–shale contacts (Eastmet), shale–tuff intercalations in basalt (A14, Kennecott), and on the margins of gabbro bodies and in fault/shear zones. A close association with graphitic/pyritic shale suggests distal mineralization related to a hiatus in extrusive volcanism (Abitibi style). At Eastmet, mineralization in the tuff–shale unit has given intersections up to 4.6 m at 0.276% Cu and 1.31% Zn. At the Metalsex gossan, mineralization is located in a graphitic shale–tuff horizon (8 m at 1.1% Zn) and in a steeply dipping fault zone in basalt (8 m at 2.6% Zn). Esso, who eventually acquired most of the prospective ground, intersected 3 m of 0.42% Cu, 0.53% Pb, 7.5% Zn and 18 g/t Ag at A14 in the south of the belt during percussion and diamond drill testing over 1.4 km of strike. The stratiform mineralization occurs as pyrrhotite and sphalerite in fine-grained intergrowths with quartz and dolomite on pyrite grain boundaries. Chalcopyrite forms intergrowths in the pyrite. Drilling on geochemical and geophysical anomalies by Aztec/Chevron encountered mostly low-grade copper–zinc mineralization with up to 28 m of 748 ppm Zn. Outokumpu reviewed exploration in the area in 1991.

References: Marston (1979), Watkins and Hickman (1990), GSWA-WAMEX - I 1733, I 1813, I 3608, I 3810, I 5657.

Tuckabianna

Prospect: Cu; Zn
Location: 27°30'50"S, 118°07'E; 26 km east-southeast of Cue

Partially stratiform sulfides that have been partly remobilized (pyrrhotite, sphalerite, chalcopyrite, marcasite and galena) occur in felsic–intermediate volcanogenic metasedimentary rocks (argillaceous unit) of the Gabanintha Formation. In exploration by Pennzoil (1975–76), rock chips collected in the nose of a syncline, showed up to 3.9% Cu, 0.175% Pb, 0.5% Zn and 15 g/t Ag over 2 m. The best diamond-drill intersections were 5.22 m at 1.22% Zn and 2.86 m at 1.37% Cu. The copper is in a stockwork beneath the zinc horizon. Thickness and grades decrease away from the syncline axis and at depth, and follow-up percussion drilling was unsuccessful. CSR (1976–81) tested a prospective horizon beneath banded iron-formation in intermediate volcanics in the Tuckabianna area. Surface and drill geochemistry was weak. Neither pyroclastics, for proximal potential, nor fine-grained cap rocks or chert, to indicate distal mineralization, were found.

References: Watkins and Hickman (1990), GSWA-WAMEX - I 340, I 5983.

Gullewa Greenstone Belt

Whiskey Hills (Edamurta, Whisky Hills, Bunnawarra, Grants)

Prospect: Zn; Cu
Location: 28°34'S, 116°29'E; 30 km southwest of Yalgoo

From 1973, exploration was carried out in the eastern part of the Gullewa Greenstone Belt, within the Gabanintha Formation, following minor copper production from 300 m of pits and shallow opencuts in the 1960s. Unimin/ CRA (1973–78) discovered gossanous/siliceous horizons over a 4 km strike length in garnet–quartz–chlorite schist and lapilli-textured metafelsic rocks of the Whiskey Hills sequence. Two main mineralized horizons separated by an amphibolitic unit were recognized following geochemical and Turair surveys. In the upper horizon, in the zinc–copper-rich Grants Prospect (pyrite, sphalerite, chalcopyrite), 5.5 m of 3.44% Zn and 9.7 m of 1.4% Zn and 0.15% Cu were intersected in diamond drilling. In the lower horizon (also in the Grants Prospect), copper-rich banded iron-formation with semi-massive and disseminated pyrite and chalcopyrite, gave 3.15 m of 3.8% Cu. Samantha (1978–87) concentrated on gold exploration. Follow-up by Dalrymple from 1991 indicates a prospective zone over 3 km of strike. The Grants prospect has potential for a copper–zinc resource below 250 m.

References: Louthean (1992), Marston (1979), Watkins and Hickman (1990), GSWA-WAMEX - I 4550.

Mugga Mugga (Gullewa, Golden Stream, Mugga King, Murdaburia Hill, Murdalyou Range)

Prospects: Zn; Pb; Cu; Ag; Au
Location: Murdalyou Range — 28°45'S, 116°20'E
Mugga Mugga — 28°40'S, 116°15'E
About 60 km southwest of Yalgoo

The Gullewa Greenstone Belt contains a package of mafic–felsic volcanic rocks, exhalative cherts and fine to coarse sedimentary rocks of the Gabanintha Formation folded around a major easterly trending synform. Zones of chlorite and talc–chlorite and chlorite–carbonate alteration occur within the sequence. Base-metal exploration in the southern part of the belt has continued since 1974, following the Gossan Hill discoveries in the geologically similar Warriedar Belt.

Samin (1973–79), in the Mugga Hills and Murdalyou Range, located zones of massive pyrrhotite/pyrite associated with surface ironstones. Base-metal levels were relatively low (maximum 725 ppm Cu, 1850 ppm Pb and 530 ppm Zn in diamond drilling). Aus Anglo/ Aztec/ Esso (1974–82) defined two areas of subeconomic mineralization (Fig. 48).

(a) In the Murdalyou Range a number of stratiform, linear discontinuous lenses were located in chert, in contact with chloritic schist. Maximum diamond-drillhole intersections were 3 m at 2.91% Zn and 1 m at 5.5% Zn.

(b) At Mugga Mugga, near the Mugga King Mine (Fig. 48), a massive-sulfide gossan was located in association with banded iron-formation and chert and amphibolite over 3.5 km of strike. Diamond drilling indicated two zones of massive sulfides, an upper zone 17 m thick and a lower zone 5 m thick. The best intersection was 5 m at 1.15% Pb, 0.59% Zn and 44.5 g/t Ag. The close association with mafic volcanics (amphibolite) in this prospect is not typical of Archaean volcanogenic mineralization. Other explorers in this area included CRA (1974–75), Esso (1978–81) and Amax (1980–85). At Murdaburia Hill (Fig. 48), Amax explored a gossan in metamorphosed chemical and pelitic sedimentary rocks associated with ultramafic and felsic volcanic material. Rock chips showed up to 7.8% Cu and 2% Pb; however, drilling downgraded the prospect. Sons of Gwalia, and subsequently Gullewa Gold, are following up these results and hold a substantial portion of the Gullewa Greenstone Belt under tenement.

Reference: GSWA-WAMEX - I 522, I 1228, I 1721, I 1740, I 2718.

Prospects in other greenstone belts

Dalgaranga (Rosary Well, Lasoda, Gum Well, Strong Hill)

Prospect: Pb; Zn; Cu
Location: 27°45'S, 117°13'E; 84 km southwest of Cue

Exploration has been carried out by many companies in felsic volcaniclastic rocks of the Gabanintha and Dalgaranga Formations in the Dalgaranga Greenstone Belt. CEC (1973–80) identified base metals in limited outcrop at Seivwright Gossan, recording 0.3% Cu, 3.00% Pb and 0.062% Zn on a basalt–rhyolite contact. BHP (1969–72) detected up to 1% Zn and up to 0.5% Cu in diamond drilling in graphitic black shales. CRA has bteen exploring in the area since 1982, following up the results of CEC. CRA has found encouragement in the distribution of deep surficial cover and has responded with extensive use of SIROTEM and INPUT surveys. Outokumpu, in joint venture with CRA, is also presently active in the area.

Reference: GSWA-WAMEX - I 382, I 1368, I 3922.

Mount Mulcahy

Deposit: Cu; Zn; Pb; Ag
Location: 27°03'30"S, 117°41'59"E; 45 km northwest of Cue

Several lenses of polymetallic, stratiform sulfides lie in thin units of chert, shale, phyllite and tuff in tholeiitic volcanics of the Mindoola Formation in the Weld Range Greenstone Belt. Two gossans, 750 m apart, are located on the southern limb of an east-plunging, boat-shaped syncline. They are limonitic and contain chrysocolla. The associated lenses lie close to the contact with overlying basalt and plunge to the north-northwest.

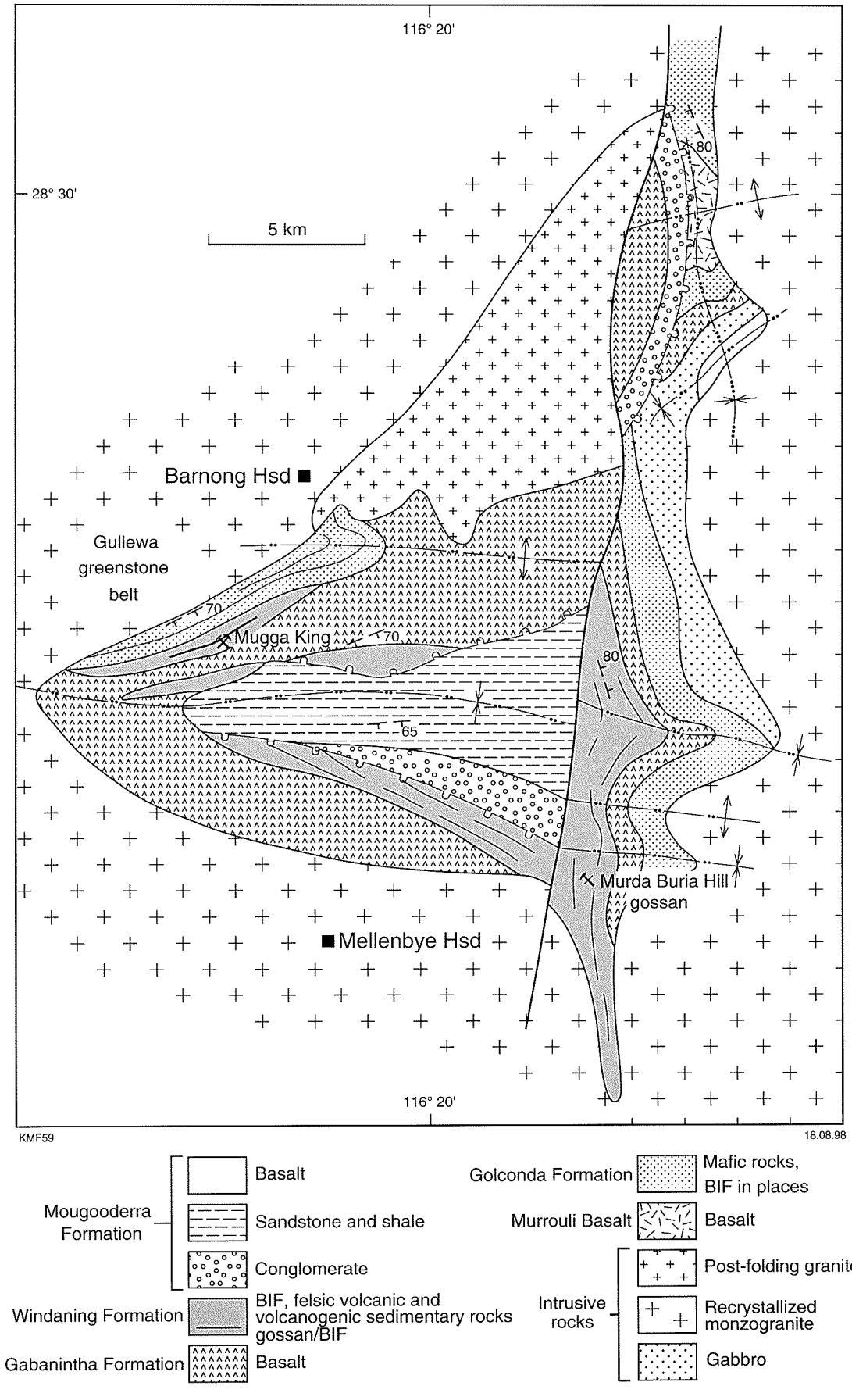


Figure 48. Mugga Mugga–Gullewa: geology and base-metal prospects (*modified after* Watkins and Hickman, 1990)

The deposit was discovered during exploration by Union Oil/Homestake/Hanna (1969–72) along a 9 km mineralized contact. Drilling of the eastern body encountered 65–70% pyrrhotite with chalcopyrite, sphalerite and minor galena and pyrite. The upper part of the body, at the basalt contact, is sphalerite-rich and disseminated and veinlet-style, pyrite-rich sulfides lie beneath. This drilling produced a best intersection of 8.8 m at 7.9% Cu, 6.8% Zn, 0.5% Pb and 58 g/t Ag and indicated reserves of 250 000 t at 3.77% Cu and 2.75% Zn. WMC (1972–74) tested possible extensions of the deposit in the sedimentary sequence and found only minor sulfides. Pegmin/Seltrust (1981–86) also concentrated relatively shallow percussion drilling on the metasedimentary rocks beneath the contact zone and away from the main deposit. They calculated an indicated resource of merely 0.427 Mt at 2.8% Cu, 1.9% Zn, 19 g/t Ag and 0.13% Au. Southwest Goldmines/BHP/West Australian Metals (1986–91) reviewed all data and suggested that deeper drilling is required, particularly along the extensions of the sediment–basalt contact. They calculated a measured resource of 0.133 Mt at 2.9% Zn, 4.35% Cu, 33.7 g/t Ag and 0.43% Au.

References: Marston (1979), Watkins and Hickman (1990), GSWA-WAMEX – I 1454, I 2871, I 5834.

Twin Peaks (Murgoo, Breakaway Hills, Southern Flyer, Tranquility Heights)

Abandoned mine: Zn; Pb; Ag
Location: 27°22'30"S, 115°58'50"E; 185 km west of Cue

Sphalerite mineralization expressed as gossans is found in cherty horizons within felsic tuff in highly deformed, amphibolite-grade volcaniclastic rocks of the Gabanintha Formation in the Twin Peaks Greenstone Belt. Copper and cupreous ore, to a total of 8.47 t of contained copper, were mined from the oxidized zone in the periods 1906–1908, 1949, and 1951–1955.

Kennecott (1966) found only minor chalcopyrite in poorly exposed pyroxenite. Amoco/Cyprus (1978–88) located three areas of surface anomalism on the eastern side of the greenstone belt, with a best bottom-hole RAB result of 2 m at 0.71% Cu, 0.78% Zn, 0.76% Pb and 8.5 g/t Ag. Diamond drilling intersected low-grade sphalerite, pyrrhotite and chalcopyrite giving 0.6 m at 0.1% Cu, 18.01% Zn, 10.65% Pb, and 113 g/t Ag (Breakaway Hills). Both stratiform and feeder-vein mineralization types were recognized showing intense silicification, chloritization and epidotization. At Tranquility Heights a 28 m-thick mineralized zone was intersected giving 1 m at 1.65% Zn, 0.19% Pb and 3 g/t Ag. Southern Flyer is copper-rich. Since 1988 a joint venture between Poseidon and Jilbadgi Gold has covered much of the belt and found four new conductors in EM surveys in the northern part of the belt.

References: Marston (1979), Metals Gazette 3/90, GSWA-WAMEX - I 69A, I 2276, I 3576.

Tallering (Carlinga Well)

Prospect: Au; Pb; Cu; Zn
Location: 28°01'S, 115°53'E; 15 km west-southwest of Yuin Homestead

A broad zone of altered quartz-rich schists, 300 m by 2.8 km, in the Windanning Formation of the Tallering Greenstone Belt hosts widespread disseminated pyrite. Three phases of deformation have obliterated sedimentary and volcanic features in what are interpreted as shallow-water, distal rhyodacitic tuffs, flows and sedimentary rocks. Gossans in two horizons were drilled by EZ (1973–80) but results did not improve on rock-chip levels; 0.148% Cu, 1.6% Pb, 0.625% Zn. Only zinc values held up in cuttings. Follow-up work by Preussag (1981–85) gave weak results with up to 0.94% Cu, 0.8% Pb and 0.56% Zn in surface samples (Watkins and Nightjar prospects). WMC (1981–85) obtained a drill intersection of 3 m at 4.4% Cu beneath old gold workings at Carlinga Well; however, results of geophysical surveys (including SIROTEM, resistivity and ground magnetics) and other drilling were discouraging. Gold and base-metal potential is being explored presently by CRA/Roebuck (1985 on) and Callina/Pioneer (1986 on) in the same area.

Reference: GSWA-WAMEX - I 1456, I 2138, I 2515.

Sanford (Barloweerie)

Prospect: Zn; Pb; Ag
Location: 27°10'30"S, 116°18'E; 170 km northeast of Mullewa

Gossanous zones in felsic tuffs and amphibolites (?after basalt) were located by WMC (1974–75) and further tested in diamond drilling by Haoma/Mount Martin (1983–88) in the Barloweerie Greenstone Belt. The best intersection was 1 m at 600g/t Ag, 0.18% Cu, 3.1% Pb, 9.5% Zn.

Reference: GSWA-WAMEX - I 466, I 5222.

Perenjori (Ninghanboun)

Prospect: Zn; Pb; Cu
Location: 29°08'S, 116°28'30"E; 37 km north-northeast of Perenjori

Gold and base-metal exploration is current in a metamorphosed sequence of felsic, intermediate and mafic volcanic rocks, sedimentary rocks and banded iron-formation of the Windanning Formation in the Ninghanboun Hill area of the Koolanooka Greenstone Belt. Sipa–Ashling (1988 on) have recognized both the similarity and proximity to the Golden Grove–Scuddles environment in this area. Base-metal and gold anomalism was defined in soil geochemistry over the felsic and intermediate volcanic rocks. Maniws gossan, discovered in 1991, is low in base metals but has gold potential in relation to an RC intersection of 2 m at 11 g/t Au. The Stephen prospect, discovered in 1992, is a gossan zone representing oxidized, massive, banded and breccia-fill sulfides over 1.8 km of strike. The best drillhole intersections to date are 5 m at 1.9% Cu and 1 m at 11.3%

Zn and 4.1% Pb followed by 1 m at 3.6% Zn and 1.2% Pb. A third target, Koens gossan, is low in base metals.

References: Louthean (1992), Mining Journal 24/7/92, Metals Gazette 2/92, West Australian 2/2/93.

Wongan Hills (Yerecoin)

Prospect: Cu
Location: 30°55'19"S, 116°38'25"E; 6.1 km west-southwest of Wongan Hills

Base-metal exploration has taken place in amphibolite-grade mafic and felsic metavolcanic and sedimentary rocks at the southern end of the Wongan Hills Range, in the Wongan Hills Greenstone Belt. Otter (1975–76) located a 350 m, north-northwest trending limonitic gossan ridge in ferruginous garnet–mica schist and quartzite. Drilling showed no persistence to depth but intersected a separate mineralized zone with up to 1 m at 1.75% Cu. Below 120 m the mineralization consists of veinlets and disseminations of chalcopyrite and magnetite with minor arsenopyrite, pyrite, cubanite and marcasite in quartz–biotite–muscovite–chlorite–magnetite(–fayalite–grunerite) schist.

Comprehensive follow-up exploration by Aquitaine/Billiton/BHP (1975–91) tested the full extent of the greenstone belt using modern geochemical and geophysical techniques and testing prospects to diamond-drilling level. They postulated that this belt was a southern extension of the Warriedar Belt. In the Ninan area, in the southern part of the belt, they outlined coincident gold and copper anomalism with displaced lead, zinc and silver anomalism at Bald Hill, suggesting a volcanogenic exhalative-vent system. The copper mineralization at Ninan occurs in semi-massive magnetite chlorite rocks in the core of a faulted, north-northwesterly plunging antiform. The mineralized horizon was traced over 4.5 km in magnetic surveys. The best diamond-drill intersection was 6 m at 1.3% Cu. At Bald Hill, about 1 km northeast of Ninan, gossans are in quartz–mica schists close to banded iron-formations and a mafic contact. Rock chips showed up to 940 ppm Pb and 2380 ppm Zn, with associated anomalies for As, Bi, Ba and P_2O_5; levels in drilling were weaker.

References: Marston (1979), GSWA-WAMEX - I 2555, I 5414.

Narndee (Quandong Well, Twin Tanks, Homestead, Yalanga Bore)

Prospect: Cu; Zn
Location: 28°56'S, 118°11'E; 65 km southwest of Youanmi

A sequence of felsic and mafic metavolcanics and sediments of the Windanning Formation contains stratiform sulfides in a small north-striking belt east and northeast of the Narndee layered mafic–ultramafic complex (Fig. 49). The mineralization is hosted by felsic and metasedimentary (chert, banded iron-formation) units. Esso/Freeport/Inco/ Westralian Nickel (1971–82) tested the Twin Tanks gossanous chert, initially located by Inco in 1971 (Ruddock, I., 1995, pers. comm.), which is underlain by chloritized, and intensely sericitized felsic and volcaniclastic rocks. They located sulfide mineralization with minor zinc (<1%). BHP (1973–4) drilled quartzitic banded iron-formation northwest of Quandong Well and intersected 2 m at 2.65% Cu but with low zinc. Westfield/Whim Creek (1972–77) obtained 7.3% Cu and 0.125% Zn in rock chips. Newmont/BHP (1976–78) intersected only low-grade copper at Quandong Well and also explored the North Homestead gossan to shallow drilling level. Duval (1983–84), drilling at Yalanga Bore in metasedimentary rocks and tuffs intruded by dolerite, intersected semi-massive sulfides with up to 1.75% Zn in a possible porphyry skarn.

AAR/Billiton/Normandy Poseidon (1986–94) re-assessed the area and carried out grass roots exploration including rock-chip sampling and EM surveys, RAB and percussion drilling. In the North Homestead gossan area drilling intersected stringer to semi-massive pyrite and pyrrhotite with minor copper and zinc in mafic volcanics and chert. Drilling of a twin peak EM conductor, representing massive sulfides, chloritization and silicification in felsic volcanics and exhalites over about 1 km of strike, gave a best intersection of 8 m at 1.95% Zn, 0.4% Pb and 4.2 g/t Ag. Potential remains untested along strike and downdip. At Twin Tanks a distinctive aeromagnetic horizon related to the prospect was traced along strike and is associated with a chalcophile geochemical trend an order of magnitude lower than that at Golden Grove, beneath 30 to 40 m of cover. Felsic lavas 5 km north of Twin Tanks show minor sericite–talc alteration. Sampling of the gossanous chert, however, gave maxima of only 0.368% Cu (in chert) and 680 ppm Zn (in tuffs), with negligible lead, although the geochemical signature did suggest a hydrothermal volcanogenic origin for the weak mineralization. The project was relinquished in 1994 because of the generally poor geochemical results and somewhat discouraging geological factors.

References: Marston (1979), Metals Gazette 8/88, Louthean (1993), GSWA-WAMEX - I 1242, I 1348, I 1457, I 1735, I 2722, I 7486.

Southern Cross Province

Freddie Well

Prospects: Zn; Cu
Location: 28°45'S, 118°40'50"E; 20 km southwest of Youanmi

Stratiform sulfide lenses are present over 500 m along strike in quartz–sericite schist (felsic metavolcanic and volcaniclastic rocks) between a layered mafic intrusion and granitoids, within the West Youanmi Greenstone Belt (Fig. 50). Thin horizons of quartz–sulfide rock ('Freddite') are interpreted as metamorphosed banded iron-formation. The sulfides comprise sphalerite, pyrrhotite, cobalt-rich pyrite and chalcopyrite with magnetite. Sphalerite in some lenses reaches 50%.

Conwest/CRA/GMA have explored in the area since 1970. Pre-1980 diamond drilling gave intersections up to

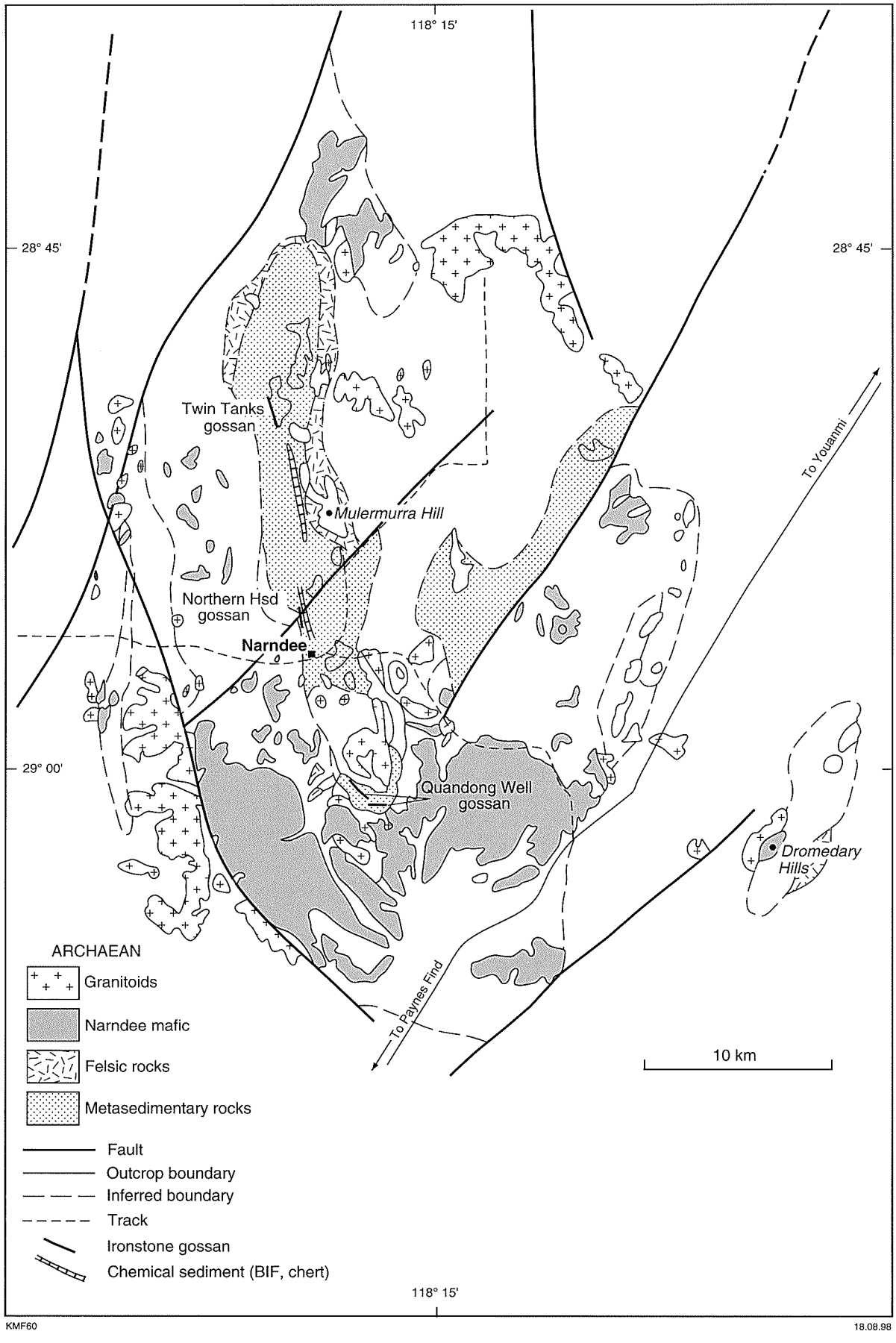


Figure 49. Narndee area: geology and base-metal prospects (*after* Billiton)

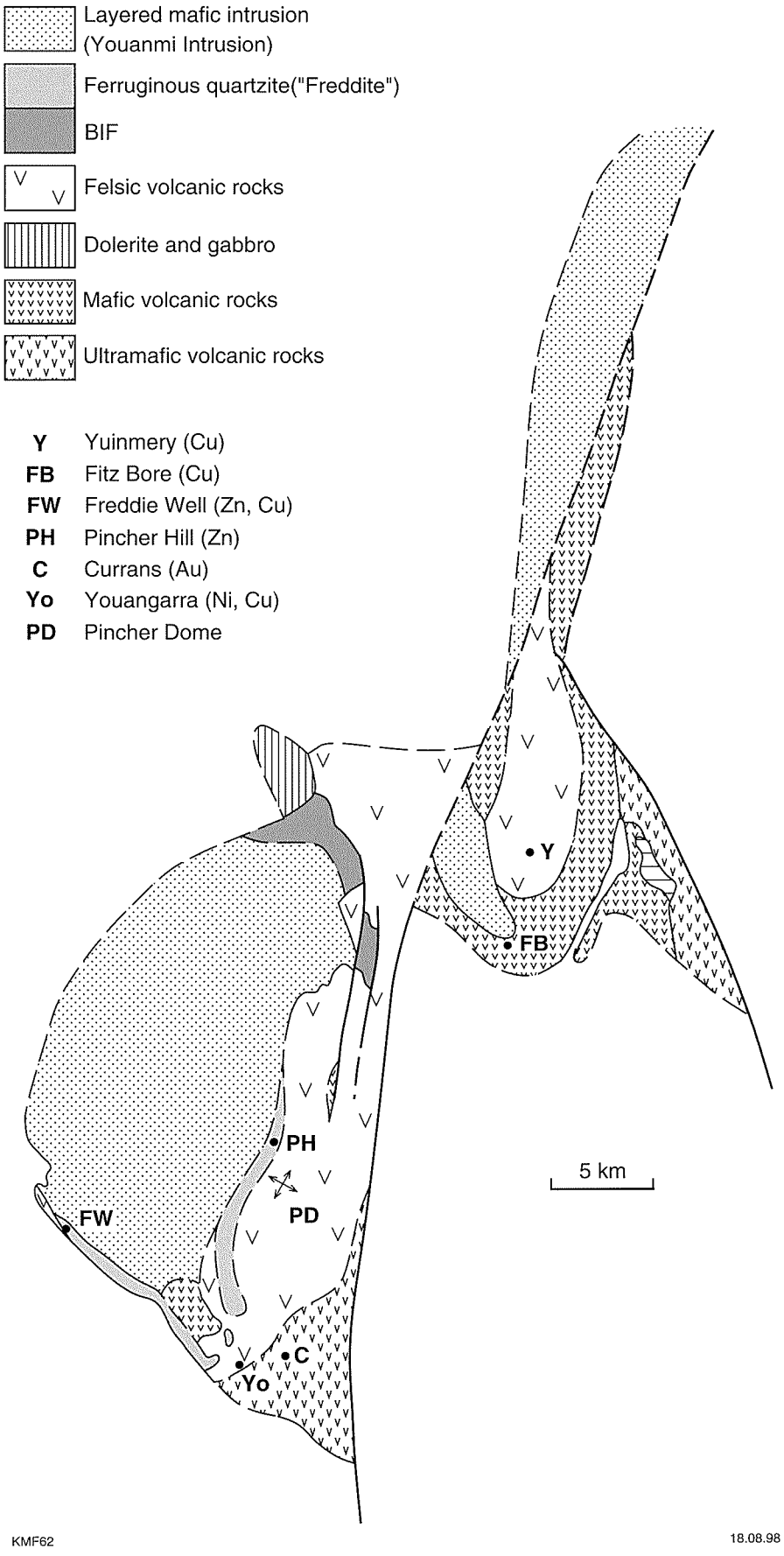


Figure 50. Youanmi greenstone belt: geology and base-metal prospects

6.4 m of 22.5% Zn and 0.66% Cu and led to the establishment of an inferred resource of 0.5 Mt of 10% Zn and 0.2% Cu. Later drilling and extensive surface exploration, '. . . has seriously downgraded the potential for a major orebody . . .' (I 3406). Later exploration on a possible strike equivalent of the Freddie Well prospect, at Shirley Bore, found no massive sulfides. GMA planned further work on Freddie Well and Pincher Well in 1994. Esso (1982–84) attempted to repeat the result of Conwest's best intersection (above). The hole, 15 m away, failed to intersect mineralization, being drilled entirely in gabbro/dolerite. Further exploration on strike from the Freddie Well prospect, to the southeast at Cooliboo Bore, located disseminated sulfide, at 1–3% and locally up to 10% in drilling EM anomalies. The sulfides were predominantly pyrite and pyrrhotite, but with some chalcopyrite.

References: Marston (1979), Stewart et al. (1983), GSWA-WAMEX - I 2285, I 3406, 3891, 6927.

Pincher Well (Pincher Hill)

Prospect/Occurrence: Zn; (Au)
Location: 29°43'S, 118°47'E; 15 km south-southwest of Youanmi

Stratiform sulfides occur in hydrothermally altered andesitic–dacitic flows, tuffs and minor banded iron-formation, chert, freddite (silica–magnetite banded iron-formation containing gedrite–grunerite–chlorite–iron sulfides with sphalerite and pyrite) and volcanogenic argillite of the West Youanmi Greenstone Belt. The sulfidic chert is draped in annular fashion around the predominantly felsic Pincher Dome (Fig. 50). The sulfides themselves are concentrated in small-scale drag folds and shear zones. WMC (1971–73) followed soil and chip sampling with percussion drilling of gossans. The best intersections from separate holes are 1.57 m at 13.8% Zn, 3.95 m at 1.93% Zn and 2.96 m at 7.15% Zn. Newmont/BHP/Eastmet (1977 on) have continued exploration in this area to diamond-drilling level. Eastmet (now GMA) plans further exploration on this prospect in 1994. An inferred resource for the prospect of about 20 Mt at 2% Zn has recently been quoted (Minerals Gazette 2/94).

References: Louthean (1994), Stewart et al. (1983), GSWA-WAMEX - I 2102.

Yuinmery (Smith Well, Fitz Bore)

Prospects: Cu; Zn
Location: 28°35'S, 118°54'E; 8 km east-northeast of Youanmi

Stratiform sulfides are found in metachert, banded iron-formation and andesitic–rhyodacitic volcaniclastic rocks overlying tholeiitic basalt in a major northerly plunging synform within the East Youanmi Greenstone Belt (Fig. 24). The Freddie Well deposit lies 20 km along strike to the southwest. Mineralization is mostly disseminated but with some thin massive zones. Esso (1981–84) reported pyritic gossan with traces of chalcopyrite and sphalerite and maximum levels of 0.81% Cu and 0.205% Zn. WMC (1969–76) intersected up to 1.3 m of 3.5% Cu and 0.91% Zn. Arboyne/Meekal/RGC (1986 on) are currently exploring in the Yuinmery area.

References: Marston (1979), GSWA-WAMEX - I 2286, I 2348.

Montague Range (Mount Townsend, Bevan, Eds Bore, Neds Bore)

Prospects: Zn; Cu
Location: 27°16'45"S, 119°31'30"E; 36 km southeast of Youno Downs

Since 1968, exploration has been carried out by a number of companies in the upper felsic volcano-sedimentary sequence on the eastern limb of the synformal Gum Well Greenstone Belt. INCO (1968–75) recognized a base-metal anomalous black shale–chert unit which may be traceable over 75 km of the belt. Sulfidic, graphitic metapelites were intersected below gossans 300 m north of Eds Bore. The best percussion hole gave 5.3 m at 2.66% Zn and 3.81 m at 3.11% Zn. Diamond drilling gave up to 3 m at 3.65% Zn and 0.4% Cu in narrow bands of pyrrhotite, sphalerite, chalcopyrite mineralization. Amax/Amoco (1969–72) explored the area, mainly for nickel–copper targets, and located low-level copper gossans in the Mount Townsend–Mount Marion area of the Montague Range. A chert–gabbro contact gave up to 0.313% Zn. CRA (1982–90) identified anomalism over 20 km of strike. Aerial EM and follow-up soil and RAB geochemistry outlined two targets, Neds Bore and Bevan. At Bevan, RC drilling encountered up to 6 m at 7.49% Cu and 1 m at 5.74% Zn in graphitic metasedimentary material. Follow-up diamond drilling at greater depth intersected only minor base-metal sulfides with up 0.23% Cu and 0.92% Zn. Strike extensions were also tested to little effect. Percussion drilling at Neds Bore gave a best intersection of 28 m at 0.29% Zn, and a diamond hole returned 61 m at 0.35% Zn. The area was subsequently surrendered. Neds Bore prospect is within tenements presently held by Dalrymple/Metana/Pancon (1985 on) while the Bevan prospect is held by CRA/Arimco/Polaris Pacific (1983 on).

Reference: GSWA-WAMEX - I 564, I 572, I 4682.

West River (Last Venture, Copper King)

Abandoned mines and prospects: Cu; Zn; Ag
Location: 33°47'S, 119°53'E; 34 km southwest of Ravensthorpe

Exploration for base metals in a volcano-sedimentary succession (of mid-amphibolite grade) in the Ravensthorpe Greenstone Belt identified stratiform sulfide mineralization occurring in metavolcanic rocks at or near mafic–felsic contacts, but which may also be remobilized in quartz veins. The Last Venture copper mine contains stratiform massive sphalerite in thin lenses and pyrite–chalcopyrite quartz veins in cordierite–anthophyllite–almandine–quartz–feldspar–biotite schist (derived from tuffaceous sediment). Drilling by CRA/Carr Boyd/NGM in 1975 gave an intersection of 1.63 m at 2.43% Cu, 6.68% Zn and 31.7 g/t Ag. The Copper King mine is 7.5 km south of Last Venture and consists of quartz veins,

containing sphalerite aggregates and disseminated pyrite–chalcopyrite, in quartz–feldspar–biotite schist. Channel sampling by CRA and partners gave 1.3 m of 0.73% Cu and 3.05% Zn.

Pancontinental (1990–92) examined the mafic–felsic sequence over a 12 km strike length and found it to be volcanic-dominated in the lower part and sediment-dominated in the upper part (Fig. 51). They found the cordierite–anthophyllite-bearing horizon to be host to, or adjacent to, mineralization at both the Last Venture and Copper King mines. They identified two horizons of this iron–magnesium-enriched and sodium–calcium-depleted lithology which they consider to represent sea-floor tuff with potential for VMS deposits along strike. Stratigraphically conformable alteration along 6 km of strike was interpreted as sea-floor alteration. Along strike to the north, the upper horizon showed a trend from copper to zinc enrichment, possibly indicating more distal settings related to an exhalative system to the south. Despite their favourable interpretation of the setting, only limited reconnaissance was carried out.

References: Marston (1979), GSWA-WAMEX - I 1615, I 6420.

Eastern Goldfields Province

Teutonic Bore

Abandoned mine: Zn; Cu; Ag; Pb
Location: 28°24'50"S, 121°08'30"E; 55 km north-northwest of Leonora

The Teutonic Bore deposit is a large sulfide lens within a sequence of submarine tholeiitic–komatiitic and felsic metavolcanic rocks, tuff and agglomerate intruded by biotite granitoid. The deposit lies on the western limb of a south-plunging anticline, and comprises a main stratiform lens and an adjoining, basal 'stringer' vein stockwork in quartz siderite, ankerite veins (Fig. 52). The conformable lens, which is 320 m long by 30 m thick, pinches out at about 200 m. Copper is dominant in the basal stockwork and at the top of the stratiform lens, with zinc (and lead) stronger in the core and at the margins. The main ore minerals in the lens are banded pyrite and sphalerite with irregular concentrations of chalcopyrite and galena and minor arsenopyrite, tetrahedrite, pyrrhotite, cosalite, bismuthinite, stannite, aikinite and famutinite. Before mining, the stratiform zone contained 1.4 Mt of ore grading 4.16% Cu, 16.4% Zn, 1.22% Pb and 203 g/t Ag. The stringer zone characterized by pyrite, sphalerite, chalcopyrite veins and disseminated sulfides, contained a further 0.75 Mt at 2.38% Cu, 1.92% Zn and 52 g/t Ag. The deposit is oxidized to 90 m, with a strongly leached oxide profile to 85 m overlying a thin zone of supergene chalcocite enrichment (Nickel, 1983; Greig, 1984).

The deposit lies between 0 and 150 m above a contact between a suite of tholeiitic basalt and an underlying felsic sequence (Hallberg and Thompson, 1985). The hanging-wall is in tholeiitic basalt–dolerite whereas the footwall is in chert, argillite and black shale, and a basaltic breccia of at least partially hydrothermal origin. Much of the mineralization is within the sedimentary unit, which thickens from 3 to 20 m in the deposit. Footwall alteration is characterized by chlorite, quartz, siderite, ankerite, dolomite, sericite and chloritoid, representing the addition of copper, zinc, lead, silver, tin, iron, magnesium, potassium, barium and fluorine and the depletion of calcium, sodium and strontium. The stringer zone is characterized by silica, chloritoid and paragonite alteration.

Evidence of turbidity currents and synsedimentary deformation (Barley, 1992) is consistent with deep-water deposition. Textural and structural evidence suggests that active growth faults controlled the deposition of felsic epiclastic sediments and the overlying basalt brought about the formation of sea-floor depressions and provided conduits for ascending hydrothermal solutions. The solutions seem to have spread laterally within the host sequence as well as exhaling onto the sea floor during a break in volcanism. Hallberg and Thompson (1985) consider the deposit to have formed in an extensional tectonic regime.

Gossanous stringer mineralization was discovered by CEC in 1974 as a result of mapping and gossan sampling within the felsic sequence. Australian Selection (Seltrust) joined CEC in a joint venture from 1976 and discovered the massive gossan. Following the commencement of diamond drilling in September 1976, pre-development reserves were proved up in six months. Openpit mining began in 1980 and underground mining in 1982. Mining was completed by October 1984. Seltrust (BP Minerals) were bought out in 1990 but MIM (CEC) has continued exploration in the area. Chevron (1983–87) explored for extensions of Teutonic Bore in the Wilsons Creek Well and Cutmore Well areas and obtained a maximum of only 0.653% Zn in samples.

References: Marston (1979), Davies and Blockley (1990), Greig (1984), Hallberg and Thompson (1985), Barley (1992), Barley et al. (1992a), GSWA-WAMEX-I 4029.

Wendys Bore

Prospect: Zn; Pb; Ag
Location: 28°28'50"S, 121°10'E; 26 km north of Tarmoola Homestead

Exploration by BP/Chevron/Walgardy took place in the extension of the Teutonic Bore stratigraphy to the south of Teutonic Bore, but 100m lower in the sequence, in an area previously explored by Esso and Aquitaine. Units strike northerly and dip 70° west. Sphalerite–pyrite mineralization is hosted in a quartz–sericite–chlorite–carbonate rock (altered rhyolite) beneath a chert and graphitic shale unit that lies between mafic volcanic rocks and underlying rhyolites. Massive pyrite is located in the chert. The best intersections in two diamond drillholes were 1.3 m at 2.6% Zn and 1.5 m at 1.8% Zn. A deeper diamond hole intersected two zones: 1 m at 2.9% Zn, 1.5% Pb, 55 g/t Ag and 5.9 m at 2.2% Zn, 0.4% Pb and 58 g/t Ag. This may represent a discrete body related to a minor vent. Further drilling failed to extend the mineralized zone.

References: GSWA-WAMEX - I 3273, I 5832.

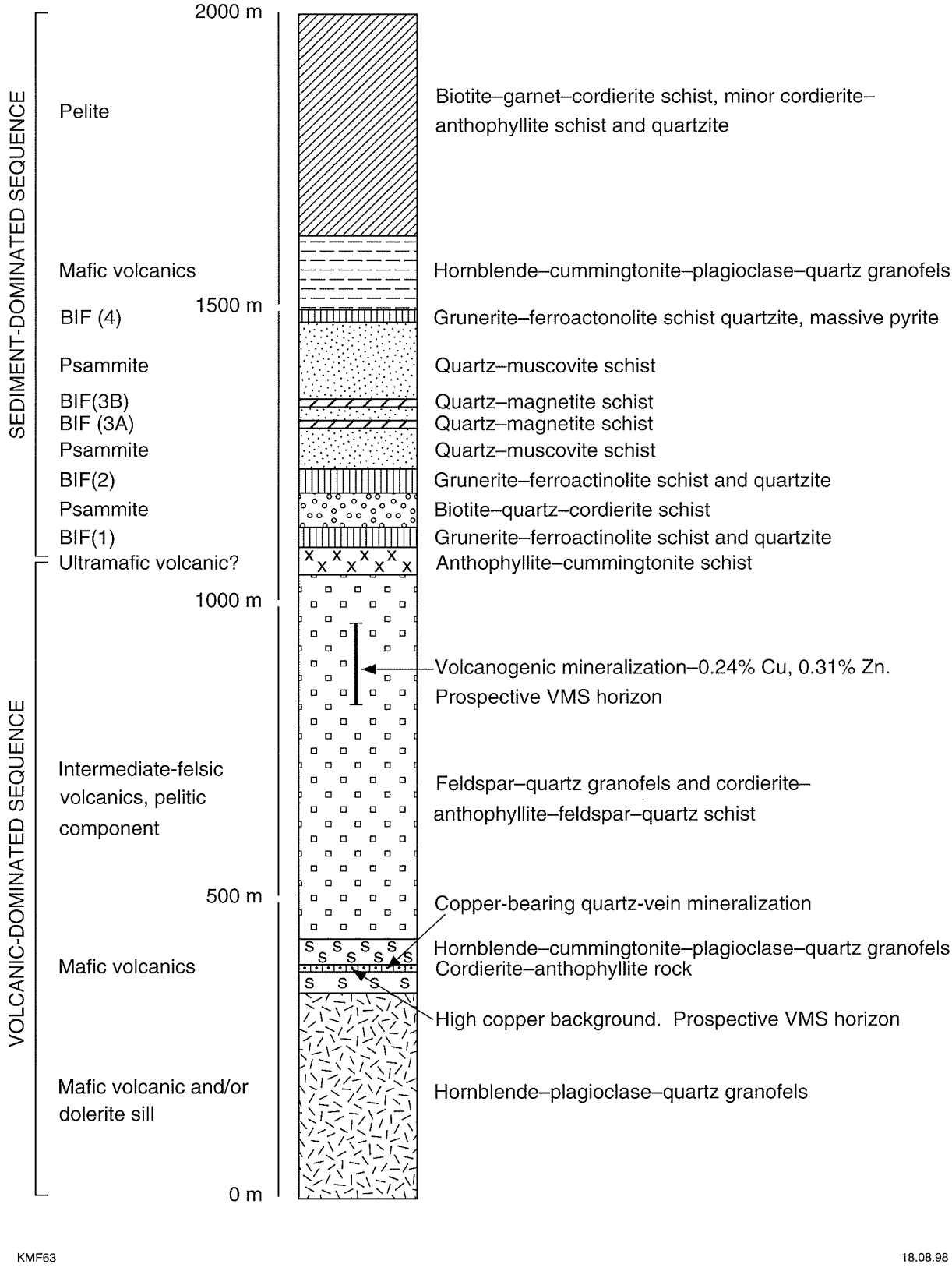


Figure 51. West River: volcano-sedimentary succession (*after* Pancontinental Mining Ltd)

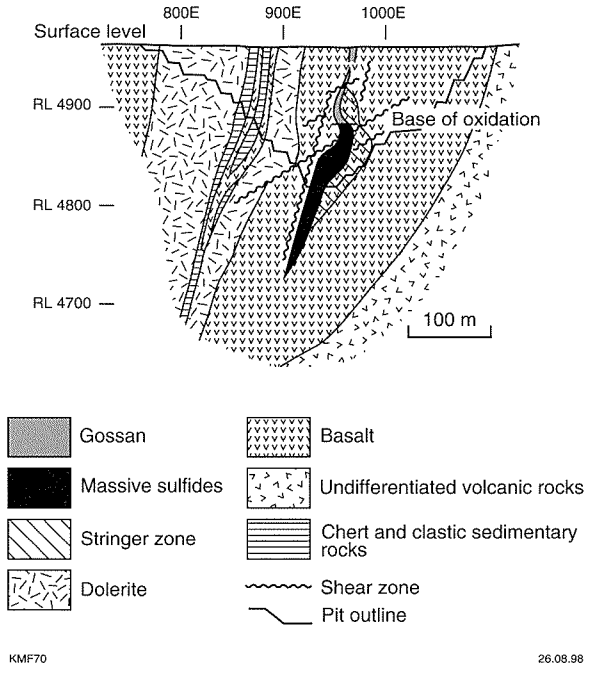


Figure 52. Teutonic Bore: schematic cross section (*from* Barley, 1992 *modified after* Greig, 1984)

Doyle Well

Prospect: Zn; Cu
Location: 28°37'30"S, 120°52'30"E; 9 km northeast of Sturt Meadows Homestead

Exploration by Mines Administration (1969–73) for nickel–copper targets on the western margin of the Mount Clifford Greenstone Belt located pyrite, pyrrhotite and traces of chalcopyrite and sphalerite in a zone of metasedimentary rocks about 60 m wide, between a basic to intermediate volcanic sequence and an ultrabasic complex. The sedimentary rocks consist of carbonaceous shales and interbedded siliceous rocks interpreted as metagreywacke. Several chert bands are present near the top of the sedimentary unit. Diamond drilling of geophysical and geochemical anomalies intersected stringer sulfides within the carbonaceous argillite beneath serpentinite and underlain by basic to ?intermediate volcanic rocks. Up to 1.52 m at 1.71% Zn and 0.5 m at 2.2% Zn were intersected in two holes. These sections were considered to represent originally stratabound mineralization which had been remobilized.

Reference: GSWA-WAMEX - I 2647.

Nambi (Mount Zephyr)

Occurrence/prospect: Zn; Ag
Location: 28°24'S, 121°47'30"E; 88 km northeast of Leonora

During exploration for VMS copper–zinc by Esso (1977–82) in the Margaret Greenstone Belt, soil and rock-chip sampling encountered lead–zinc anomalism in a unit of chloritized, sericitized and pyritized silicic tuff 50 m wide within an upper dacitic volcano-sedimentary sequence overlying mafic volcanic rocks. The succession strikes northeast, dips to the east and has been metamorphosed to lower amphibolite facies. The gossanous tuff unit was traced over 1.2 km of strike. Diamond drilling beneath previous percussion holes intersected up to 12 m of 1.2% Zn, 0.24% Pb and 16 g/t Ag. Further drilling failed to extend the mineralization, and this was partially due to stoping out of the target horizon to the west by granite.

Reference: GSWA-WAMEX - I 2456.

Anaconda (Eulaminna, Mount Malcolm)

Deposit/abandoned mine: Zn; Cu; Pb
Location: 28°58'08"S, 121°46'11"E; 43 km east of Leonora

The Anaconda Mine, which produced about 4320 t of copper from supergene ore between 1899 and 1908, is located at or near the top of a sequence of rhyodacitic volcanic and volcaniclastic sedimentary rocks, including greywacke, siltstone and pyritic and carbonaceous shale, where they give way to a pillowed calc-alkaline, tholeiitic basalt unit. The host sediments are interpreted as a product of distal volcanism transported as submarine mass flows and turbidity currents (Hallberg, 1985; Barley, 1992). Sedimentary breccias containing angular lithic-wacke, shale, siltstone and sulfide clasts, are interpreted as fragmented stratiform-sulfide mineralization that is a product of local gravitational slumping (Marston, 1979).

The deposit is situated on the west limb of the south-southwesterly shallow-plunging Kilkenny Syncline (Figs 53 and 54). The host horizon is mineralized over a strike length of 430 m in four lens-like shoots dipping east-southeast at 45–75°. The primary mineralization is predominantly massive pyrite with subordinate iron-bearing sphalerite and chalcopyrite associated with chlorite and carbonate alteration. Below 24 m, a sample of primary ore material showed 14.4% Zn. Rich zones of secondary enriched copper between 30 and 60 m below surface were the focus of early mining. Native copper, chalcocite and minor copper carbonates were present in this zone. Marston (1979) gives details of the old workings.

From 1968 to 1973, EZ conducted diamond drilling in the vicinity of the old mine. Drilling on the north-dipping northern shoot gave a best intersection of 7.16 m of 2.13% Cu and 9.56% Zn. Mineral textures included fine layering with cross-cutting quartz, carbonate and pyrite veins. Drilling in the southernmost shoot obtained a best intersection of 2.6 m at 4.7% Cu and 4.2% Zn in angular breccia. Copper–zinc ratios are variable in detail but seem to be generally higher in the southern shoot. The northern and southern extensions of the mineralized zone were tested with percussion drilling by Seltrust in 1978–79 but encountered only thin zones of base-metal anomalism.

The prospect contains an indicated resource of 0.877 Mt at 1.97% Zn, 0.96% Cu and 6.32 g/t Ag.

References: Blockley (1971), Marston (1979), Reynolds et al. (1975), Hallberg (1975), Barley (1992), Mining

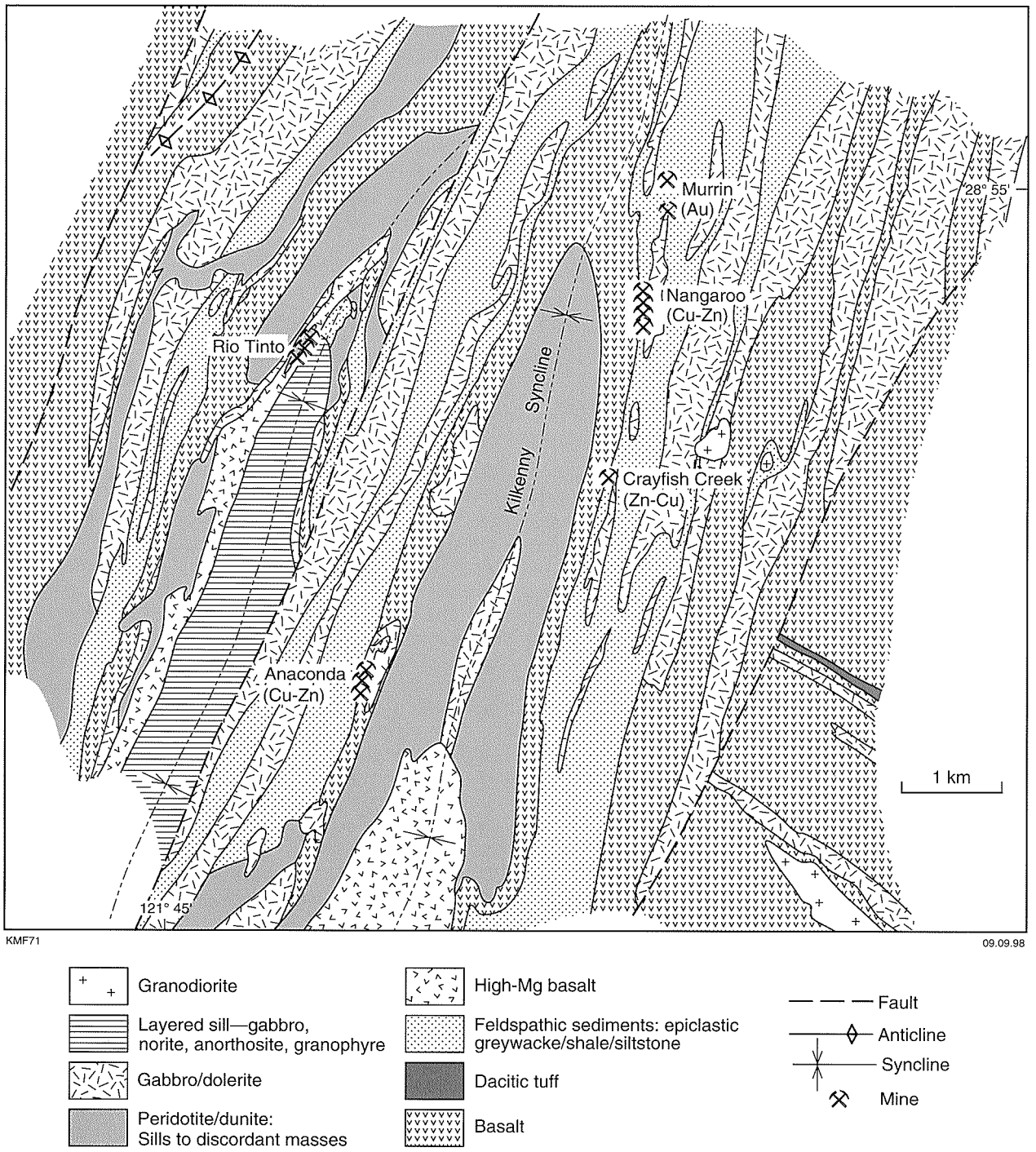


Figure 53. Murrin area: geology and base-metal prospects (*compiled from* Hallberg, 1985; Marston, 1979)

Magazine February 1991, GSWA-WAMEX - I 1174, I 5998.

Nangaroo (Minara, Butte City)

Abandoned mine: Cu; Zn
Location: 28°55'50"S, 121°48'20"E; 46 km east of Leonora

This deposit is situated at the northern end of the eastern limb of the Kilkenny Syncline at the same stratigraphic level as Anaconda (Figs 53 and 54), on the boundary between felsic volcanic and volcaniclastic rocks and tholeiitic pillow basalt. Like Anaconda, Nangaroo was worked for supergene copper ores between 1899 and 1908 and for cupreous ores between 1950 and 1967, yielding a total of 275.7 t of copper.

Exploration by Australian Selection (1964–87) initially relied on magnetics, INPUT and EM surveys in an area of poor outcrop. Only graphitic shale horizons were detected. Later IP surveying, in conjunction with

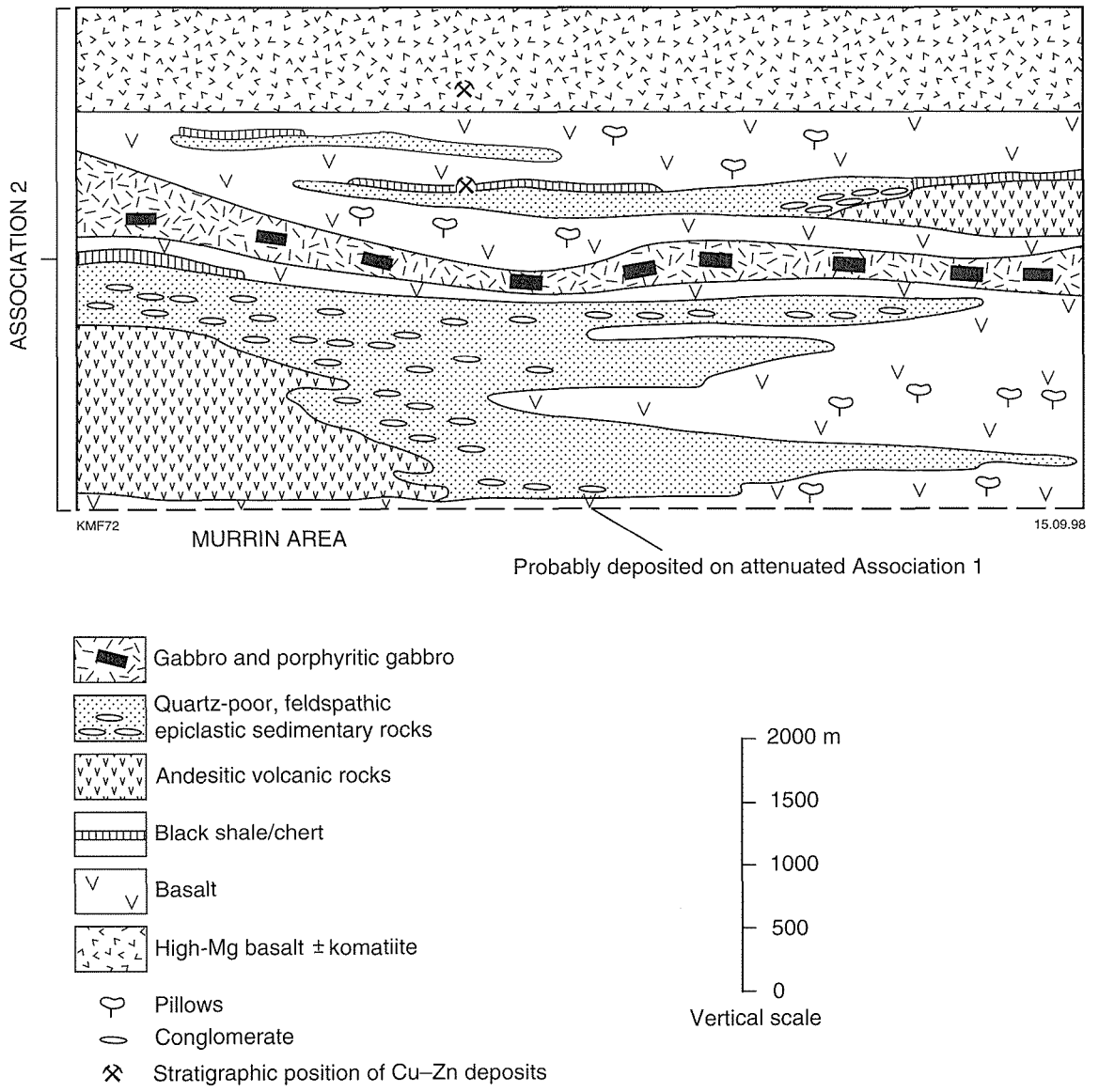


Figure 54. Murrin area: generalized stratigraphy and position of copper–zinc prospects (*after* Hallberg, 1986)

geochemical sampling, was more successful in defining targets. In association with the old workings, a mineralized zone 400 m long and 75 m wide was defined at the surface. Small siliceous gossans contained limonite, azurite, malachite and para-atacamite. Diamond drilling in 1970 intersected interbedded basalt, felsic volcanics, tuff, sedimentary breccia and carbonaceous shale. Felsic volcanic rocks are more conspicuous than at Anaconda and rapid facies changes more common. Detailed correlation of sedimentary units between holes 60 m apart proved impossible. Several small shoots of massive sulfides, up to 4 m thick and 400 m long, were recognized in drilling. The shoots are pyritic with variable amounts of pyrrhotite, iron-bearing sphalerite and chalcopyrite and they lie at the top of felsic units where these are overlain by mafic volcanic material. Cassiterite is a common accessory. Fragments of identical sulfides are found in volcano-sedimentary breccias within the sequence. Carbonate–chlorite alteration is associated with the mineralization, with carbonatization being particularly intense. Copper:zinc ratios average about 0.5 for massive and disseminated sulfides. Intersections of up to 6 m at 14.7% Cu, 9.5% Zn, 18.7 g/t Ag and 4.4 m at 10.2% Cu and 2.9% Zn were encountered in the longest shoot coinciding with the main gossan and old workings.

References: Blockley (1971), Marston (1979), Reynolds et al. (1975), Barley (1992), GSWA-WAMEX - I 5998.

Rio Tinto

Prospect: Zn; Cu
Location: 28°55'50"S, 121°45'30"E; 42 km east of Leonora

Located about 4 km north-northwest of Anaconda (Figs 53 and 54), the small Rio Tinto deposit is on a faulted westerly repeat of the Kilkenny Syncline. This deposit is

hosted by a narrow horizon of felsic tuffs, lavas and sedimentary rocks, some of which are carbonaceous, within tholeiitic and komatiitic basalt, well above the stratigraphic level of Anaconda. The small, zinc-rich massive sulfide is located at the top contact of the felsic horizon. Gossan sampling by Australian Selection gave a maximum of 7.5% Zn and 5.5% Cu. The results from six diamond drillholes were insignificant.

References: Marston (1979), Reynolds et al. (1975), GSWA-WAMEX - I 5998.

Crayfish Creek

Prospect: Zn; Cu
Location: 28°56'30"S, 121°48'30"E; 47 km east of Leonora

The Crayfish Creek prospect lies 2.5 km south from Nangaroo (Figs 53 and 54)and is at the same stratigraphic level. This prospect is in a complex sequence of felsic tuff, agglomerate, carbonaceous shale, greywacke, and rhyolite flows with andesite. Mineralization is at the top contact of rhyolite with dacite–andesite and is associated with carbonate and chlorite alteration. The prospect was discovered by Australian Selection during percussion drilling of a small gossan; a 10 m intersection gave 0.4% Cu and 7.5% Zn.

Reference: GSWA-WAMEX - I 5998.

Tuff Hill

Prospect: Zn; Au; Cu
Location: 27°38'30"S, 122°14'E; 5 km west-southwest of Duketon

Exploration by CEC/Esso (1973–88) located disseminated sulfides at Tuff Hill, in quartz–sericite schist interpreted originally as rhyolite tuff and minor breccia (possibly altered mafic tuff). The deposit is in the north central Duketon Greenstone Belt in felsic volcanic and sedimentary rocks, which form a north-northwesterly trending wedge between mafic–ultramafic rocks and banded iron-formation. Gossans extend about 500 m north–south along strike and dip about 60° to the west. Following successful target definition using TEM, percussion drilling intersected zinc-dominant disseminated and massive sulfides in pyroclastic volcanic rocks. Diamond drilling intersected narrow zones of massive sulfides (≤0.3 m), mainly sphalerite with some pyrite, chalcopyrite and galena, occurring mostly as veins. The best intersection was 0.8 m at 2.9% Zn, 1.3% Pb, 0.26% Cu and 70 g/t Ag, with a deeper intersection giving 0.1 m at 4.7% Cu, 2.7% Pb, 0.6% Zn and 325 g/t Ag. Mineralization is associated with sericite, silica, carbonate and chlorite alteration.

Reference: GSWA-WAMEX - I 5573.

Mason Hill

Prospect: Zn; Pb; Ag; Au
Location: 27°36'15"S, 122°12'30"E; 7 km west-northwest of Duketon

Anomalous lead–zinc values were located by CEC in the north-central Duketon Greenstone Belt in faulted rhyolite–andesite flows, tuff and breccia with minor chert, mafic and sedimentary rocks during an exploration program that included Tuff Hill and Fisher Well. Gossans identified during the work were also enriched in cobalt, bismuth and gold. Percussion drilling indicated significant mineralization over 400 m of strike in rhyolite breccia, with intersections up to 3 m at 4% Zn, 1% Pb and 0.2% Cu. Gold up to 5.5 g/t was also recorded. Follow-up diamond drilling intersected narrow high-grade zones of crudely layered sphalerite–galena–pyrite with minor chalcopyrite and tennantite in rhyolite breccia. A typical intersection was 0.3 m at 9.3% Zn, 1.6% Pb, 0.07% Cu, and 57 g/t Ag. Fine stringer mineralization with quartz, chlorite veining and remobilized galena and sphalerite may indicate remobilization in association with faulting, rather than feeder zones. Alteration in the form of sericitization, silicification and tourmalinization was reported.

Reference: GSWA-WAMEX - I 5998.

Fisher Well

Prospect: Pb; Zn
Location: 27°42'30"S, 122°16'15"E; 8.5 km south of Duketon

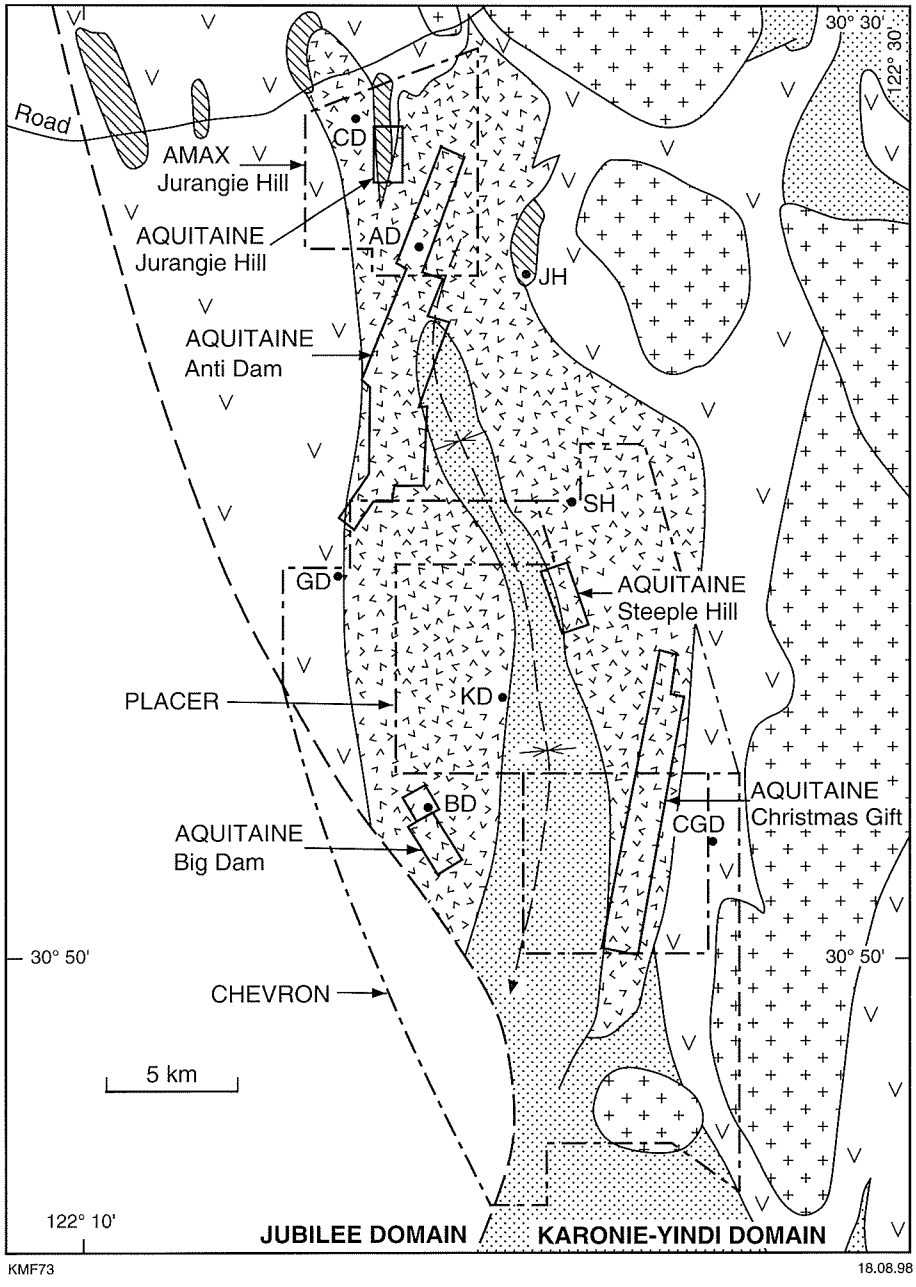
This prospect was identified during exploration in the southerly extension of the Duketon Greenstone Belt sequence seen at Tuff Hill and Mason Hill. In this area the sequence comprises cyclic rhyolitic and andesitic ash-tuff, agglomerate and breccia with minor kaolinitic and carbonaceous sedimentary rocks. Chert horizons, however, are absent, indicating no significant periods of quiescence. The area is interpreted to be within a broad anticlinal axis. Percussion drilling followed RAB geochemistry and encountered disseminated and vein pyrite with sphalerite, subordinate galena and minor chalcopyrite in the coarser tuffs and agglomerates of three volcanic cycles. Chlorite, sericite, silica and tourmaline alteration is associated. Grades of mineralization are comparatively low; 24 m at 0.4% Zn, 16 m at 0.43% Zn and 0.3 m at 2.5% Zn. A diamond hole intersected 5.3 m at 1.2% Zn in brecciated, altered tuffs.

Reference: GSWA-WAMEX - I 5998.

Anti Dam (Colour Dam, Jurangie Hill)

Prospects: Zn; Au
Location: 30°33'S, 122°18'E; 5 km southeast of Kurnalpi

The Anti Dam prospects were found during exploration for volcanogenic copper–zinc massive sulfides in dacitic–rhyodacitic tuff in contact with banded iron-formation, carbonaceous shale, siltstone and possibly greywacke in an oxidizing depositional environment in the Kurnalpi Greenstone Belt. The felsic volcanic rocks lie within the Karonie–Yindi structural–stratigraphic domain of Swager (1994), where they form a major volcanic centre folded into a south-plunging, northerly trending regional F_2 syncline (Fig. 55). They are overlain by fine-grained slates with local banded iron-formation. Swager (1994) considers that they represent a volcanic-arc association.



Felsic volcanic rocks

Sedimentary rock

Mafic volcanic rocks

Komatiite

Granitoid

Domain boundary

Synform, plunge direction

BIF

Chert, slate marker bed

Prospects

GD	Gessners Dam
CD	Colour Dam
AD	Anti Dam
JH	Jurangie Hill
SH	Steeple Hill
KD	Kym Dam
BD	Big Dam
CGD	Christmas Gift Dam

Figure 55. Steeple Hill Syncline: geology and exploration (*after* Swager, 1994)

Exploration for VMS targets in the 1970s was concentrated on the felsic volcanic rocks between Colour Dam, Gessner Dam and Christmas Gift Dam. Numerous gossanous layers and lenses, often associated with chert and black shale, were identified. Amax (1971–74) discovered anomalous gossans in a northerly striking zone 40 m wide with banded iron-formation on the west side of the south-southeasterly plunging Steeple Hill syncline, east of Colour Dam. Following mapping, ground magnetic and IP surveys, percussion drilling intersected up to 0.7% Zn over 36.5 m. Other intersections included 3.1 m at 1.3% Zn and 3.1 m at 1.0% Zn. Follow-up work by Aquitaine (1974–79) further detailed the stratigraphy and led to percussion and diamond drilling following delineation of surface geochemical anomalies and a TEM survey. Sulfide mineralization was encountered in three holes. Sphalerite was recognized as the main sulfide, with minor galena and chalcopyrite. A discordant zone of chloritic and carbonate alteration was interpreted as a possible feeder zone. Alteration indicated iron, magnesium and calcium metasomatism. The main mineralized zone was interpreted as a fracture zone by Aquitaine, and therefore also as part of a potential 'plumbing' system. The best assay from this drilling was 1.9% Zn. Aquitaine considered the potential for VMS mineralization would be greater in horizons indicating quiescence, but no such horizons were located. Follow-up work by Newmont (1977) focused on exhalative zones in the assemblage, but RAB drilling failed to locate anomalism in the prospective zones east of Jurangie Hill and south of Lake Yindarlgooda. Core resampling by Esso (1981–83) gave 525 ppm Cu, 1450 ppm Pb, 7450 ppm Zn, 47 g/t Ag and 16.6 g/t Au over 1 m. They interpreted the mineralization as being associated with an altered quartz–porphyry intrusive.

Other exploration in this general area included that by Aquitaine at Anti Dam, Steeple Hill and farther south in the Christmas Gift Dam area, in the 1970s (Fig. 55). At Anti Dam, follow-up of magnetic anomalies encountered no evidence of sulfide mineralization. Pulse EM anomalies were due to surficial effects. At Steeple Hill, Aquitaine tested a zone of gossanous chert 2 km long on a rhyolite–black shale contact. Drilling intersected massive and disseminated pyrite and pyrrhotite but base-metal levels were low. In the Christmas Gift area, on the eastern limb of the syncline, two gossan lines were explored over 10 km. Surface sampling gave up to 0.25% Cu and 1.4% Zn in the black shale sequence but drilling indicated mostly pyrite and pyrrhotite at depth. Only minor chalcopyrite and possible sphalerite were seen in thin zones. An intersection of 1 cm gave 1.05% Zn and 0.16% Cu. The environment was interpreted as being distal from a volcanic centre between 5 and 10 km to the north. Chevron (1984–85) followed up this work in a large area south of Lake Yindarlgooda (Fig. 55). Results from rock-chip and pisolite sampling were low. Exploration by CSR/Placer (1983–90) in the Jurangie Hill–Steeple Hill area initially included VMS targets. Geochemical and structural studies were followed by a SIROTEM survey and RC and diamond drilling. Only minor anomalism was encountered in surface sampling. Drilling of a SIROTEM anomaly northwest of Kims Dam located only semi-massive pyrite and pyrrhotite banding.

References: Swager (1994), GSWA WAMEX - I 44, I 575, I 644, I 851, I 1073, I 2030, I 2764, I 2915, I 3110, I 4475.

Kanowna

Occurrence: Zn; Au; Cu
Location: 30°37'50"S, 121°37'50"E; 2.5 km southeast of Kanowna

Exploration by Great Boulder Mines/Noranda (1968–75) within an intermediate to dacitic–rhyolitic volcanic and volcaniclastic sequence in the Kanowna Greenstone Belt located an 18.5 m-thick horizon of lapilli tuff containing pyrite, and minor sphalerite, galena and chalcopyrite. Samples running up to 2 m of 0.25% Cu, 1.7% Zn and 7 g/t Au were associated with intense chloritization and magnesium metasomatism. An overlying chert was tested with negative results. Alteration was also associated with a major tectonic lineament which may have had a role in the distribution of extrusive and intrusive activity in the area. Subsequent detailed mapping in 1975 by Samin suggested that mineralization formed beneath the chert horizon close to a volcanic vent.

Reference: GSWA-WAMEX - I 3092.

Potential

It has been pointed out by Smith (1993), among others, that the Yilgarn Craton has a much lower density of discovered VMS deposits than similar Archaean terranes in Canada. It may be that, as Smith suggests, the major difference is in the masking effect of deep weathering in Western Australia. The discoveries of Gossan Hill in 1971 and Scuddles in 1979 confirm the potential for major deposits, and the relatively subtle geochemical and geophysical signatures of the Scuddles mineralization lend support to Smith's suggestion.

In terms of the areal distribution of prospective greenstone terranes, the Eastern Goldfields Province would seem to have the most potential for further discoveries. Barley (1992) and Witt (1994) proposed marginal-basin and arc settings for the Norseman–Wiluna belt reflecting westward dipping subduction. This would suggest maximum potential in the arc-related tholeiitic and calc-alkaline volcanic units. In contrast to this essentially terrane-based concept is the suggestion from recent mapping that the stratigraphy of the eastern Yilgarn Craton can be correlated across major structures. In this scheme intermediate to felsic volcanic rocks occur within at least two stratigraphic levels. The subdivision of the felsic volcanic units proposed by Hallberg et al. (1993) separates three main suites: the Black Flag Group of the Kalgoorlie area; the rhyolites and dacites of the bimodal suite in the Teutonic Bore–Kanowna area in the Gindalbie; and the andesitic volcanic rocks of the Murrin area and farther east. Table 12 lists the relative features of these groups. The deep-water environment of the bimodal suite, and the presence of the Teutonic Bore deposit within it, suggest

good potential. Features such as growth faulting and sub-basins in the Teutonic area are positive. In the same sequence, however, in the Melita area, Witt (1994) noted negative features such as explosive volcanism to explain the apparent lack of success in exploration. Clearly the detailed mapping of local variables is vital in any realistic assessment of generally favourable suites. Witt et al. (1996) pointed to important features which need to be identified, including subaqueous environments, synvolcanic faulting, volcanic centres with related calderas and cauldrons, and subvolcanic intrusives. Cas et al. (1993) suggested good potential in the Black Flag Group, based on similarities with the Golden Grove lithologies and its deep-water environment. However, this contrasts with the negative geochemical features outlined by Witt et al., (1996). The andesitic volcanic rocks of the Murrin area and farther east have lower potential, particularly due to shallow water or subaerial environments. However, deeper water environments do exist within this sequence, in the Duketon Greenstone Belt and in the Edjudina area.

In the Murchison region, VMS mineralization is associated with the deep-water intermediate to felsic volcanic rocks in the Gabanintha and Windaning Formations. Apart from the Golden Grove deposits a number of other prospects have been explored. Barley (1992) has described the favourable lithogeochemistry of this group (Table 5), and Clifford and Sheppy (1991) and Cas et al. (1993) have summarized local lithological and synsedimentary tectonic features associated with Scuddles.

It would seem, therefore, that most of the felsic volcanic successions in the Yilgarn Craton retain potential for the further discovery of VMS mineralization apart from, possibly, the shallower water units and certainly the subaerial units. It seems clear that further discoveries will result from a more detailed knowledge of the environment in which volcanism took place, the types of flows and sediments, indications of hiatus with associated chemogenic chert, and evidence for the fault-controlled formation of sub-basins or grabens.

Sylvania Inlier

Geological framework

Tyler (1991) has recently updated the geology of the Archaean Sylvania Inlier and assessed its relationship to the Yilgarn and Pilbara Cratons. The inlier of granite–greenstone terrane at the southern edge of the Pilbara Craton is unconformably overlain by late Archaean to Palaeoproterozoic mafic and felsic volcanic, intrusive, carbonate and clastic sedimentary rocks and banded iron-formation of the Hamersley Basin (2.75–2.3 Ga). To the south and east the inlier shows an unconformable and faulted contact with sedimentary rocks of the Bangemall Basin. The inlier is made up predominantly of granitoid but also contains discontinuous greenstone belts of mafic/felsic metavolcanic rocks of low to medium metamorphic grade, mafic intrusions and metasedimentary rocks. The latter are considered to have formed on an earlier granitoid basement and were subsequently extensively intruded by granitoids.

The main belt, the Jimblebar Greenstone Belt, is divided into eastern and western halves by the Battery Fault. The successions in the two halves, which may have some overlap, make up a 12 km thickness (Fig. 56). The succession is dominated by mafic and ultramafic volcanic rocks and sills. Felsic volcanic rocks occur only in a prominent ridge of quartz–feldspar–chlorite schist and quartz–albite–chlorite–hornblende–biotite–garnet schist, towards the northwest margin of the belt. At Copper Knob the rock is porphyroclastic with 40–50% of quartz–feldspar porphyroclasts. This unit is overlain by a 'hybrid' intermediate schist. Metasedimentary rocks and chert occur in the lower part of the succession north of Coobina Bore in a horizon of quartzite and pelitic schist 200 m wide. A second metasedimentary unit forms a horizon 400 m wide of interlayered chert, quartzite, quartzofeldspathic schist, pelitic schist and calcareous meta-psammite, northwest of Jimblebar and south of Mindoona Bore. The quartzofeldspathic schist may be of felsic volcanic origin. Banded iron-formation is only associated with metasedimentary rocks in the eastern part of the western belt, southwest of Jimblebar. No banded iron-formation is associated with the Copper Knob felsic material.

Geochronological patterns and rare-earth element geochemical patterns suggest that the southern part of the Pilbara Craton, lying beneath the southeastern Hamersley Basin and including the Sylvania Inlier, formed a separate terrane which merged with the northern Pilbara between 3.0 and 2.76 Ga, and was not related to events which produced the Yilgarn Craton.

Mineralization

Banded iron-formation hosts epigenetic gold, with associated sulfide minerals, that has been mined at Jimblebar. Pyrite is the dominant sulfide but pyrrhotite and chalcopyrite are also present. The stratabound copper–zinc occurrences in the inlier occur at two stratigraphic levels within the Jimblebar Greenstone Belt and are associated with a felsic volcanic unit and with metasedimentary rocks respectively. Barley (1974) has suggested that the low nickel:cobalt ratios of iron sulfides in this association (<0.5:1) indicate a magmatic–hydrothermal origin for the Copper Knob mineralization, namely volcanic–exhalative. Tyler (1991), while recognizing some uncertainty due to the lack of preservation of primary sedimentary and igneous features, indicates that the available evidence points to the Jimblebar greenstones forming in a cratonic rift environment. Galena associated with barite has been found near Murramunda, within an east-southeasterly trending fault zone forming the northern margin of the Coobina ultramafic body.

The small size of the Jimblebar Greenstone Belt and the relatively restricted distribution of felsic volcanic rocks suggest only minimal potential for further deposits of VMS mineralization.

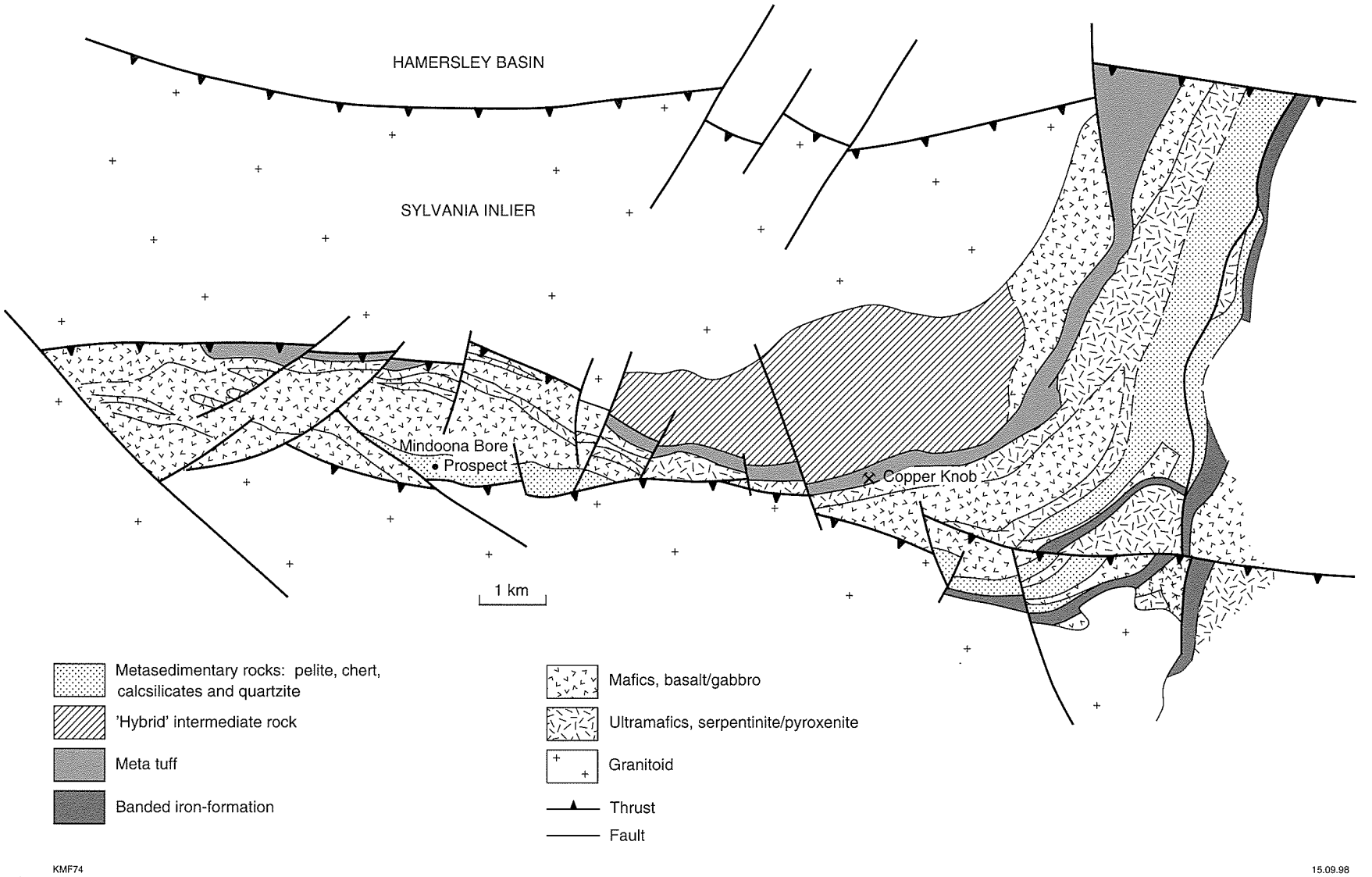


Figure 56. Jimblebar greenstone belt: geology and base-metal prospects (*modified after* Tyler, 1991)

Deposits, prospects and occurrences

Mindoona Bore

Prospect: Zn; Pb; Ag
Location: 23°28'30"S, 120°04'30"E; 7.5 km west of Copper Knob

Exploration by Billiton/Geopeko between 1986 and 1989 encountered anomalous zinc in the Jimblebar Greenstone Belt. The disseminated/?massive-sulfide mineralization occurs within the metasedimentary unit 400 m wide in the western part of the belt. It lies within silicate facies banded iron-formation, near the base of the metaclastic unit, which is about 1 km stratigraphically below the Copper Knob felsic rocks.

The anomalism was picked up by stream-sediment and soil-geochemical sampling. SIROTEM surveys gave no significant conductors but gradient-array IP surveys mapped an area of disseminated mineralization. The best intersections from three RC percussion drillholes were 16 m at 0.6% Zn, 0.13% Pb, 5.6 g/t Ag and 27 g/t Cd, and 2 m at 3.1% Zn within 10 m of 0.77% Zn. Pyrite with minor chalcopyrite was recognized in the cuttings. High levels of cadmium and silver suggest a volcanic–exhalative origin.

Previous exploration in the area by Vam Ltd and Endeavour Resources located minor copper mineralization.

Reference: GSWA-WAMEX - I 5751

Jimblebar–Copper Knob (Copper Range)

Abandoned mine/prospect: Cu; Zn
Location: 23°27'S, 120°09'E; 35 km east-southeast of Newman

A quartz–feldspar–chlorite(–hornblende–garnet–stilpnomelane) schist (meta–felsic volcanic) within the easterly trending arcuate belt of greenschist facies metavolcanic rocks in the northeast part of the Jimblebar Greenstone Belt is anomalous in copper over a strike length of 10 km and a width of 200 m. Within this schist are zones of iron-rich copper–zinc mineralization. At Copper Knob the mineralization is expressed as limonite–malachite staining in the schist concentrated at the ridge summit. Ore produced from the small-scale workings between 1959 and 1962 (84.09 t of cupreous ore containing 8.37% Cu) contained malachite plus cuprite, tenorite, chalcocite, bornite and chalcopyrite. Primary sulfides comprise 45% pyrrhotite and 40% chalcopyrite with sphalerite and pyrite (Barley, 1974). The copper:zinc ratio is 5.7.

Van Zam Ltd and Endeavour (1968–75) showed that surface enrichment extended to about 50 m. Diamond drilling of a zone measuring 300 m by 50 m obtained best intersections of 1.8% Cu and 0.48% Zn over 9.1m. Further percussion drilling established an indicated resource of 1 Mt at 0.77% Cu in the oxidized zone and estimated a potential 0.5 Mt of 1.8% Cu and 0.5% Zn over a strike length of 122 m and to a depth of 122 m in the primary zone. A resource of 22.5 Mt at 0.38% Cu was estimated over a strike length of 360 m and to 500 m depth. Aquitaine (1977–86) conducted pulse EM surveys and located two conductive bodies. Drilling intersected only minor sulfides with copper up to 1.15% over 1 m. Billiton/Geopeko (1986–89) explored mainly gold targets. Geopeko/Belgravia Resources (1985 on) are continuing exploration in the area.

References: Marston (1979), Barley (1974), GSWA-WAMEX - I 2454, I 4378.

Halls Creek and King Leopold Orogens

Geological framework

A tectonic reappraisal of the related King Leopold and Halls Creek orogens is currently being undertaken by GSWA. Griffin and Grey (1990) and Plumb (1990) summarized published work to that date. Griffin and Tyler (1992) and Tyler et al. (1995) have presented results of the reappraisal and remapping of the Halls Creek Orogen, and Tyler and Griffin (1992) have updated the interpretation of the King Leopold Orogen.

Halls Creek Orogen

Three northeasterly trending zones have been defined in the southern part of the Palaeoproterozoic Lamboo Complex (Griffin and Tyler, 1992: Tyler et al., 1995): the Eastern zone is dominated by the Halls Creek Group; the Central zone is characterized by massive and layered mafic and ultramafic intrusions and is dominated by the Tickalara Metamorphics in the northeast; and the Western zone is dominated by the Whitewater Volcanics and turbiditic metasedimentary rocks of the Marboo Formation (Table 13 and Fig. 57). The Eastern and Central zones are separated by the Halls Creek, Osmond, and Angelo Faults and the Western and Central zones by the Ramsay Range and Springvale Faults. The Central and Western zones are extensively intruded by granitoid rocks of the Bow River batholith. Granite also intrudes the southern part of the Eastern zone.

In the Western zone the Marboo Formation (Tyler and Griffin, 1993; Tyler et al., 1995), a thinly bedded turbiditic sequence deposited at ~1.87Ga, outcrops along the western edge of the Kimberley Basin succession. It is unconformably overlain by the late-tectonic rhyolitic to andesitic ash-flow tuffs and agglomerates of the Whitewater Volcanics (1.86 Ga), which are comagmatic with the older 1.86 Ga granitoids of the Bow River batholith, which intrude the Marboo Formation.

In the Central zone the Tickalara Metamorphics range from lower amphibolite to granulite grade. The metavolcanic and metasedimentary sequence is intruded by sheets of foliated and recrystallized granite and gabbro, with minor ultramafic presence. The distinctive Koongie

Table 13. Stratigraphy and geochronology of the Halls Creek and King Leopold Orogens

	King Leopold Orogen	*Western Zone*	*Halls Creek Orogen Central Zone*	*Eastern Zone*
Spielers Event (500 Ma)	D_5		D_7 Antrim Plateau Volcanics	D_7 Antrim Plateau Volcanics
Precipice Event (560 Ma)	~~~~	~~~~	~~~~	~~~~
	D_4 Mount House Group	D_6 Louisa Downs Group Kuniandi Group	D_6 Louisa Downs Group Kuniandi Group	D_6 Albert Edward Group Duerdin Group
	~~	~~~~	~~~~	~~~~
Yampi Event (>1.00 Ga)	$D_3 - M_3$: medium grade	D_5 Colombo Sandstone Crowhurst Group	D_5	D_5 Osmond Range succession
		~~		~~~~
				Pegmatite veins (1.74 Ga) San Sou Granitoid
	Hart dolerite (1790 Ma) Kimberley Group	Hart Dolerite Kimberley Group	?Kimberley Group	?Kimberley Group
HALLS CREEK OROGENY	~~~~	~~~~	~~~~	~~~~
			Moola Bulla Formation	Moola Bulla Formation
1835–1850 Ma			~~~~	~~~~
			Mount Christine Granitoid Sally Downs Granitoid (1820 Ma)	Mount Christine Granitoid (1820–1805 Ma)
	Speewah Group (1835 Ma)	Speewah Group ?1820 Ma granitoids		
	~~		Emull Gabbro/McIntosh Gabbro (1830 Ma)	D_4/M_4
			D_3/M_3 Alice Downs Ultramafics	D_3/M_3
			Mabel Downs Granitoid Koongie Park Formation (1840 Ma)	
				Woodward Dolerite
	~~	~~~~	~~~~	~~~~
HOOPER OROGENY	granitoids	Bow batholith		upper Olympio Formation
				Butchers Gully Member
1865–1850 Ma		Toby + Springvale Layered mafic bodies	D_2/M_2 (1860–1850 Ma)	
			Dougalls Tonalite	
	D_2/M_2 Whitewater Volcanics	D_2/M_2 Whitewater Volcanics		
	~~		granitoid sheets (1865 Ma)	
	D_1/M_1	D_1/M_1		mafic granulites lower Olympio Formation
	Ruins Dolerite		Tickalara Metamorphics (?1865 Ma)	
	Marboo Formation (?1870 Ma)	Marboo Formation		Biscay Formation (1880 Ma)
				Saunders Creek Formation
				~~
				Sophie Downs Granite Ding Dong Downs Volcanics

SOURCE: Modified from Tyler et al., 1995; Griffin and Tyler, in press

~~~~ Unconformity
~~~~

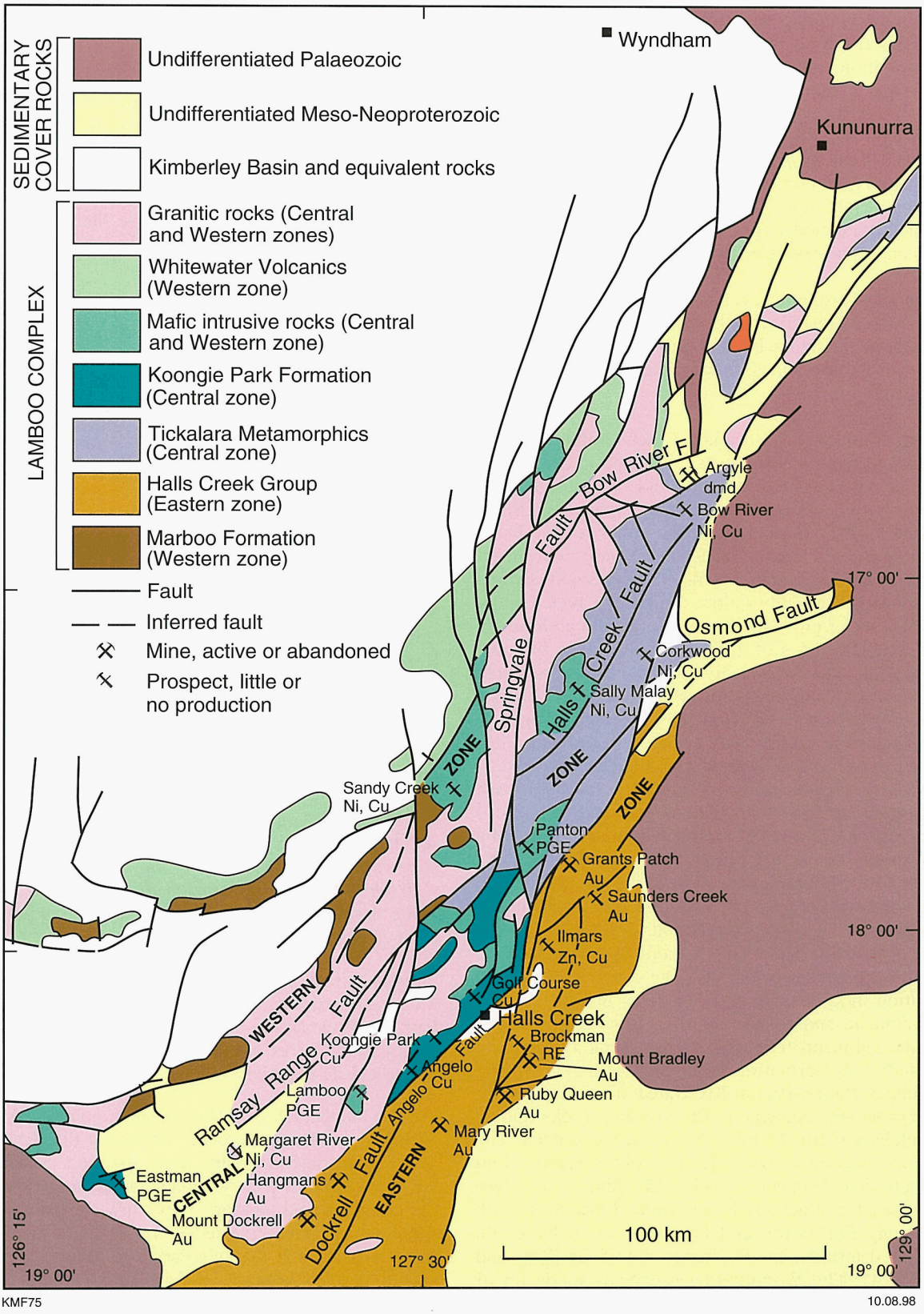


Figure 57. Halls Creek Orogen: geology and base-metal prospects (*modified after* Plumb, 1990)

Park Formation has been recognized in the south of the Central zone, adjacent to the Mount Angelo Fault (D. M. Sewell, this volume). This formation is predominantly felsic volcanic and volcaniclastic with calcareous and pelitic metasedimentary rocks and banded iron-formation. Included within it is basaltic material, which was previously considered to be part of the ~1.88 Ga Biscay Formation of the Halls Creek Group. A zircon age of 1.84 Ga (Page et al., 1994), however, suggests that the Koongie Park Formation is younger than the Biscay Formation and also cannot be correlated with the turbiditic Olympio Formation, which it also probably postdates. A Pb model age of ~1.82 Ga has been obtained from samples of Koongie Park galena.

The post-orogenic events in the Central zone are dominantly magmatic with the younger mafic–ultramafic intrusions including the Lamboo Sill and the younger 1.83 to 1.81Ga gabbro and granitoid intrusions of the Bow River batholith.

In the Eastern zone, the Halls Creek Group sedimentary rocks have previously been considered to include the oldest in the combined orogens and to represent pre-orogenic sedimentation. A proposed revision by Griffin and Tyler (1992), however, puts the bimodal Ding Dong Downs Volcanics (basic and felsic volcanic with intercalated sedimentary rock) and the intrusive Sophie Downs Granite unconformably below the Halls Creek Group, defining a lower pre-Halls Creek Group with preliminary U–Pb SHRIMP ages of 1.90 to 1.92 Ga. The bimodal volcanic unit suggests an active rift environment (Plumb, 1990). The probably unconformably overlying Saunders Creek Formation is composed of braided-stream to shallow-marine quartz-rich sandstone and indicates tectonic activity and basin segmentation. The Biscay Formation is dominated by mafic volcanism with interbedded shallow-water calc-silicate and terriginous sedimentary rocks in a rift-basin environment. The mafic rocks are predominantly pillow basalts but also include dolerite sills. Minor amounts of 1.88 Ga metamorphosed felsic volcanic and volcaniclastic material occur in the upper part of the Biscay Formation (Tyler et al., 1995) to the east of the Halls Creek Fault in the vicinity of the Little Mount Isa prospects. The overlying Olympio Formation indicates the onset of basin-margin faulting and tectonism and consists of fine- to medium-grained turbiditic sediments formed in a synorogenic flysch basin with sediment derivation from the northwest. In the McClintock Range–Panton River area, a broad sequence of intermediate, trachyandesitic volcanic rocks named the Butchers Gully Member has been recognized. The sequence includes pillow lavas, volcaniclastic, and carbonate-rich sedimentary rocks. This unit occurs close to the basal contact of the Olympio Formation with the Biscay Formation and has been dated by U–Pb SHRIMP determination on zircons at 1.85 Ga (Page and Sun, 1994). The Woodward Dolerite is made up of compositionally uniform sills emplaced into the Halls Creek Group.

Deformation within the Halls Creek Orogen, in the Mesoproterozic to the Palaeozoic, is characterized by strike-slip movement along large, regional-scale faults (Dow and Gemuts, 1969; Tyler et al., 1995; Thorne and Tyler, 1996).

King Leopold Orogen

The stratigraphy and tectonic evolution of the King Leopold Orogen have some similarities with those of the Western zone of the Halls Creek Orogen. The oldest unit in the Hooper Complex, the turbiditic Marboo Formation, is intruded by sills of the Ruins Dolerite. The oldest deformation D_1 is represented only as a layer-parallel foliation, S_1 in the Marboo Formation. Marboo deposition and D_1 deformation have probably taken place in an extensional environment.

The Whitewater Volcanics (1.86 Ga) is also present in the Hooper Complex and is represented by rhyodacitic lavas, tuffs and volcaniclastic rocks. A second, greenschist-facies metamorphic and deformational event preceded intrusion of granitoids chemically related to the Whitewater Volcanics, some of which are subvolcanic.

Mineralization

Stratiform volcanogenic copper–lead–zinc(–silver–gold) mineralization occurs in sedimentary–volcanic sequences of the Halls Creek Orogen, both within the Biscay Formation of the Halls Creek Group in the Eastern zone (Little Mount Isa, Twin Hills, Ilmars), and in the younger Koongie Park Formation in the Central zone (Koongie Park prospects–Onedin, Sandiego, Hanging Tree, Gosford, Mount Angelo, Atlantis, Golf Course and Eastmans Bore).

In the Koongie Park Formation subeconomic zinc–copper–lead(–silver) mineralization is present in calc-silicate units where it forms small stratabound and locally stratiform bodies. These take the form of steeply plunging shoots associated with tight isoclinal folds. The mineralization comprises sphalerite, chalcopyrite and minor galena with pyrite, pyrrhotite and magnetite. Talc, phlogopite and albite dominate the alteration assemblages with minor, local chlorite and sericite.

Mineralization in the Biscay Formation in the Little Mount Isa prospects is generally similar to that at Koongie Park, being hosted in carbonaceous and chert–carbonate sedimentary rocks associated with acid volcanic and volcaniclastic material.

The association of felsic volcanic, volcaniclastic and chemical sedimentary rocks suggests a distal volcanogenic environment for this mineralization. Sewell (this volume) considers that systematic facies variations within the chemical sedimentary rocks are comparable with sedimentary exhalative facies variations. The detailed work carried out at Koongie Park by Billiton and its joint venture partners suggests an association between the best development of mineralization and thicker basinal sequences. Evidence that some of the mineralization is epigenetic indicates some remobilization of the syngenetic ore during folding. Structural control is evident from the concentration of massive sulfides in tight folds with shoots parallel to the fold axes.

At Mount Angelo, to the south of Koongie Park, in addition to massive sulfides associated with the sedimentary–volcanic sequence, copper and weak gold mineralization is associated with a quartz–feldspar porphyry. Chalcopyrite is associated with minor bornite, tetrahedrite, pyrite, sphalerite and molybdenite. The alteration assemblage includes adularia, sericite, albite, quartz, epidote, chlorite, rutile, sphene and sulfide minerals.

In the King Leopold Orogen, massive stratabound sulfides are recognized at two prospects in felsic volcanic and metasedimentary units of the Marboo Formation. The copper–lead–zinc in sulfides with associated silver grade up to about 10% collectively in drillcore at Turtle Creek, and are also present but at lower grades at Colemans Creek. The Chianti prospect, a stratiform copper–lead–zinc occurrence in slate and quartz–sericite schist with no apparent volcanic affinity, is also located in the Marboo Formation.

Exploration history

Exploration for stratabound base-metal targets has been carried out in the Halls Creek Orogen since the early 1960s. Peko Mines NL (I 34) identified the potential of the upper Biscay Formation between 1962 and 1963 in work continued by Pickands Mather (1963–72) (I 251) and subsequently by the Koongie joint venture involving Kennecott (I 6157, 740, 741), Newmont, North Broken Hill, Asarco (I 2379), BP Minerals, RT Min. Corp., Anglo Australian Resources and Billiton (1972 on). This work is reviewed in the following section by D. M. Sewell. The early exploration in this area was greatly promoted and assisted by the joint GSWA–BMR 1:250 000 geological mapping program carried out in the early 1960s (Dow and Gemuts, 1969; Gellatly et al., 1974), during which some of the prospects described below were first recognized.

Australian Anglo American (I 617, 263) conducted regional base-metal exploration along the Halls Creek Fault in the mid 1970s including work on copper–zinc targets in the Biscay Formation. Surface geochemistry and EM surveys identified some anomalies in the Five Mile Creek area but scattered anomalies at Halls Creek South were not followed up. BHP (I 2489) and CRA (I 738) were also involved in regional and detailed geochemical and geophysical exploration for VMS targets in the late 1970s and early 1980s along the boundary between the Biscay and Olympio Formations. The Emull prospect was included in this work. No substantial target felsic volcanic rocks were located. More recently, Troy Resources (I 4734, 8088) in the Moola Bulla area, north of Koongie Park, has sampled gossans over 3 km of strike for zinc levels up to 0.3%. This is in an area of felsic volcanic and carbonate rocks and chert previously sampled by PMI in the 1960s for results of up to 3.0% Pb.

In the King Leopold Orogen early regional exploration and prospect evaluation by WMC (1957–60) (I 1534) and Pickands Mather (1963–73) (I 251) examined a number of vein-type and stratiform copper prospects mostly within the Marboo Formation and Tickalara Metamorphics. Most of these prospects were of limited potential. WMC with Richenda Minerals (1973–74 and 1980–81) (I 780, 1200) examined the stratiform, shear, and possibly dolerite-related copper–lead–zinc prospects along the northeast limb of the Richenda Anticline. Regional stream-sediment geochemistry successfully defined the prospective areas. Exploration continued to drilling level without establishing any economic potential. Century (1987–88) (I 3614) further sampled the related Sandy Creek shear zone. Current exploration in the area by Pancontinental and Moonbeam Nominees is directed towards base-metals and gold.

Deposits, prospects and occurrences

Halls Creek Orogen

The Koongie Park and Little Mount Isa zinc–copper–lead deposits East Kimberley Region

Contribution by D. M. Sewell[1]

The Koongie Park and Little Mount Isa base-metal and gold prospects are some 45 km apart in the East Kimberley region of Western Australia. The Koongie Park prospects are located about 20 km southwest of Halls Creek and incorporate the Onedin, Sandiego, Hanging Tree, Gosford, Mount Angelo and Atlantis prospects. The Little Mount Isa prospects are some 25 km northeast of Halls Creek and cover an area which includes the Ilmars, Twin Hills and Little Mount Isa prospects (Figs 58 and 59). Small base-metal resources have been outlined at Sandiego, Mount Angelo, Atlantis, Onedin and Ilmars.

Access to the prospects is by the Great Northern Highway from Halls Creek township and then along established unsealed roads. Exploration was conducted in these areas to 1995 under a joint venture agreement between Billiton Australia and Anglo Australian Resources NL.

This contribution presents an outline of the geology of the Koongie Park and Little Mount Isa base-metal and gold prospects including deposit geology, resource estimates, and regional stratigraphic and structural controls associated with the mineralization. An introductory section on the regional geological setting in the Kimberley region and a discussion of the possible genesis of the deposits are also presented.

History of exploration

In 1962–63, limonitic gossans containing secondary copper, lead and zinc minerals were reported in the Halls Creek region during regional mapping by the BMR and GSWA and by Peko Mines NL. Most of the

[1] Formerly of Billiton Australia, presently with Acacia Resources Ltd.

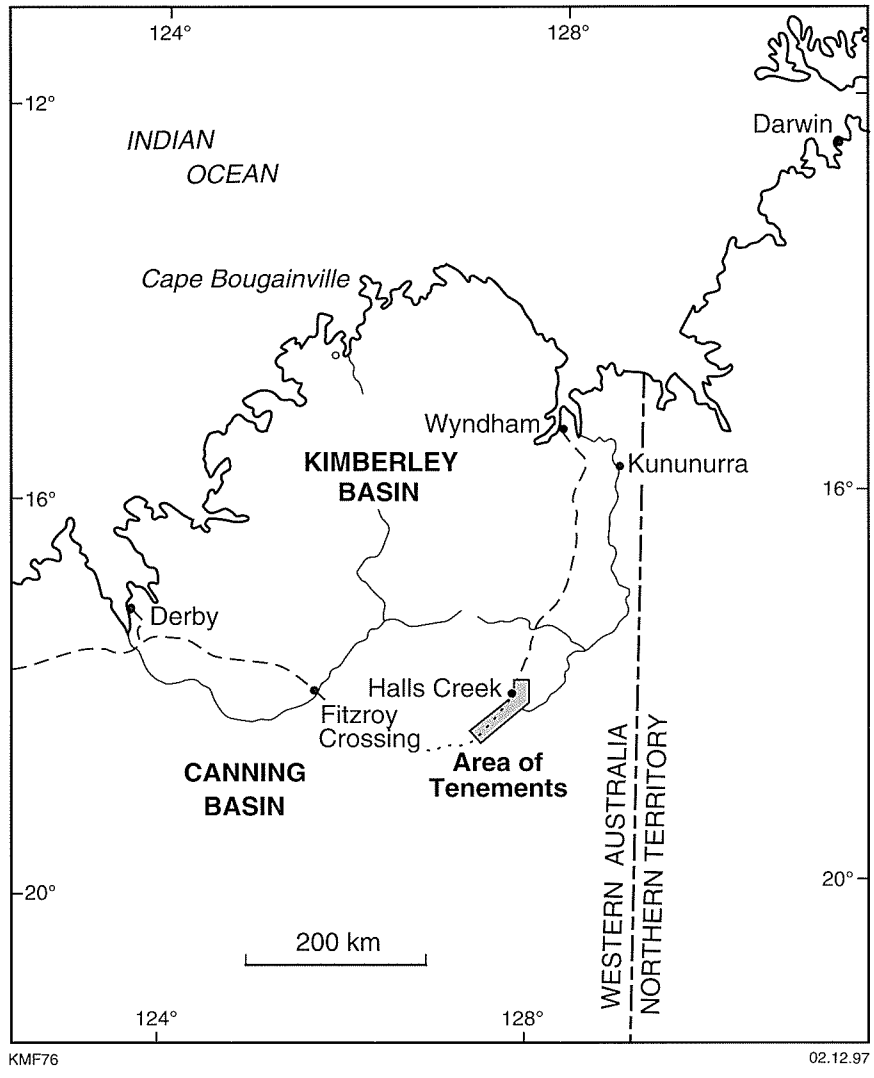


Figure 58. Koongie Park, east Kimberley: locality

mineralization was found near the top of the Biscay Formation in dolomite and dolomitic shale and was apparently localized along shear zones.

Between 1963 and 1972, Pickands Mather followed up lenses of massive-sulfide mineralization in the Halls Creek area. This work, mainly diamond drilling of gossanous zones at the Mount Angelo, Little Mount Isa, Twin Hills and Ilmars prospects, outlined subeconomic base-metal sulfides, as well as barren massive sulfides.

At Mount Angelo a massive-sulfide deposit, hosted by shales and carbonates of the Koongie Park Formation, contains an inferred resource of 122 000 t at 1.63% Cu. The Mount Angelo porphyry-copper deposit, hosted by sheared granophyric microgranite, contains an inferred resource of 21 Mt at 0.44% Cu.

In 1972, Kennecott pegged tenements over known copper–lead–zinc–silver gossans as part of its Gordons Downs 3 and 4 projects at Koongie Park and Little Mount Isa respectively. Intensive exploration from 1972 to 1977, mostly within the gossan areas, included geological and structural mapping, rock-chip and soil sampling, diamond and percussion drilling. Four main areas (Gossan areas 1–4) were outlined at Koongie Park with significant base-metal mineralization hosted by chert, banded iron-formation and carbonate-rich assemblages. The four areas were Onedin, Hanging Tree, Gosford, and the most significant deposit, Sandiego. Work at the Ilmars prospect suggested that it contained 'about 2–10 Mt at ~2% Cu and was therefore uneconomic'. Work at the Little Mount Isa and Twin Hills prospects failed to locate significant mineralization.

From 1978 to 1979, Newmont continued testing the known mineralized prospects, as well as drilling magnetic anomalies coincident with EMP conductors between the main prospects. At Little Mount Isa, drilling of an EMP conductor returned uneconomic mineralization. At Koongie Park, detailed work including extensive trenching, percussion and diamond drilling, detailed EMP, ground-magnetic surveys and low-level aero-magnetic surveys failed to locate significant extensions of

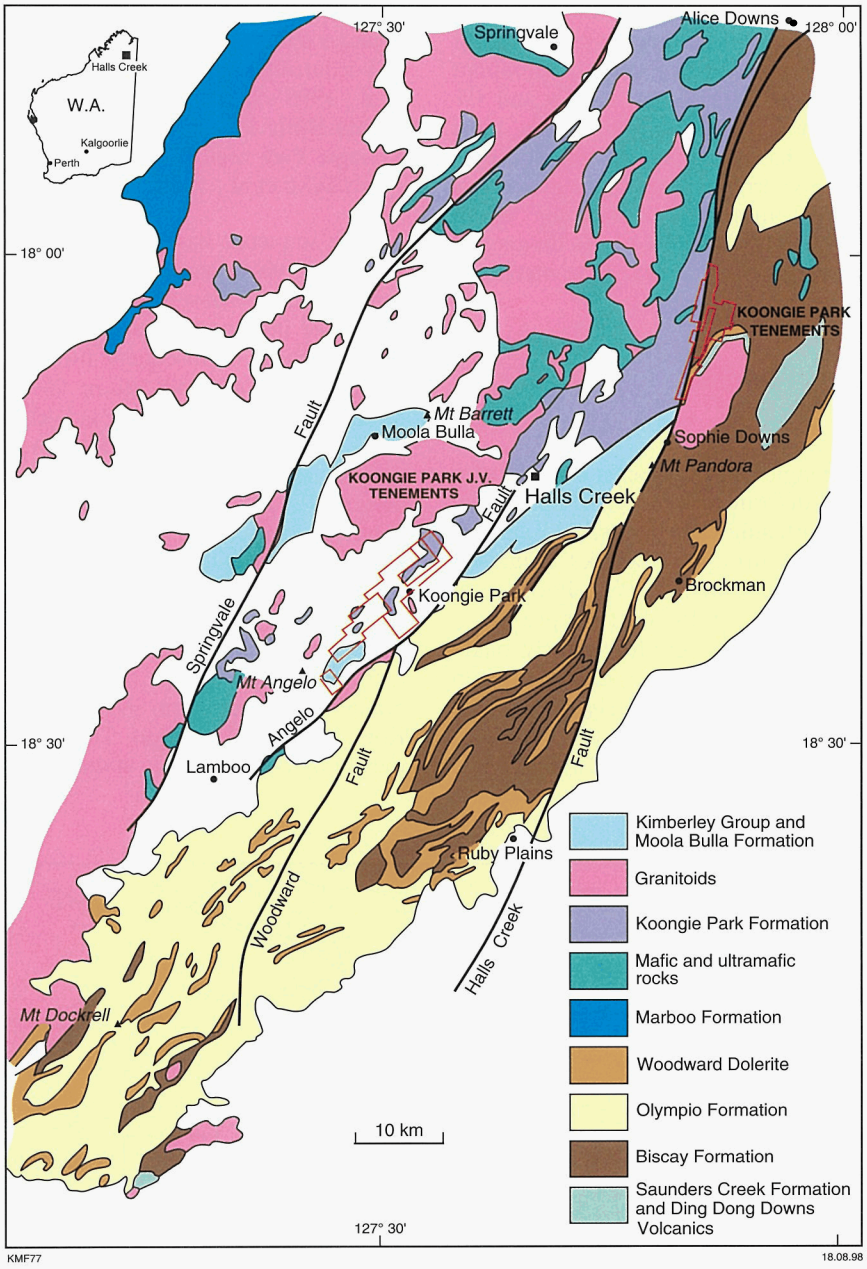


Figure 59. Regional geological setting of Koongie Park mining tenements (*after* Billiton)

the mineralization in the known prospects. However, several geochemical anomalies were outlined, at Onedin, Rockhole, Blue Heron, Cliffs, Highway, Dugong, Atlantis, Earthdam, and Parmelia.

During 1980 and from 1983 to 1988, North Broken Hill and Asarco drilled the supergene-enriched zone of the Sandiego prospect. This fieldwork established a demonstrated resource at Sandiego of about 0.30 Mt of supergene material at 6.7% Cu and 287 g/t Ag and 4.0 Mt of primary ore at 0.5% Cu, 0.8% Pb, 7.9% Zn and 30 g/t Ag. Percussion and RAB drilling in other geochemically anomalous areas, failed to locate significant base-metal mineralization. Limited testing was completed for gold in the sulfide deposits. In the Ilmars area, Asarco concentrated on gold exploration, intersecting 9 m at 4.1 g/t Au in an oblique intersection.

During 1989, BP Minerals/RT Min Corp in joint venture with Asarco continued testing the gold and base–metal potential of the Little Mount Isa and Ilmars prospects with reconnaissance bulk-leach drainage sampling and detailed mapping. This work located several low-order gold anomalies but no significant base-metal mineralization.

Since 1989 at Koongie Park, and 1990 in the Little Mount Isa group of prospects, exploration work conducted by Billiton Australia in joint venture with Anglo Australian Resources identified additional gossans with strong

geochemical anomalies. Extensions of the mineralization have been outlined in several of the known prospects. At Koongie Park, further work at the Onedin prospect 'outlined a resource of 1 Mt at 11% Zn, 1% Cu and 1% Pb' associated with complex parasitic folding. The most significant new discovery has been at the Atlantis (Puseye) prospect, where percussion drilling of a surface gossan has located a small massive-sulfide body containing 'about 0.1 Mt at 14% Zn, 0.3% Pb and 0.2% Cu'. At Ilmars and Little Mount Isa, drilling intersected weak base-metal and gold mineralization.

Koongie Park prospects

Geology

The setting for the Koongie Park prospects consists of a steeply dipping, highly deformed sequence of spheroidal felsic lava, argillites, volcaniclastic rocks, and various intercalated chemical sedimentary rocks (Fig. 60) collectively grouped as the Koongie Park Formation. These units were originally believed to represent a transitional period between the predominantly basic volcanic and calcareous sedimentary rocks at the top of the Biscay Formation, and the overlying arkosic sandstones, greywackes and shales of the Olympio Formation. Recent work by GSWA and AGSO has indicated that the 1.84 Ga Koongie Park Formation is a younger unit, separate from the 1.88 Ga Biscay Formation and occurring within a different zone of the orogen. (Tyler et al., 1995). It is locally overlain unconformably by the Moola Bulla Formation in the southeastern part of the Koongie Park area (Griffin and Tyler, 1992; Page et al., 1994; Tyler et al., 1995).

The sequence has been regionally metamorphosed to greenschist facies and is folded isoclinally in many of the prospect areas. Most of the sulfides appear to have been mobilized into, and are spatially related to, the isoclinal fold structures. Subsequent folding events have locally thickened the mineralization. The main folds, trending northeasterly, locally plunge in both directions and appear to be related to an F_3 fold event (Orth, 1993). In the Atlantis and Mount Angelo prospects, northerly trending, broad ($?F_2$) fold structures predominate (Fig. 60). In the Sandiego and Onedin prospects the mineralized zones are cut by shears which appear to have locally remobilized some of the sulfides.

Dolerite and granite bodies outcrop along the western margins of the Koongie Park prospect areas. In the east, granitic rocks appear to intrude the lower sections of the Koongie Park Formation. These granitic bodies are cut locally by dolerite dykes at the Atlantis prospect.

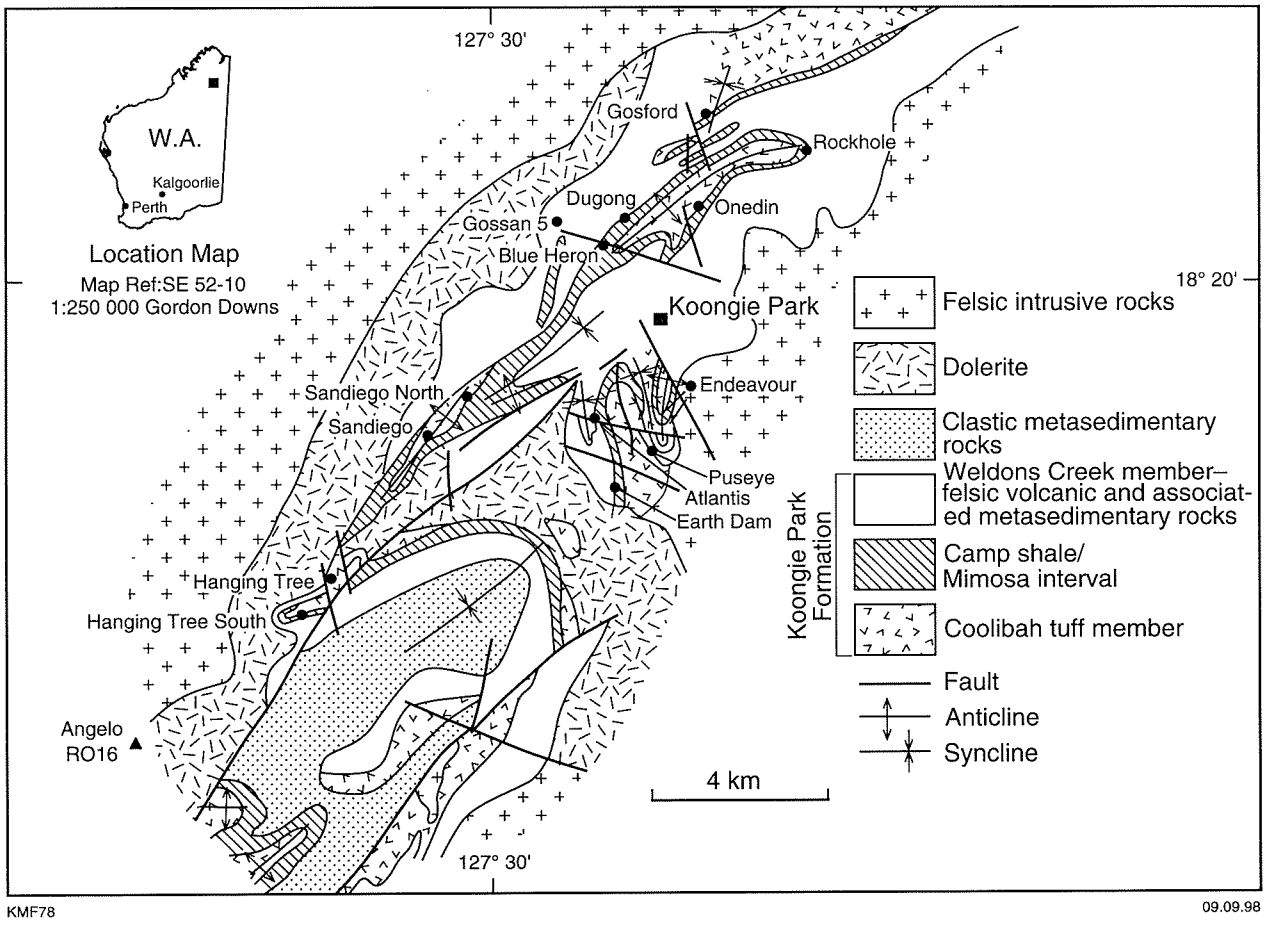


Figure 60. Koongie Park prospect locations: geology (*after* Billiton)

Table 14. Idealized stratigraphic column of Koongie Park Formation

Weldons Creek lava member		>100 m	spherulitic lava
		0.5–10 m	tuffaceous interbeds
Camp shale member Total thickness 100–300 m			
		1–40 m	tuff and siltstone
	Mimosa interval	0.1–5 m	chert
		0.1–2 m	quartz, carbonate, tremolite, chlorite, magnetite
rock			
		0.5–2 m	laminated quartz magnetite
		0.1–10 m	medium- to coarse-grained tuff
		0.5–2 m	alternating bands of tch, mtr and sm
		0.5–5 m	tuff with feldspar and carbonate clasts
		1–10 m	siltstone
		1–10 m	black shale
		1–10 m	tuff
	disseminated	0.1–7 m	fine-grained chlorite tuff
		0–10 m	chert
	massive sulfide	1–20 m	quartz, carbonate, tremolite, chlorite, sulfide
magnetite			rock
		0–10 m	chert
		1–30 m	carbonate
		2–20 m	talc, chlorite, carbonate
		1–5 m	talc, chlorite, carbonate with quartz eyes
Coolibah tuff member		>100 m	crystal tuff
		0–8 m	lapilli tuff

Stratigraphy

In considering stratigraphy for this area, it should be noted that the only formally recognized and defined unit is the Koongie Park Formation. Division of this formation into three members, and one further interval within one of these, is a device employed by Billiton Australia to assist in the ordering and understanding of the geology.

The Koongie Park Formation is composed of three members (Table 14); from the base upwards, the Coolibah tuff member, the Camp shale member with a carbonate-dominated lower portion known as the 'Mimosa interval', and the Weldons Creek lava member.

The *Coolibah tuff member* consists of layered rhyolitic and dacitic lapilli and quartz-eye volcaniclastic rocks and lavas and forms the footwall to all known mineralization. This member outcrops as a light reddish brown, massive friable rock with prominent phenocrysts of quartz. In drillcore this unit is dark green with quartz phenocrysts up to 12 mm in size within a strongly foliated matrix comprising muscovite, quartz and chlorite. Laminated chert–carbonate beds are developed towards the top of the sequence. In the Atlantis area, the base of this unit is transitional into more basic andesitic and basaltic lavas.

The *Camp shale member* commonly forms the hangingwall to the mineralization, and consists of a monotonous sequence of cleaved siltstones, and sericitic metasiltstone which is carbonaceous at the base. Interbedded with this sequence are fine-grained andesitic to dacitic volcaniclastic rocks and lavas, with rare thin locally mineralized chert–BIF layers. The lower portion of the Camp shale member is known as the 'Mimosa

interval' and is characterized by an abundant carbonate content. This unit consists of intercalated chert beds, chloritic schist, banded magnetite or pyrrhotite–chlorite rock, black shale (locally pyritic), impure dolomite, calc-silicates, carbonated chlorite–amphibolite rock, fine-grained andesitic lava and volcaniclastic rocks.

The *Weldons Creek lava member* comprises massive and homogeneous spherulitic dacite–rhyolite lava flows that are quartz-crystal rich to aphanitic. Thin banded iron-formation units are present throughout the member. Interbedded siltstone and sandstone is present towards the top of the sequence.

The base-metal mineralization is confined to the 'Mimosa interval' and consists of a mixed chemical sedimentary material with abundant silicate, oxide and sulfide facies minerals. The best known mineralization is associated with relatively thick basinal sequences of the Camp shale and 'Mimosa' units, which are intensely folded and locally sheared.

Mineralization and prospect geology

Onedin (Gossan Area 1)

The geology in the Onedin area is dominated by a northeasterly trending isoclinal F_3 antiform (Orth, 1993) that appears to plunge in both directions (Fig. 60) and is complicated by many locally overturned isoclinal parasitic folds developed along the eastern margin (Fig. 61). In general, the core of the antiform is composed of the Coolibah member, with a schistose fabric progressing outwards into the Camp shale and Weldons Creek lava members (Fig. 60).

The zinc–copper–lead mineralization, which lies within chert and oxide-facies iron minerals at the surface, is hosted at depth by dolomitic calc–silicate–sulfide facies units of the Mimosa submember. The mineralization appears to be best developed near and within the hinge zones of small parasitic folds (Fig. 62).

There is evidence in the drillcore and in thin section of possible shearing and remobilization of the mineralization along cleavage planes. This shearing seems to cut F_2 structures and possible F_3 structures at the surface (Orth, 1993). The mineralized zone, which appears to consist of a number of variably plunging discrete shoots, is currently believed to be one horizon which has been refolded and plunges at about 60° to the southwest. Zinc and lead grades decrease with depth into more copper-rich assemblages.

The ore consists of stringer to massive or banded fine-grained sphalerite, pyrrhotite, coarse chalcopyrite, pyrite and minor galena. Low-level gold values have been recorded at the top of the lens. Magnetite is locally

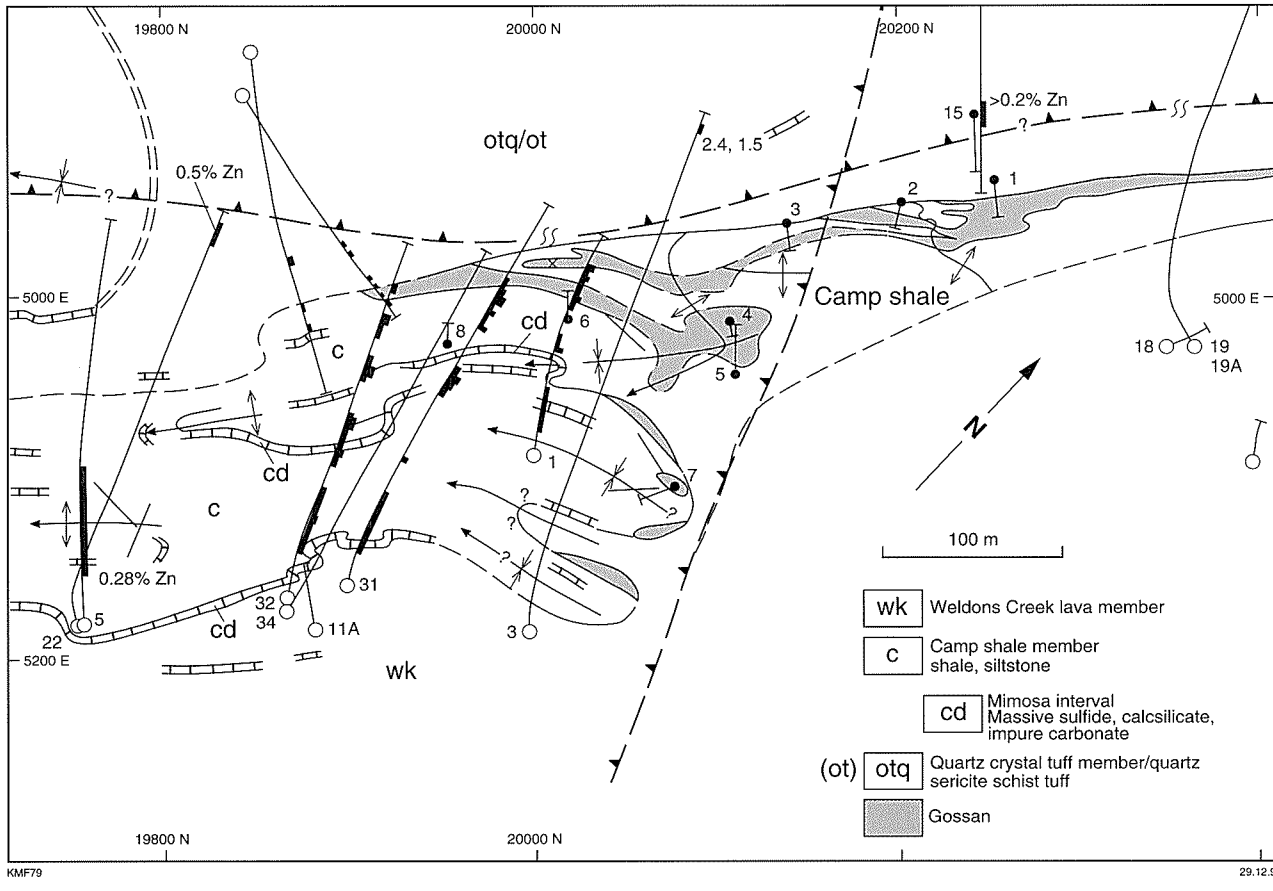


Figure 61. Onedin prospect: geological interpretation (*after* Billiton)

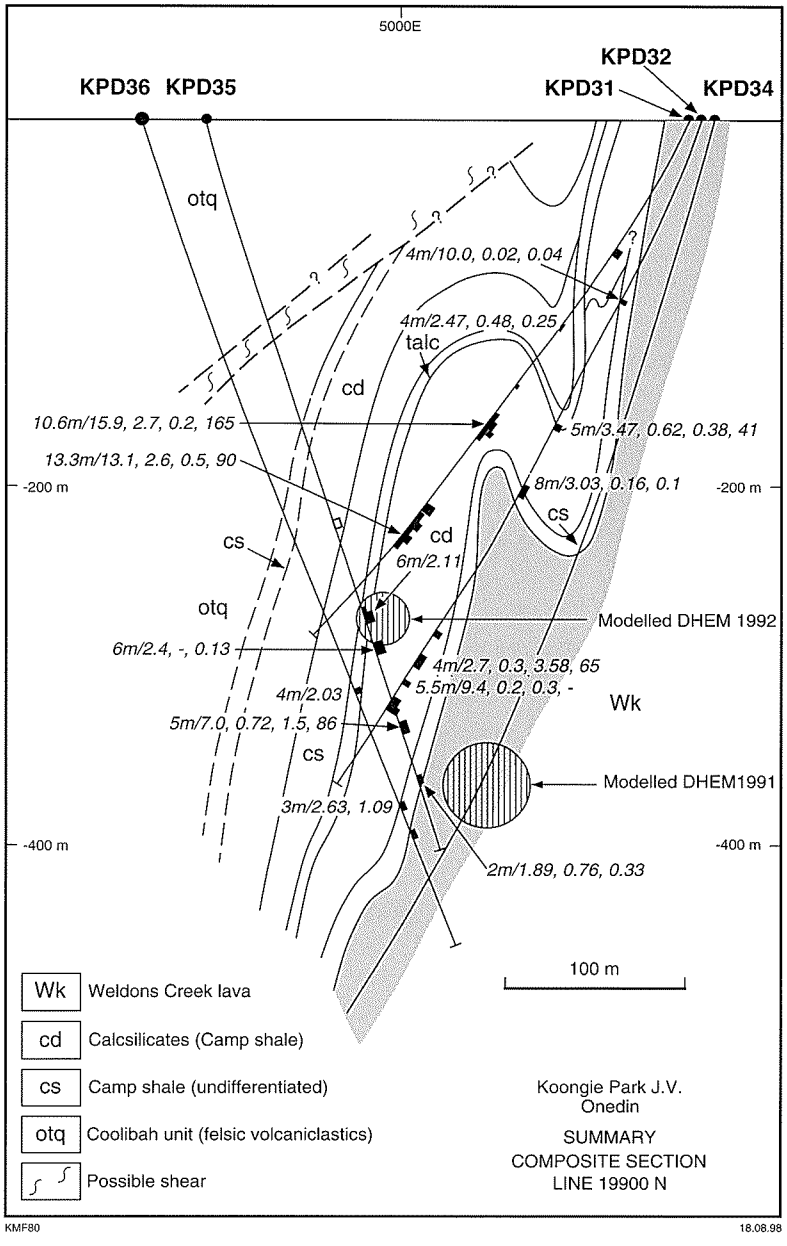


Figure 62. Onedin prospect: composite section 19900N (*after* Billiton)

associated with the main mineralization. The pyrrhotite invariably consitutes a strong downhole and surface EM conductor, and it extends tens of metres into the hangingwall and footwall sequences forming a halo to the main sulfide lens. Accessory Bi and Te minerals are present as inclusions in galena with possible tetrahedrite and tennantite. The sulfides mostly have granoblastic textures, with only pyrite being euhedral; late crystals enclose galena and/or chalcopyrite. Many of the galena crystals have replaced pyrrhotite.

The main alteration assemblages are magnesium rich after magnesium-rich carbonates, particularly below the mineralization, and consist of talc and phlogopite. Chloritzation, silicification and sericitization are pervasive.

An informal resource estimate for the prospect, using a width of 50 m, down-plunge extension of about 275 m, thickness of 25 m, with SG of 2.8, is 'approximately 1 Mt at about 11% Zn, 1% Pb and 1% Cu'. However, owing to the complexly folded nature of the mineralization this figure is likely to be optimistic.

SANDIEGO (Gossan Area 2) — *modified after* Woodhouse (1989) and Leeming (1979)

In the Sandiego area, the Coolibah unit is overlain by the mineralized carbonate-rich chlorite schists and cherts of the 'Mimosa interval'. These are overlain by siltstone (Camp shale) and Weldons Creek lavas. The prospect is dominated by an anticlinal structure that plunges steeply to the south-southwest.

Zinc–lead–copper–silver mineralization occurs in steep, southward-plunging, discontinuous sulfide gossans along the western limb of a fold over a strike length of 350 m (Fig. 63). Although no single lithology controls sulfide precipitation, the mineralization characteristically follows a mixed chemical sediment with abundant silicate-, oxide- and sulfide-facies iron minerals. Available evidence suggests a strong structural control on the localization of the mineralization, with massive sulfide shoots confined to tight folds and aligned parallel to the plunge of fold axes (Doepel, 1990).

The best intersections result where the host sequence is at its maximum thickness. To the north the host horizon lenses out, whereas in the south a major shear zone appears to have truncated the mineralized host. The best supergene mineralization, consisting of copper–silver (–gold), occurs at the coincidence of the shear zone with the primary ore. Later cross folding appears to have locally modified the sulfides into shoots of higher grade material.

The primary sulfides exhibit a crude zonation with a major footwall component of massive sphalerite, pyrrhotite and accessory galena overlain by a major hangingwall stringer zone of chalcopyrite and pyrite (Figs 64–66). Magnetite is an important accessory in much of the mineralization and contributes to the elevated magnetic signature of the deposits. The supergene sulfides consist of chalcocite and unidentified silver minerals. Gold mineralization identified to date is associated with copper in the hangingwall; the best intersection is 6m at 2.4 g/t Au.

The deposit extends to a depth of about 600 m, has a mineralized strike length of 180 m and an average thickness of 15 m. The ore zone delineated by drilling has the following resources (Carello, 1987):

(a) an upper supergene zone containing a demonstrated resource of 335 000 t at 6.71% Cu and 288 g/t Ag, with Au grades locally exceeding 2 g/t.

(b) a lower primary zone containing an indicated resource of 4.3 Mt at 0.51% Cu, 0.83% Pb, 7.9% Zn and 31 g/t Ag

The deposit has not been adequately closed off by deep drilling and over 50% of the primary ore is inferred from only one intersection (DDH 28C).

Hanging Tree (Gossan Area 3) — *modified after* Warne et al. (1976)

Located 3.5 km along strike from Sandiego, this zinc–lead–copper prospect consists of three discrete gossans

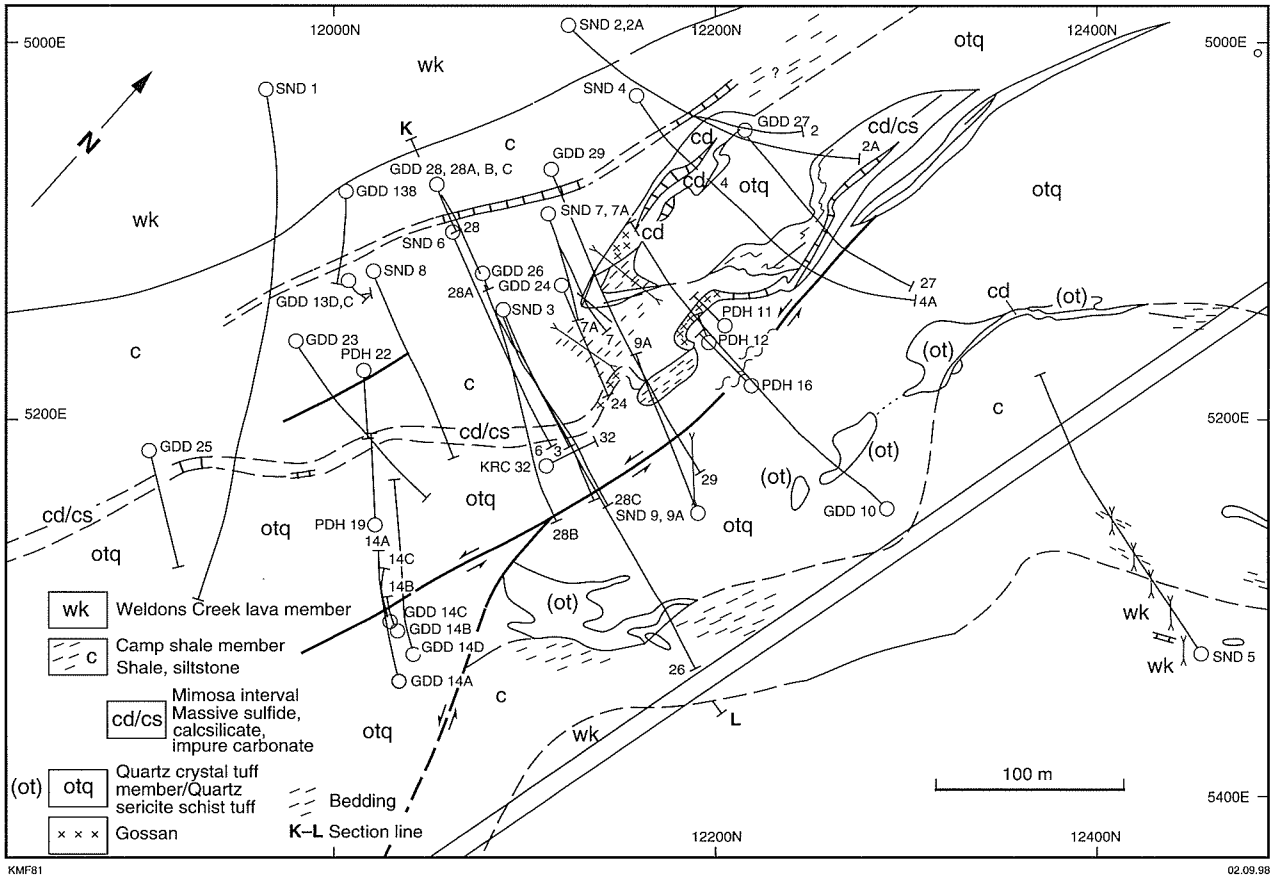


Figure 63. Sandiego prospect: geological compilation (*after* Billiton)

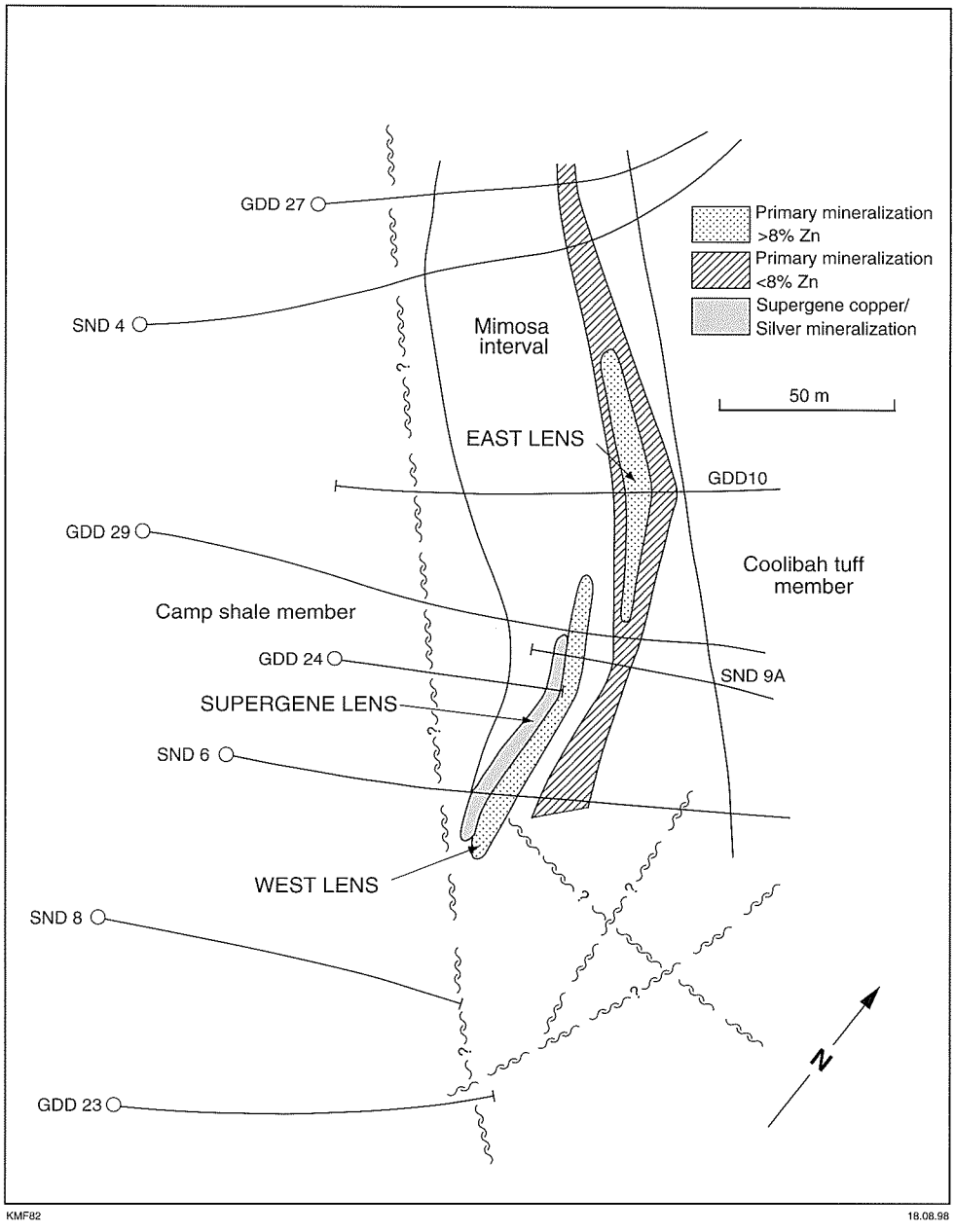


Figure 64. Sandiego prospect: 150 m-level plan (*after* Billiton)

within the 'Mimosa interval' of the Camp shale along the western limb of a northerly plunging anticline (Fig. 60). The geology of the area is complicated by strike-slip faulting and extensive dolerite intrusives. The main gossan forms outcrops over a strike length of about 150 m in a silicified, brecciated carbonate horizon with graphitic interbeds. Rock-chips percussion and diamond drillholes into this zone intersected stringer and disseminated sphalerite, galena and chalcopyrite in shale units (cut by dolerite) gave values up to 0.37% Cu, 0.57% Pb and 0.9% Zn. Pyrrhotite was intersected beneath a magnetic gossan in the southern part of the prospect within mafic, carbonated schists (presumably of the 'Mimosa interval'). The pyrrhotite and graphitic horizons appear to be the EM conductors in the prospect.

Gosford (Gossan Area 4) — *modified after* Warne et al. (1976)

At the Gosford prospect, about 3 km north of Onedin, the geology consists of a weakly mineralized gossan 3 to 7 m wide composed of numerous lenses of banded iron-formations that are magnetic and silicified with brecciated chert bands of the 'Mimosa interval'. The rocks have a very strong planar fabric and several tight isoclinal folds have been mapped.

The main zinc–copper–lead gossan strikes northeast, plunges steeply at about 80° to the southwest, and can be traced discontinuously at the surface over a distance of about 80 m. Structural mapping has indicated that the mineralization is associated with the western limb

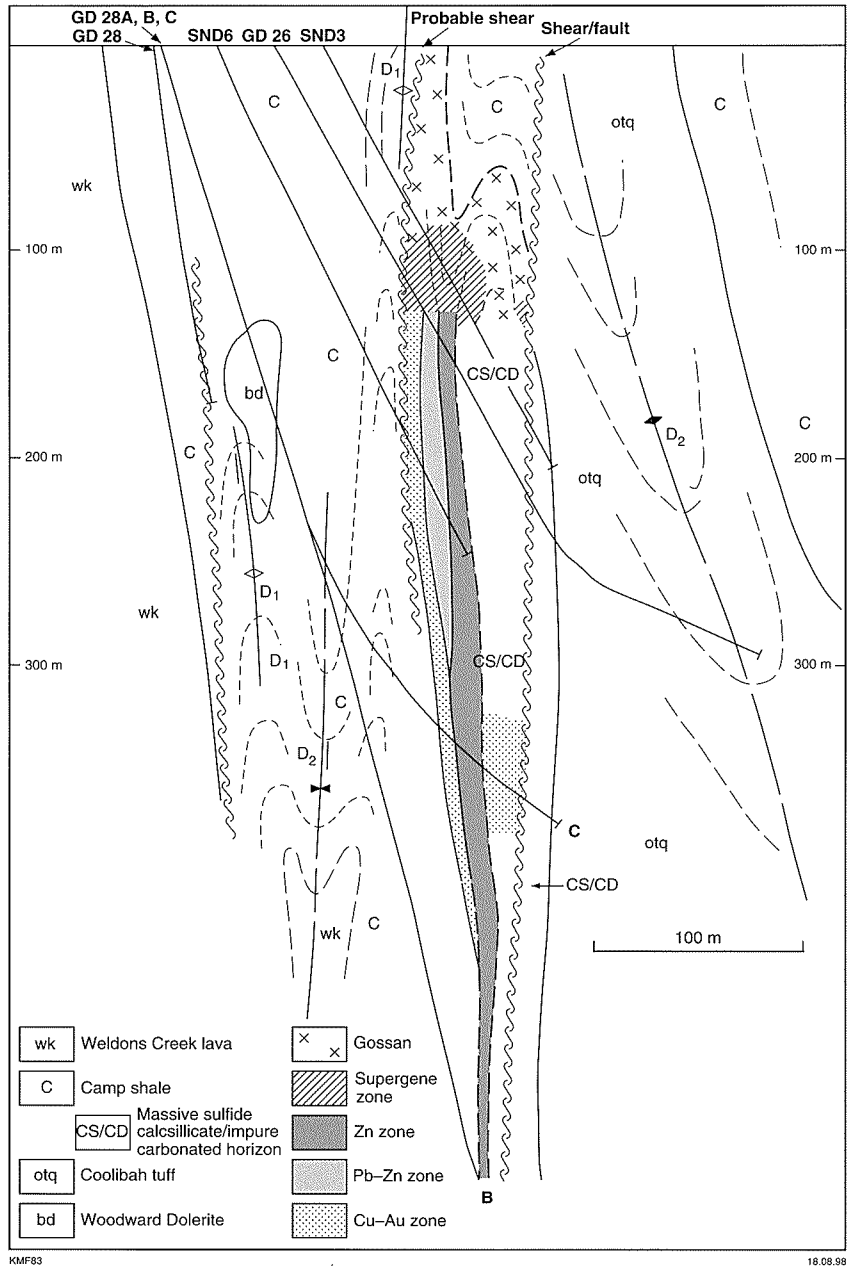


Figure 65. Sandiego prospect: geological interpretation (*after* Billiton)

of a syncline that closes to the southwest. The geology is complicated by numerous isoclinal fold structures (related to several events) that plunge steeply westward.

Initial diamond and percussion drill testing by Kennecott returned a single sulfide intersection of 6.31 m at 0.31% Cu, 2.45% Pb and 11.2% Zn. Follow-up diamond and percussion holes by various workers, downdip and along strike within the same horizon, intersected only pyrite and pyrrhotite with minor sphalerite. The southwest and downdip extension of the mineralized fold has been truncated by dolerite. The dolerite appears to have intruded along a pre-existing north-trending fault in the southwest.

Mount Angelo — *after* Fehlberg (1988)

This prospect covers two base-metal deposits (Fig. 67) and lies in a fault-bounded wedge at the southwestern end of the Halls Creek Orogen. The prospect is located within a suite of deformed felsic volcanic and sedimentary rocks of the Koongie Park Formation. Members of the Koongie Park Formation recognized in and around the prospect include the Coolibah tuff, 'Mimosa interval' and Weldons Creek lava. The Weldons Creek lava unit is overlain unconformably by shale and greywacke. These units, which were originally believed to be part of the Olympio Formation (Riley, 1974), are now thought to be part of the Moola Bulla Formation (Griffin and Tyler,

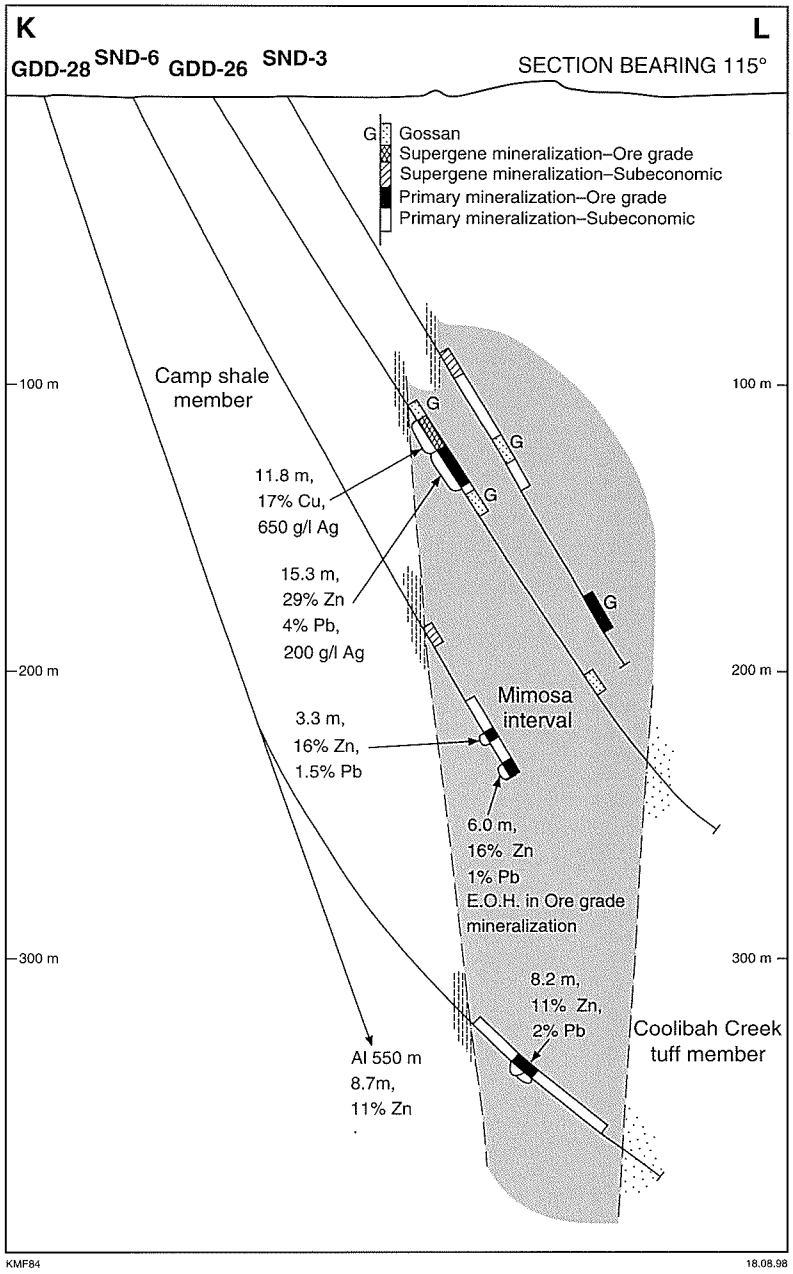


Figure 66. Sandiego prospect: section K–L (location shown in Figure 63) (*after* Billiton)

1994a). The sequence is cut in the south by the Bow River batholith, which locally comprises quartz–feldspar porphyry and granodiorite.

A weak porphyry-copper system in the southern portion of the prospect is associated with late-stage differentiates of the Bow River batholith. At the northern end of the prospect, a massive-sulfide body is hosted by volcanogenic rocks of the Koongie Park Formation.

The Mount Angelo massive-sulfide copper–silver body is hosted by the 'Mimosa interval'. This mineralization lies within a zone of interbedded tuffaceous and chemical sedimentary rocks in the lower tuffaceous section of the interval. The mineralization, which consists primarily of copper and silver, occurs as two lenses of massive base-metal sulfides in shale with associated stringer zones elongated in a northeast direction. A pyritic halo surrounds the mineralized zone. Spherulitic lava and associated tuff of the Weldons Creek lava member overlie, and in places enclose, the shale lenses. Numerous dolerite intrusive bodies cut the ore sequence, which is associated with a major strike-slip fault. At least three episodes of deformation are recognized in the area.

Irregular and contorted limestone and quartz–magnetite lenses are believed to be lateral equivalents of the mineralized bodies (Riley, 1974). Disseminated malachite zones and stringer gossans are also locally present in the Weldons Creek lava member. At depth

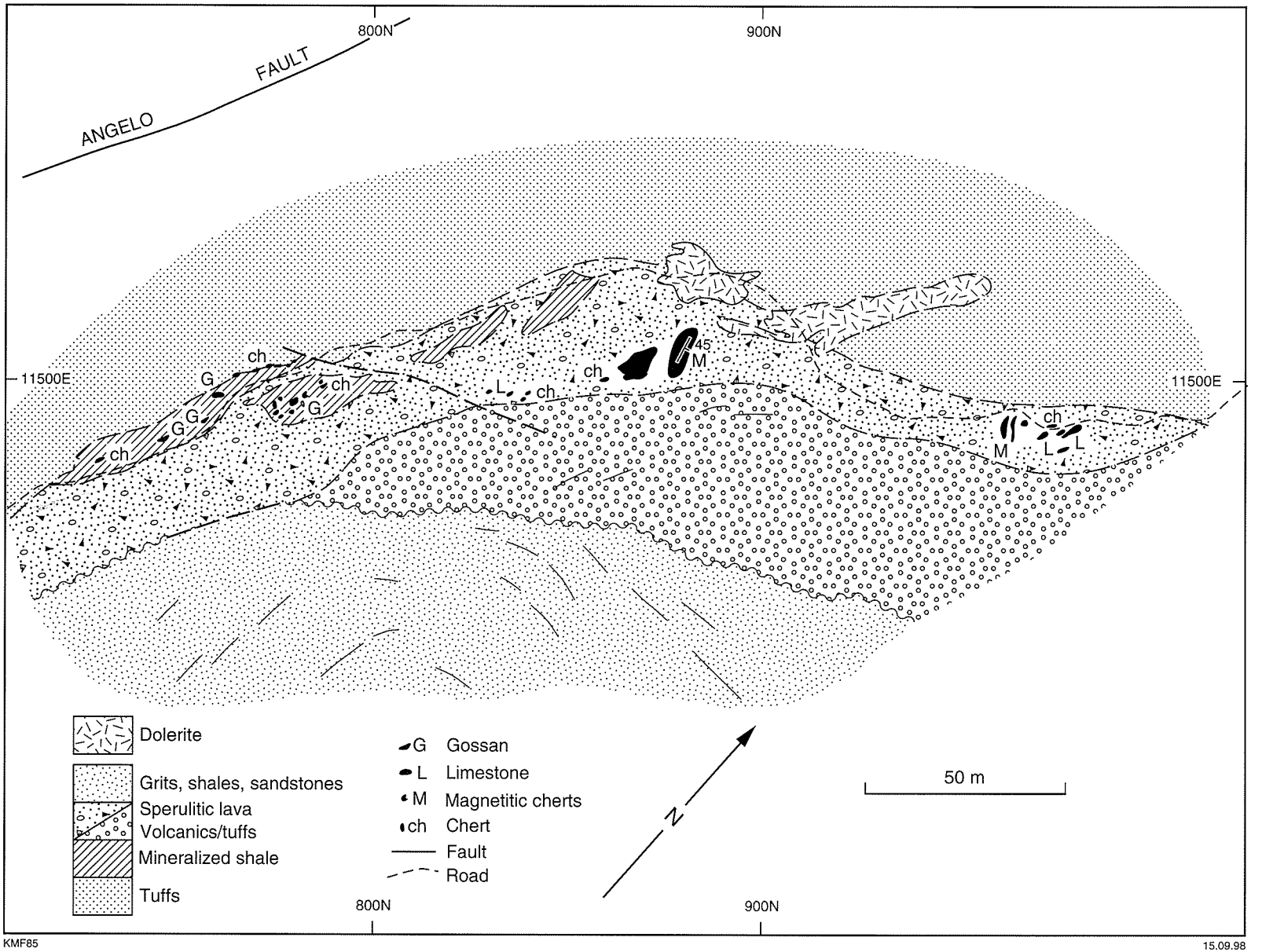


Figure 67. Angelo Valley prospect: geological interpretation (*after* Billiton)

these zones consist of disseminated veinlets of copper sulfides (which are possibly shear controlled) hosted by coarse tuff.

Resource estimates for the various zones identified in the massive sulfides, based on initial drilling are Carbonate gossan — 76 Mt at 1.0% Cu, 9.6 g/t Ag; Silver Blanket — 35 Mt at 1.1% Cu, 45.0 g/t Ag; Chalcocite Blanket — 11 Mt at 7.7% Cu, 19.1 g/t Ag; and Primary Sulfide — 200 Mt at 2.0% Cu.

The Mount Angelo porphyry-copper body is hosted by a sheared granophyric microgranite at the southern end of the prospect. The primary sulfide mineral is chalcopyrite with minor amounts of bornite, tetrahedrite, pyrite, sphalerite and molybdenite (Blain, 1969). The chalcopyrite as described by Blain (1969) is concentrated in poorly defined north-northeasterly trending linear zones that are characterized by local hydrothermal alteration of the host rock. Alteration minerals consist of K-feldspar (adularia), sericite, albite, quartz, epidote, chlorite, rutile, sphene and sulfides.

Mineralization has been established over an area 600 m long, 400 m wide and down to 300 m vertically. 'Resource estimates (*after* Fehlberg, 1988) give 144 Mt at ≥0.2% Cu'. Gold mineralization, based on shallow RAB holes to depths of about 30 m, is very low grade and although there is a supergene zone, the reported gold values are subeconomic (best intersection gave 8 m at 0.2 g/t Au).

Atlantis (Puseye)

The main geological feature at Puseye, as deduced from RAB drilling, is a southerly plunging anticline. The anticline has been refolded by a later northwesterly trending event which may have localized the mineralization (Fig. 68). The core of the anticline consists of intermediate and felsic schist of the Coolibah member

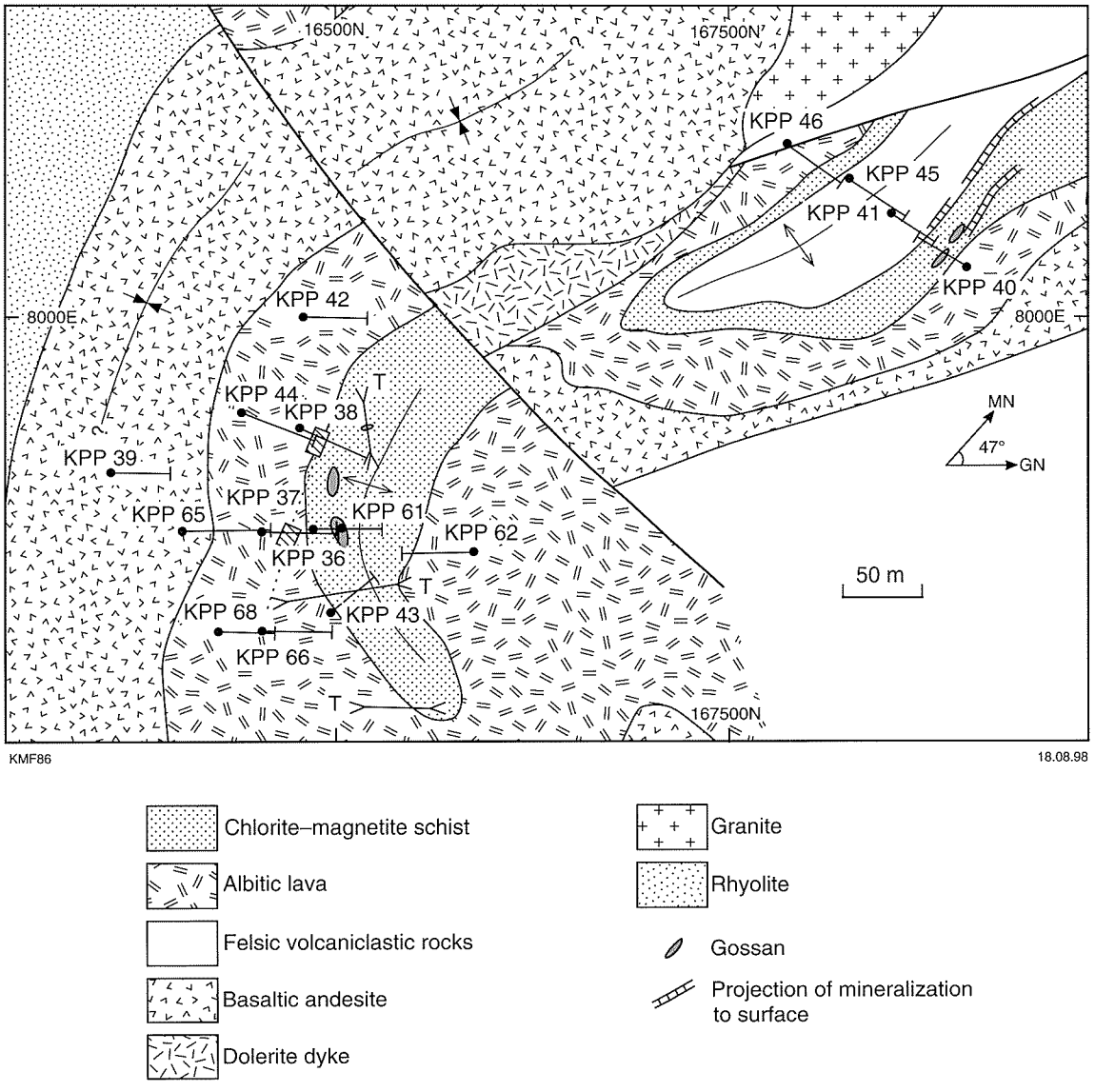


Figure 68. Puseye prospect: drillhole locations (*after* Billiton)

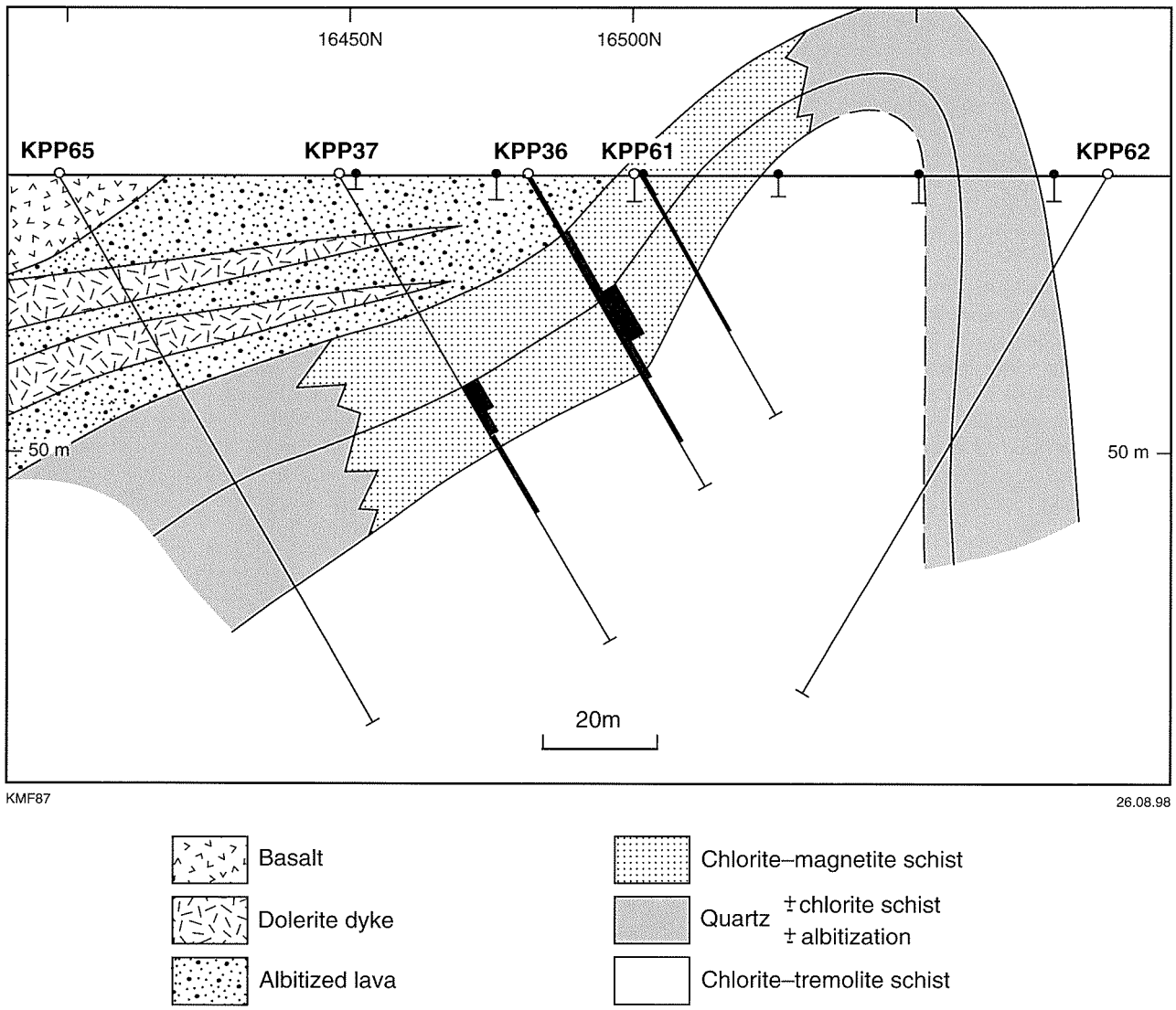


Figure 69. Puseye prospect: cross section 8135E (*after* Billiton)

overlain by the 'Mimosa interval' of the Camp shale member, and consisting here of chloritic schist with magnetite, chert and massive sulfides. Felsic and andesitic lavas overlie the sequence (Fig. 69).

Mineralization in the chert–magnetite pod, consists mainly of zinc with minor lead and copper and is best developed in the western limb of the anticline, where it appears to plunge towards the south-southeast from the surface in the hinge of the later fold. The main alteration assemblages include: phlogopite, tremolite, chlorite, actinolite and talc in the footwall schists of the Coolibah member. Albite and epidote are common in the lavas overlying the mineralization. Most of the chlorite, and possibly some of the albite, is related to metamorphism. Accessory rutile rimmed by sphene is locally present with apatite.

An informal resource estimate for the mineralized pod is less than 0.1 Mt, based on a thickness of 8 m, a width of about 50 m and downdip extension (based on drilling) of less than 80 m. Average grades for the pod are about 14% Zn and 0.3% Pb and 0.2% Cu.

Little Mount Isa prospects

Geology

The host rocks of the Little Mount Isa prospects (Fig. 59) are tightly folded and complexly faulted and have been intruded along their eastern margin by dolerite (Fig. 70). The prospects are bounded to the west by the Halls Creek Fault, and a northeasterly plunging anticlinorium appears to control the distribution of the main prospects.

Stratigraphy

The stratigraphy is, from the base upwards, the Sophie Downs Granite, the Saunders Creek Formation, and the Biscay Formation. These rocks are intruded by the Woodward Dolerite.

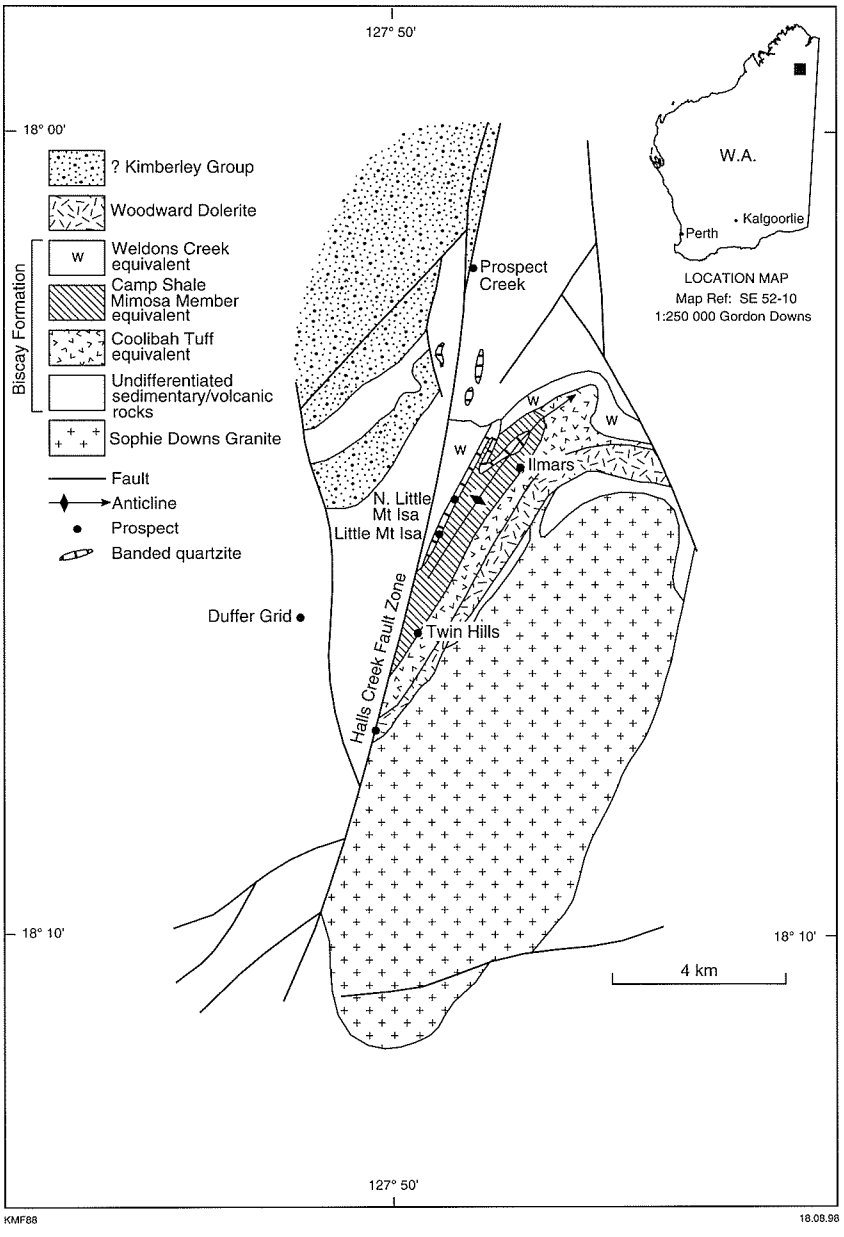


Figure 70. Little Mount Isa prospect locations: geology (*after* Billiton)

The *Sophie Downs Granite* occupies the core of a structural dome along the eastern margins of the tenements that cover the prospects, and it consists of granite and granophyre of fine to coarse grain size with varying proportions of mica and chlorite.

The *Saunders Creek Formation* consists of quartz arenite, quartzite and conglomerate and is confined to the contact zone between the Sophie Downs Granite and Woodward Dolerite at the central eastern margin of the Little Mount Isa prospects. Griffin and Tyler (1992) reported an unconformity between the Saunders Creek Formation and the underlying Sophie Downs Granite.

The *Biscay Formation* incorporates a variety of rocks including carbonated basalt–dolerite, siltstone, chert, calc-silicate schist, limestone, quartzite, greywacke, black graphitic shale, rhyolitic volcanics, agglomerate and basic to intermediate schist. Gossanous horizons that mark the Little Mount Isa, Ilmars and Twin Hills prospects are hosted by acid volcanic and chert–carbonate rocks.

The *Woodward Dolerite* is composed of basalt, dolerite and gabbro lithologies and textures.

Mineralization and prospect geology

Ilmars — *modified after* Fehlberg et al. (1973) and Masham (1970)

The Ilmars zinc–copper(–gold) prospect, is located about 25 km northeast of Halls Creek. The deposit is hosted by

the Biscay Formation in felsic volcanic and sedimentary rocks similar to those found at Koongie Park (Fig. 70). The sequence, which is tightly folded and faulted, consists of intercalated carbonate, calc-silicate rock, quartz–chlorite and graphitic schist, felsic volcanic rocks and chert.

The gossans, which are formed mainly from disseminated sulfides, are lithologically controlled (at least in part) and occur where there is a change in facies from quartz–chlorite schist to calc-silicate rock. At the surface the gossans contain limonitic boxworks and are locally copper–carbonate stained and veined. They vary in width from 0.5–50 m and can be traced discontinuously along strike for about 1.5 km. Mineralization appears to be concentrated near gullies that coincide with cross-cutting east–west faults (Woodhouse, 1989). Ore minerals consist predominantly of sphalerite and chalcopyrite with minor galena. Base-metal mineralization is enriched at the surface. Oxidized mineral assemblages include cuprite, malachite, azurite, smithsonite and cerussite. Numerous low-grade gold values in the range 0.5–1.0 g/t have been reported.

Grades from the extensive percussion and diamond drilling have been generally disappointing, all being subeconomic apart from one massive-sulfide intercept of 2.5 m at 14% Zn and 2% Pb in DDH317 and one gold intercept of 4m at 4.1 g/t in a shallow percussion hole (Carrello, 1987). In the central portion of the area a zone approximately 850 m long has been defined which yielded grades of greater than 1% Zn and 0.5% Cu occur. The tonnage potential lies between 2 and 10 Mt of at least 2% Cu (and equivalent) assuming depths to 450 m, a mineralized strike length of 420 m and a width of 6–30 m. The irregular intersections obtained in the drilling to date indicate that mineralization occurs in a number of 'ore shoots'.

Little Mount Isa — *modified after* Warne (1975)

As for Ilmars, the Little Mount Isa prospect lies within a tightly folded sequence of interbedded carbonate-rich sedimentary rocks, chert and felsic volcanic rocks of the Biscay Formation. The sequence dips at 60° to the west. The main gossan forms outcrops along a steep ridge striking for about 600 m with highly anomalous copper, lead and zinc values over 300 m of strike. Sporadic gold values up to 0.2 g/t Au have also been intersected.

At the surface the gossan is very siliceous and seems to be a locally mineralized portion of a more continuous chert horizon that extends to Ilmars (Fig. 70). The gossan has a maximum thickness of 15 m and is made up of a western zone with continuous outcrops over a strike length of 490 m, separated by up to 6 m of chlorite schist from a narrower discontinuous eastern zone. Drill testing has shown that at depth, the carbonate–chert gossan undergoes a rapid facies change and is represented by a thick, black, locally graphitic, pyritic shale in a sericite schist.

Sulfide minerals are mainly pyrite and pyrrhotite. There are some narrower sections of sphalerite and galena, and others carry chalcopyrite. Quartz is the most common gangue mineral in some sections with calcite predominating in others. Mineralized drill intercepts range from 1–15.5 m thick and are invariably associated with siliceous rocks. Averaged assays from some of the better mineralized sections gave intercepts of up to 5 m at 5.0% Zn with up to 1.2% Pb locally. Although copper minerals are present in the surface gossans, drilled grades were generally less than 1% Cu.

Twin Hills — *modified after* Woodhouse (1989) and Carrello (1987)

Located 4 km south along strike from Ilmars (Fig. 70), the Twin Hills prospect is set in a sequence of felsic volcanic rocks and quartz–sericite–chlorite schist. A sheared, gossanous chert horizon 1 km long outcrops within this sequence and contains weak base-metal mineralization. Minor cordierite–chlorite is locally associated with the shear. The chert horizon contains pyrite boxworks and several malachite-stained lenses up to 10 × 3 m in size with maximum assays of 12% Cu, 3% Pb, 6.7% Zn, 22 g/t Ag and 0.88 g/t Au. Percussion and RAB drilling intersected weak base-metal and gold mineralization (≤3% Zn and 2.8 g/t Au over 1 m) in quartz–sericite schist.

Ore genesis

The regional geological setting, coupled with the style of mineralization, the alteration, and the lithological associations, suggests that ore formation took place in a volcanogenic or sedimentary–exhalative massive-sulfide setting that was later complexly folded and faulted. The mineralization occurs within a pile of predominantly felsic volcanic and volcaniclastic rocks with interbedded chemical sedimentary material in a probable distal volcanogenic environment. The prospective horizon lies within the chemical sedimentary rocks which include chert, banded iron-formation, carbonate, chloritized and carbonated volcanic rocks, volcaniclastic rocks and siltstone. Within the chemical sedimentary unit, systematic facies changes are comparable to sedimentary–exhalative facies variations with a progression from low-grade oxide facies, to carbonate facies, to silicate–sulfide facies, and to volcanic-sulfide facies.

The best known mineralization is restricted to relatively thick basinal sequences within the volcanogenic setting and probably has a strong structural control. Massive sulfides are commonly within, and apparently controlled by, tight folds with most shoots aligned parallel to the plunge of fold axes. Recent work by Orth (1993) has shown that some of the sulfides at Onedin are epigenetic and were remobilized during folding of the volcanogenic precursors. This remobilization produced areas of local thickening and upgrading after deposition of the host sequence and formation of most of the sulfides. Evidence of recrystallization is present in the epigenetic ores.

It has been suggested that shear zones, such as those intersected in the drilling and mapped at Onedin and Sandiego, may have acted as channels for mineralizing fluids. Recent work by Orth (1993) has indicated that although most of the shears post-date the mineralization and folding events, they may have acted locally as fluid

pathways for the epigenetic remobilized ore.

Conclusions

Subeconomic zinc–copper–lead(–silver) mineralization occurs in calc-silicate units in small stratabound and locally stratiform bodies at Onedin, Sandiego, Hanging Tree and Gosford in the Koongie Park area and at Ilmars, Twin Hills and Little Mount Isa in the Little Mount Isa region. The mineralization generally occupies steeply plunging shoots which are controlled by isoclinal folds. Minor remobilization of the sulfides is locally associated with shearing. Ore formation took place 40 m.y. apart in similar submarine settings typical of volcanogenic or sedimentary–exhalative massive-sulfide deposits.

Acknowledgments

Deciphering the geology of base-metal prospects of the Koongie Park and Little Mount Isa areas has been a team effort spanning at least 20 years by numerous companies and government employees. The author is grateful to all those whose observations have contributed to the present understanding. Special thanks are due to Karin Orth, Mark Hronsky, Dave Blake, Dean Hoatson, Paul Askins, Keith Kenny and Kerry Turnock who screened various drafts of this contribution.

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Golf Course (Gordon Downs 1)

Prospect: Cu; Pb; Zn
Location: 18°12'40"S, 127°39'30"E; 2 km north-northwest of Halls Creek

Discontinuous malachite-stained, limonitic gossans occur in the Biscay Formation near the north edge of the Bow River batholith, within east-northeasterly trending quartz–sericite–chlorite schist, metabasalt and metadolerite. The schist is after rhyolitic lapilli tuff and hosts a copper gossan (60 × 5 m). An overlying pyritic chert carbonate unit, which hosts zinc and weak lead mineralization over 600 m of strike, is in turn overlain by magnetite and iron-rich shale. These sedimentary rocks appear to define a localized depositional basin over the tuff.

In 1963, Peko drilled one diamond hole beneath the copper gossan but did not encounter significant mineralization. PMI carried out surface exploration in 1970–71 and Kennecott (1972–76) undertook a costeaning program across the copper gossan and defined potential for a medium-sized orebody of 0.5 to 5 Mt. Electromagnetic and IP surveys suggested only disseminated mineralization; gossan samples gave up to 11.6% Cu and 0.26% Zn. Asarco (1984–86) resampled gossans with a gold focus and best results obtained were 1.1% Pb, 0.5% Zn, 16% Cu and 0.47 g/t Au in separate samples. The prospect is presently held by AAR/Billiton.

References: Marston (1979), GSWA-WAMEX - I 34, I 251bz, I 4143, I 6157.

Eastmans Bore (Eastmans Yard, Boundary Prospect, Landrigan Creek, Bullock Bore)

Prospect: Cu; Pb; Zn; Ag; Au
Location: 18°42'30"S, 126°32'30"E; 130 km southwest of Halls Creek

Distal volcanogenic copper–lead–zinc mineralization occurs in a sequence of felsic metasedimentary rocks including rhyolite fragmentals, turbidite, quartz–sericite and calc-silicate schist and phyllite (after partly calcareous sandstone and siltstone) of the Koongie Park Formation, intruded by metagabbro. The main Eastman prospect mineralization is in sheared, chloritized rhyolitic breccia and talcose carbonate rocks represented by a zone 60 m long of disseminated malachite and chrysocolla.

In 1964–68, PMI found minor galena in shears and veins in greywacke. Mapping, surface geochemistry, and IP and EM surveys followed by diamond drilling in the Eastman prospect by Newmont and Kennco in 1969–72, encountered disseminated, low-grade copper sulfides over limited strike lengths in a zone measuring about 250 by 90 m. The best intersection was 16.9 m at 1.6% Cu and 0.28% Zn. This was considered to be a possible feeder zone to lead–zinc mineralization in an overlying carbonate-rich sedimentary unit with 0.76 m of 7.7% Zn, 3.12% Pb and 122.5 g/t Ag.

BHP (1977–85) discovered magnetic horizons within the zone defined by Newmont/Kennco. Farther to the northwest, a RAB anomaly over SIROTEM targets was diamond drilled at Landrigan Creek and gave a best intersection of 9.6 m at 2.7% Cu, 1.5% Zn, 0.3% Pb, 12.6 g/t Ag and 1.5 g/t Au in oxidized, ?hydrothermally altered chlorite–talc schist in the core of a synform. Lower grade lead–silver(–zinc) mineralization was also found in stratigraphically lower sericite–talc–clay schist with a best intersection of 0.3 m at 1.02% Pb, 2.9% Zn, 0.33% Cu and 15 g/t Ag. Peko (1986–90) followed up a reinterpretation of BHP's geochemical data. EM targets were located in the Boundary, Northern banded iron-formation, and West Landrigan areas of felsic rocks and graphitic shale. The best intersections from RC drilling were 2 m of 1.16% combined copper, lead and zinc in ironstone within chloritic schist in the Boundary area, and 28 m of 0.26% Zn in quartz–sericite schist in the West Landrigan area. Delta Gold/AAR/Aztec (1991 on) are continuing gold and base-metal exploration in the area.

References: Marston (1979), GSWA-WAMEX - I 34, I 251bh, I 734, I 741, I 2489, I 5861.

King Leopold Orogen

Turtle Creek

Prospect: Pb; Zn; Ag; Cu; Au; As; Sb
Location: 17°25'S, 125°18'40"E; 64 km east-southeast of Napier Downs Homestead

Massive stratabound sulfide mineralization is present in carbonaceous phyllite of the Marboo Formation, bounded above and below by metadolerite (Ruins Dolerite), in the northeast limb of the northwesterly trending Richenda Anticline. The mineralized sequence also includes quartz–feldspar schist and felsic tuff. A spectacular, limonitic, malachite-stained gossan, on the same northwest trend, is 270 m long and less than 6 m wide. The following mineralogy has been recorded in the massive, generally fine-grained and foliated sulfides: pyrite, pyrrhotite, chalcopyrite, sphalerite, bournonite, galena, tetrahedrite, tennantite, jamesonite, arsenopyrite, tetradymite, boulangerite, jordanite and stibnite.

WMC/Richenda (1973–74) explored a number of prospects in this area (Fig. 71). At Turtle Creek, shallow percussion drilling (22 holes) following up IP anomalies established a zone 100 m long containing high lead–zinc values, with up to 6.5% Pb and 347 g/t Ag, but with less than 1% Cu, except for a 15 m-long area of limonitic gossan. The best intersection in the subsequent diamond drilling of three holes was 2.61 m (2.38 m true width) at 2.1% Cu, 4.2% Zn, 3.5% Pb, 167 g/t Ag, 2.7 g/t Au and 4.2% As in pyritic, graphitic siltstone to 80 m depth. Zinc content increased with depth. Richenda (1980–81) carried out further percussion drilling that established a discontinuous extension of the mineralized zone to the south, where a 2 m intersection gave 1.6% Pb and 83 g/t Ag. Cygnet (1987–89) used multispectral imagery in an unsuccessful attempt to identify zones of alteration. Moonbeam (1985 on) is exploring in the area for gold and extracting 'Derby Black Granite', as ornamental stone. Pancon has continued exploration of the prospect from 1991.

References: Marston (1979), GSWA-WAMEX - I 780, I 1200, I 5453.

Colemans Creek (Colemans Camp)

Prospect: Cu; Pb; Zn; Ag
Location: 17°29'S, 125°21'40"E; 73 km east-southeast of Napier Downs Homestead

This prospect, located 9.5 km along strike to the southeast of Turtle Creek, consists of northwest-trending, steeply northeast-dipping, narrow gossanous malachite–cuprite–azurite-bearing stratabound lenses in strongly sheared chlorite–biotite–quartz–phyllite with greywacke and tuff units. The copper-bearing quartz veins and lenses and small areas of malachite staining persist over 75 m of strike.

WMC/Richenda (1973–74) located an IP anomaly similar to that at Turtle Creek. Two percussion holes intersected carbonaceous phyllite with minor pyrite and pyrrhotite. Copper, lead, zinc and silver levels were low. Moonbeam (1985 on) is currently exploring this prospect.

References: Marston (1979), GSWA-WAMEX - I 780.

Potential

The exact nature of the tectonic setting of the Halls Creek and King Leopold Orogens is in some doubt at present. The recent GSWA–AGSO detailed mapping in the area has contributed to a better understanding which suggests that the type of plate-tectonic processes involved were not fundamentally different from those that operate at the present (Tyler et al., 1995).

Plumb (1990), following Hancock and Rutland (1984), described the Halls Creek Province (the combined orogens) as essentially ensialic, and occupying a boundary between a supposed cratonic Archaean nucleus, concealed beneath the Kimberley Basin, and more attenuated transitional crust to the east. Early rifting in an extensional environment (Ding Dong Downs Volcanics, Halls Creek Group, Tickalara Metamorphics and Marboo Formation) was followed by a period of compressional tectonics, possibly involving oblique convergence from the southeast and limited subduction of the rift-basinal area. This would coincide with the Barramundi Orogeny, ~1.84 Ga, a widespread event in the Proterozoic of northern and eastern Australia. The Koongie Park Formation, and associated stratiform copper–lead–zinc mineralization, is associated with this orogenic period and postdates D_2 (1.85 Ga) upright isoclinal folding.

On present evidence, however, Tyler et al. (1995) suggested that the setting of the Koongie Park Formation is more in keeping with the subduction-related volcanogenic mineralization seen elsewhere in the Western Australian Precambrian, than is the rift-basin setting of the minor occurrences in the Biscay Formation. However, the host units in both cases are very similar. Minor copper-rich occurrences in slates and felsic tuffs of the Marboo Formation, in the King Leopold Orogen, suggest limited potential in this unit. On balance, the Koongie Park Formation would seem to have more potential than the Biscay Formation for economic volcanogenic base-metal mineralization. Distribution of the formation, however, is limited and it has already been extensively explored. Page (1994) has suggested a common thermal–magmatic origin for the submarine Koongie Park Formation, and the subaerial Whitewater Volcanics exposed to the west and north. Further evidence for this hypothesis would indicate some potential in the latter unit.

There seems to be limited potential for clastic-hosted lead–zinc–silver in the two orogens. The rift-basin sequence of the Biscay Formation contains little evidence of thick sequences of deeper water marine anoxic siltstone and shale that might provide suitable hosts. The turbiditic sequences of the Olympio and Marboo Formations indicate compressional, flysch-basin settings. The minor copper-dominant Chianti Prospect in the Marboo Formation is the only occurrence of this type worthy of mention.

Stratiform lead–zinc and copper mineralization in the shallow-marine Bungle Bungle Dolomite of the Mesoproterozoic Osmond Range succession, is associated with pyrite and manganese-rich shale, chert and rhyolitic tuff (**Chapter 7**). This lithological association and possible synsedimentary faulting (Dow and Gemuts, 1969) may suggest some potential for Irish-type stratiform mineralization or its clastic-hosted equivalent.

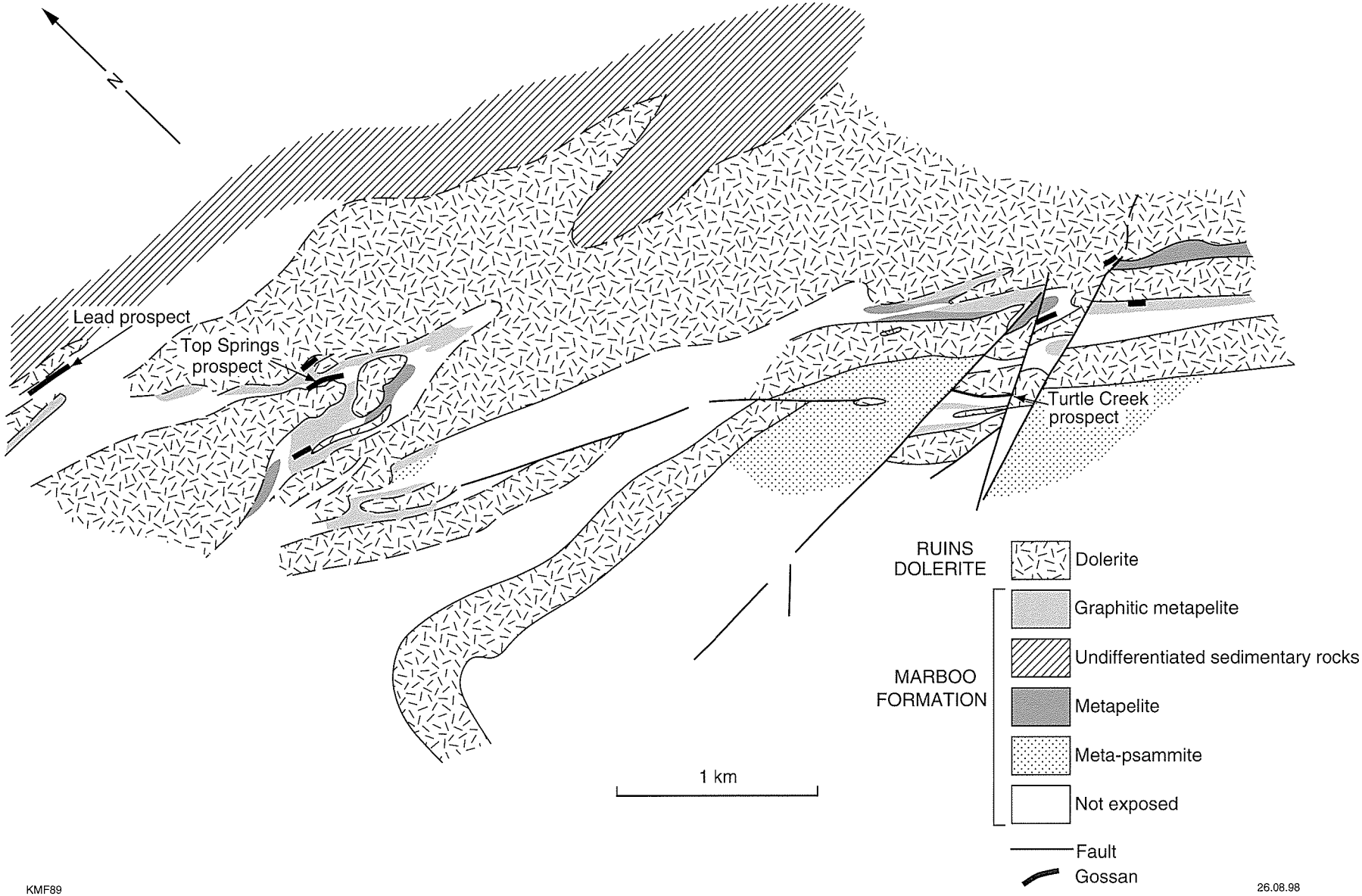


Figure 71. Richenda prospects: geology (*after* Kennecott)

Paterson Orogen

Geological framework

The geology of the northwestern part of the Paterson Orogen, the Rudall Complex and Yeneena Basin, is considered in more detail in **Chapter 7 (Sediment-hosted deposits)**. The Paterson Orogen represents a Late Proterozoic collisional orogen which truncates the eastern margins of the Pilbara and Yilgarn Cratons, and the Capricorn and Albany–Fraser Orogens.

The southeastern portion of the Paterson Orogen, outcropping in what was formerly termed the Musgrave Block, is made up of the Wingelina Complex and the Bentley Supergroup (Williams and Myers, 1990). The Wingelina Complex forms a high-grade metamorphic and plutonic basement to the cover of generally low-grade metamorphosed volcanic and sedimentary rocks of the Bentley Supergroup. The distinctive magnetic signature of the complex can be traced beneath cover to the northwest, where it emerges as the Rudall Complex.

The Wingelina Complex is made up of two distinct groups of gneiss, the Olia Gneiss and the Musgrave–Mann Complex, deriving respectively from 1.55 and 1.33 Ga precursors that underwent granulite metamorphism at about 1.2 Ga. The Bentley Supergroup comprises volcanic and sedimentary rocks deformed and metamorphosed to greenschist facies. The volcanic rocks include an approximately 10 km-thick sequence of basalt with some rhyolite, rhyodacite, dolomite and conglomerate which occurs south of the Jameson and Blackstone Ranges. A Rb–Sr date of 1.06 ± 0.14 Ga has been obtained in the lower part of the sequence. Also included within the Supergroup but possibly younger, are three large cauldron subsidence complexes of felsic volcanic rocks and granite within the Scamp, Palgrave and Skirmish Hill Cauldrons. Base-metal mineralization is associated with felsic volcanic material in the Palgrave Cauldron.

Prospects

BARROW RANGE

Occurrence: Pb; Cu
Location: 26°06'S, 127°27'E; 7 km north-northeast of Mount Eliza

During geological mapping of the TALBOT* 1:250 000 sheet, patchy disseminated sulfide mineralization was located in rhyolite of the Palgrave Volcanics. Mineralization consists of galena with a little pyrite and chalcopyrite in patches throughout the outcrop. A rock-chip sample gave 1.32% Pb.

References: Blockley (1971), Daniels (1974).

MOUNT ELIZA

Occurrence: Zn; Pb; Cu
Location: 26°05'S, 127°26'50"E; 6.4 km north-northeast of Mount Eliza

At this location Daniels (1974) found dark, glassy, altered rhyolite containing minor disseminated pyrite, galena and chalcopyrite assaying up to 650 ppm Cu, 1.15% Zn and 0.41% Pb in separate grab samples. Poorly documented copper exploration was carried out in the area by WMC (1967–71).

References: Marston (1979), Daniels (1974), GSWA-WAMEX - I 1005.

MOUNT PALGRAVE 1 (MUSGRAVE)

Occurrence: Zn; Pb; Cu
Location: 26°03'10"S, 127°17'E; 1 km south of Mount Palgrave

Minor zinc, lead and copper mineralization located by Daniels (1974) is disseminated in a granophyric volcanic plug in a cauldron-subsidence association within the Palgrave Volcanics. The mineralization consists of minor pyrite, pyrrhotite, chalcopyrite and galena and gave 0.34% Pb, 0.01% Cu and 1.55 g/t Ag in a grab sample. The mineralized plug may be a feeder for agglomerate and rhyolite in the vicinity. WMC (1967–71) also carried out reconnaissance in this area

References: Marston (1979), Daniels (1974), GSWA-WAMEX - I 1005.

Ashburton Basin

Geological framework

The Ashburton Basin is an arcuate belt of low-grade Proterozoic metasedimentary and metavolcanic rocks forming the northern part of the Capricorn Orogen and corresponding to the present-day outcrop of the Wyloo Group (~2.2–1.8 Ga) (Fig. 72, Table 15; Thorne and Seymour, 1991).

The Capricorn Orogen is a major orogenic zone between the Pilbara and Yilgarn Cratons. Although previously considered to be the product of the rifting and breakup of a single craton, the orogen is now considered (Myers, 1990a; Tyler and Thorne, 1990; Thorne and Seymour, 1991; Myers and Barley, 1992) to have resulted from the collision of two completely different Archaean cratons. In the southern Pilbara the earliest effects of this process were continental rifting and breakup of the Pilbara Craton producing the lower to middle Fortescue Group (Fig. 73), followed by a phase of sedimentation on a passive (upper Fortescue Group/Hamersley Group) and then active (Turee Creek Group/lower Wyloo Group) continental margin. This was followed by sedimentation in a subsiding deep-water foreland basin, the Ashburton Trough (Ashburton Formation), in response to a compressional regime brought about by the collision of the Yilgarn and Pilbara Cratons.

The Wyloo Group makes up the bulk of the 12 km depth of sedimentary sequence of the Ashburton Basin. The earliest units are the Beasley River Quartzite, a quartz sandstone laid down on a shallow-marine shelf and overlain by the shallow-marine Cheela Springs Basalt. Both units were laid down during an active

* Capitalized names refer to standard map sheets.

Table 15. Stratigraphic subdivision of the southwestern Pilbara, Hamersley, and Ashburton Basins

Basin	*Supergroup*	*Group*	*Formation*
Bangemall Basin		Bangemall Group	
Bresnahan Basin		Bresnahan Group	
Mount Minnie Basin		Mount Minnie Group	
Blair Basin			Capricorn Formation
			Ashburton Formation
			June Hill Volcanics
			Duck Creek Dolomite
Ashburton Basin		Wyloo Group	Mount McGrath Formation
			Wooly Dolomite
			Cheela Springs Basalt
			Beasley River Quartzite
	Mount Bruce	Turee Creek Group	
Hamersley basin	Supergroup	Hamersley Group	
		Fortescue Group	
Pilbara Craton		Granite–greenstones	

NOTE: ~~~~ Unconformity

continental margin phase of extensional tectonics. Subsequent continental collision led to uplift in the north in response to thrust-sheet stacking and flexural arching, with widespread erosion of the Hamersley and lower Wyloo Groups. The dominantly fluvial Mount McGrath Formation was formed as this eroded material was deposited in a series of deltas that fringed the southern Hamersley Basin. With subsidence of the flexural bulge, the shoreline migrated north; the shallow- to deep-marine shelf carbonates of the Duck Creek Dolomite reflect this deepening trend, as does declining siliciclastic input. Middle and upper units of the Mount McGrath Formation are mostly deeper water mudstones and siltstones. During this period limited mafic volcanism produced the June Hill Volcanics north of the Wyloo Dome.

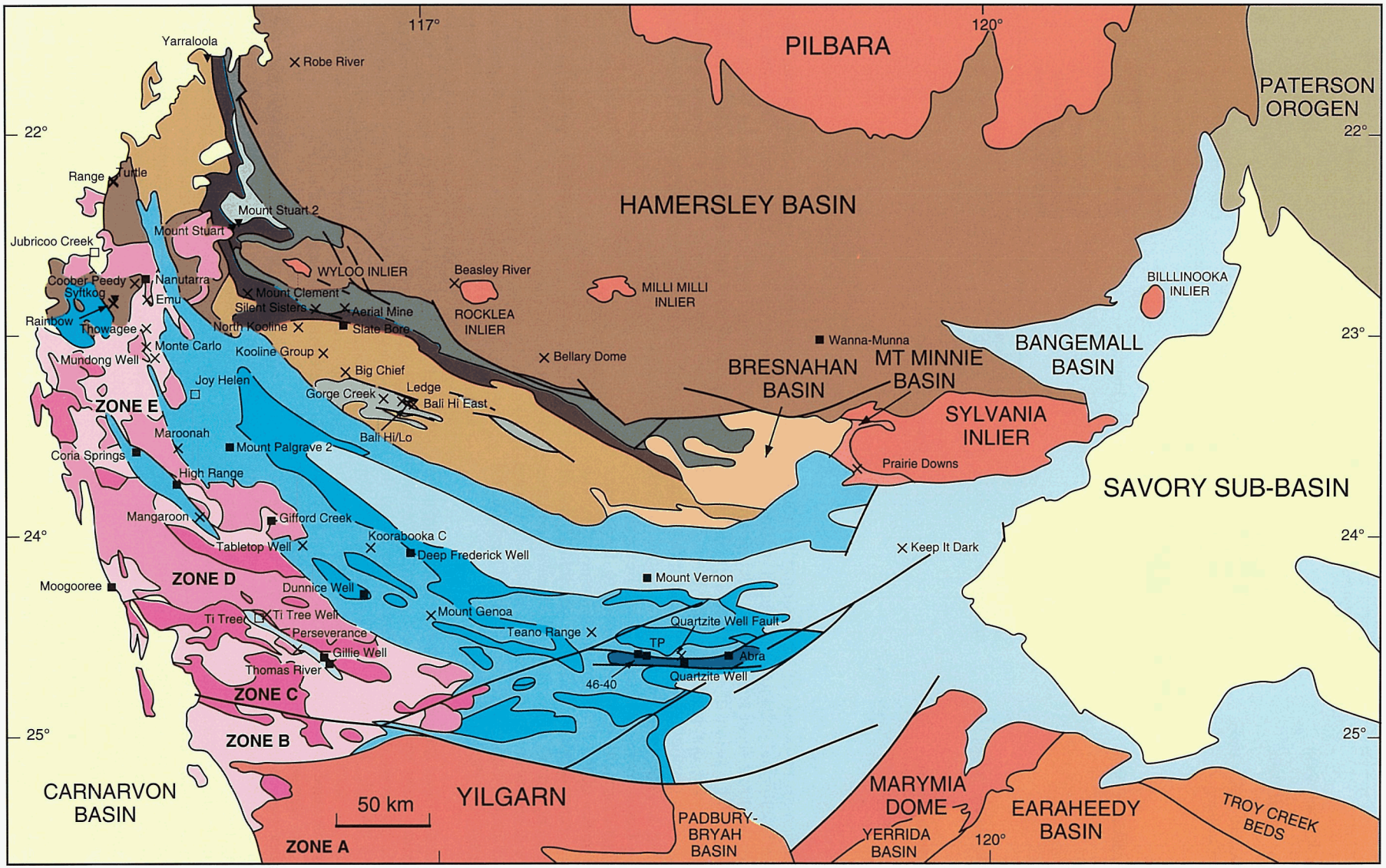
Also at this time, continued thrust-sheet stacking at the southwestern edge of the Pilbara Craton maintained subsidence and created a deep foreland basin called the Ashburton Trough. The lower levels of the Ashburton Formation are dominated by coarse granitic detritus deposited from east to west in an elongate submarine-fan system. Later deposits are more mud dominated. Further convergence caused uplift of the Gascoyne Complex in the south and produced a second north-northeasterly prograding fan system of granitic material. At the same time, uplift in the western Pilbara Craton gave rise to a third submarine-fan complex in the northwest of the Ashburton Basin. It is difficult to establish marker horizons within the Ashburton Formation because of the complex nature of the sedimentary evolution of the basin and the broad distribution of the three main lithofacies.

Large-scale folding and thickening of the succession, due to further northeasterly thrusting and thrust-sheet stacking followed and produced low to upper greenschist metamorphism beneath the overthrust terrain. This D_1 event is recognized predominantly through the widespread presence of an S_1 foliation. The most prominent folding and faulting in the Ashburton Basin, however, is the result of a major dextral wrenching event, D_2, which postdates deposition of the Capricorn Formation. This parallels the roughly west-northwesterly trending margin of the Pilbara Craton.

Mineralization

The deposits detailed below occur in the Ashburton Formation, the uppermost unit of the Wyloo Group (~2.2–1.8 Ga). The Ashburton Formation comprises deeper water chloritic mudstone with subordinate turbidite sandstone and siltstone deposited in the Ashburton Trough. The formation also includes minor amounts of conglomerate, banded iron-formation and chert, dolomite, and felsic to mafic volcanic rocks. Volcanic rocks make up about 1% of the Ashburton Formation and include localized occurrences of mafic to intermediate pillow lava, pillow breccia, coarse-grained volcaniclastic deposits, finely laminated tuff and felsic lapilli-tuff.

Doust (1984) proposed a separate unit, the Stuart Formation, overlying the Ashburton Formation. This unit included the banded iron-formation, chert, dolomite and volcanic rocks described above and other sedimentary and felsic volcanic rocks that were mapped by Thorne and Seymour (1991) as the Capricorn Formation. Doust also proposed the correlation of this unit with similar lithologies in the Gascoyne Complex. The overall coherence of this lithologically based correlation may not stand up to the more recent mapping of Thorne and Seymour (1991). However, the lithological association of distinctive 'chemical-facies' ferruginous and siliceous beds with chloritic or sericitic clastics with anomalous manganese contents may have value in defining prospect-



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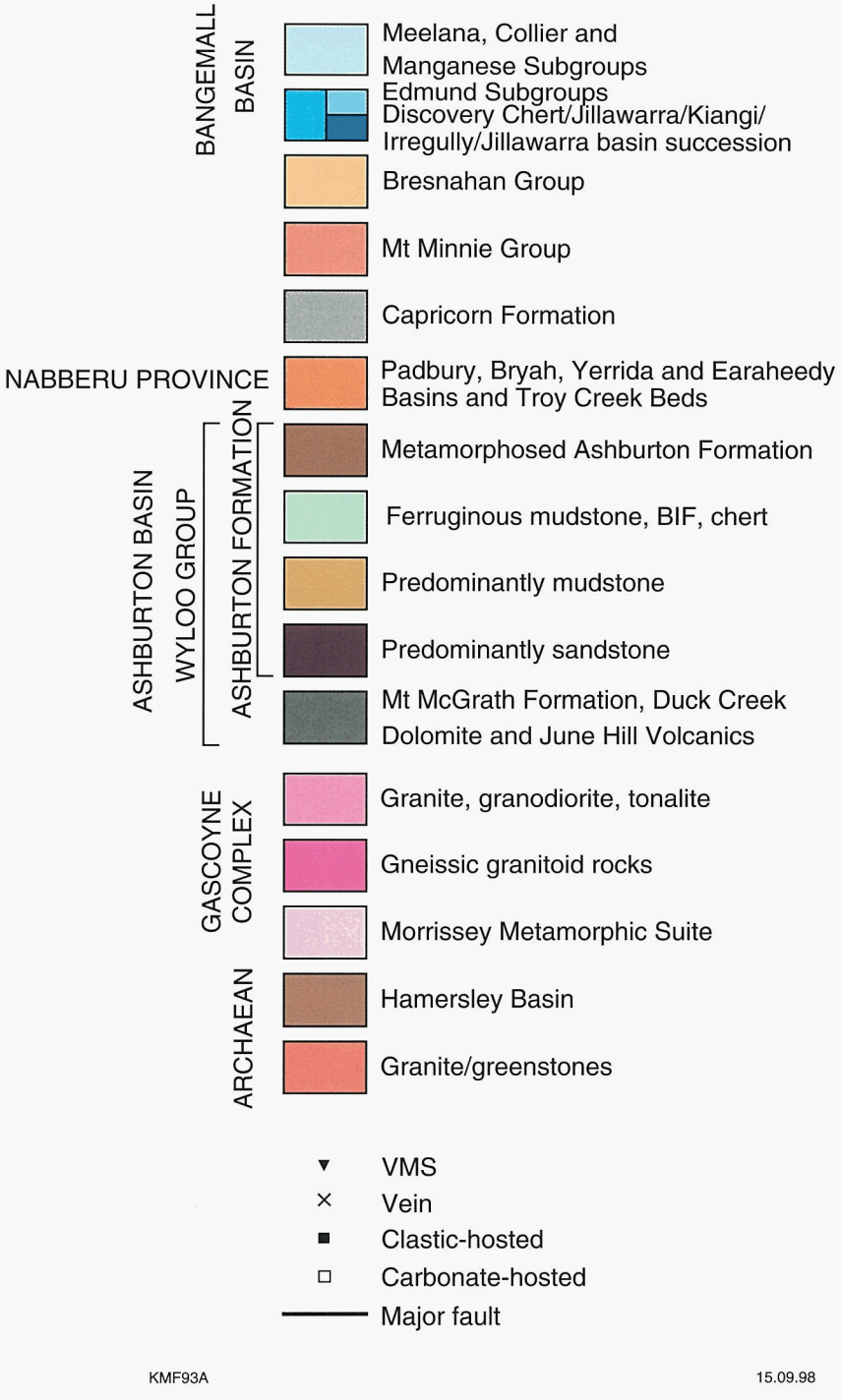


Figure 72. Gascoyne Complex, Ashburton Basin, and Bangemall Basin: geology and base-metal prospects

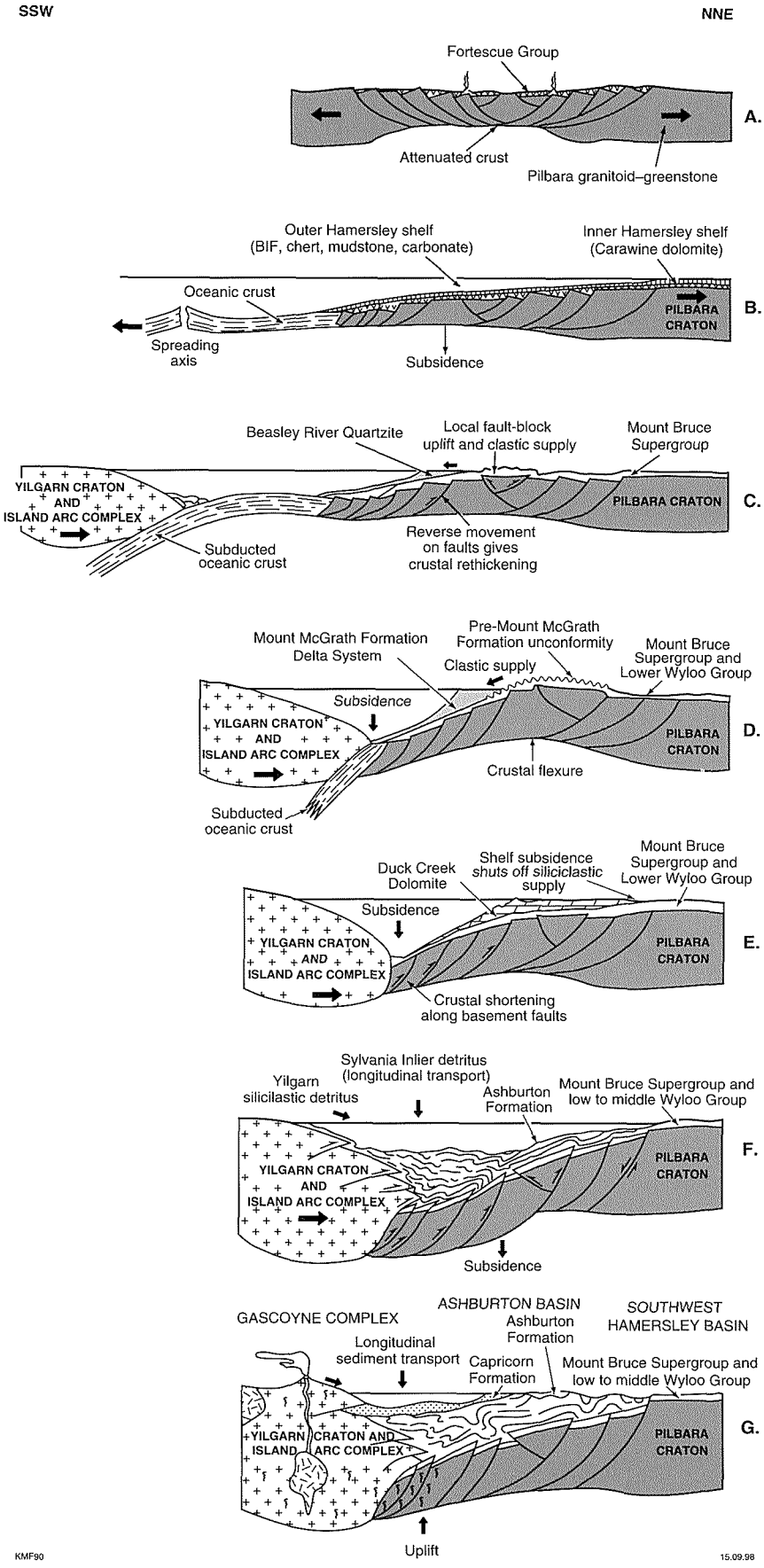


Figure 73. Tectonic model showing the evolution of the southern margin of the Pilbara Craton during the interval 2.7 to 2.0 Ga (*after* Thorne and Seymour, 1991)

ive areas for stratiform clastic or volcanic-associated base-metal mineralization.

Doust (1984) further draws analogies between the basinal–tectonic environment of these Wyloo Group sedimentary rocks and those of significant stratiform base-metal provinces throughout the world. He suggested there was potential for large-scale mid-Proterozoic stratiform lead–zinc deposits analogous to the Mount Isa, Broken Hill and Sullivan types, comparing the deep-water turbidite environment of the Ashburton Formation to the 'flysch-basin' class of Morganti (1980), which is generally associated with the advanced stages of intracratonic rifting. However, the extensional rifting typically associated with this tectonic environment contrasts with the compressional regime, outlined by Thorne and Seymour (1991), during the deposition of the Ashburton Formation in an active-margin to foreland-basin environment, associated with the Yilgarn–Pilbara Craton collision. Despite these major differences in interpretation the syndepositional faulting, noted by Doust (1984) at Mount Stuart and probably related to the continuing down-warping of the basin, may well have created sub-basins of significant size. These may have been available to mineralizing fluids through their marginal faults, thereby producing a favourable coincidence of 'chemical facies' sediments and metalliferous solutions.

Davy et al. (1991) have noted the common association of gold–copper–lead with a silver–arsenic–bismuth–antimony–thallium–uranium–zinc suite in both the pre-D_2 stratiform prospects and the post-D_2 vein type. They interpret this as suggesting a common source for the mineralization. The most likely mineralizing fluids are formation waters scavenging metals from lithic fragments and deeper connate water pressured by the compressional regime utilizing the fracture system formed in response to crustal shortening.

Exploration

Exploration for stratabound targets in the Ashburton Basin, either volcanogenic or sediment-hosted, began in the early 1970s with the work of Great Boulder Mines (I 369, 1700, 1701, 1711–13) in the Yarraloola and Mount Stuart areas. A geochemical reconnaissance by Kennecott in 1968 (I 276) had indicated anomalism associated only with minor vein-type occurrences. Mapping, sampling and drilling of the Yarraloola gossan by Great Boulder led to recognition of a stratiform pyrite zone with subeconomic base metals. A largely concealed prospective extension zone was defined and explored by WMC as a VMS target. Geophysical techniques including TEM, IP and detailed airborne and ground magnetics were used to define targets. Drilling indicated that IP anomalies were caused by graphitic shale. Later work by Noranda (I 2565) indicated that the mineralized zone had a weak magnetic signature masked by the intense response of a footwall banded iron-formation.

At Mount Stuart, Great Boulder established some geochemical anomalies which were percussion drilled by Noranda in the late 1970s (I 3050). More regional geochemistry by CRA (I 1711–2) and EZ (I 2603) on VMS and sediment-hosted models encountered some anomalism but there was no indication of sulfide mineralization in follow-up drilling. Noranda (I 2276) also drilled gossans indicative of sulfides in graphitic shale in the Ashburton Formation at Syftkog. Magnetic and EM targets revealed only weak base metals in percussion drilling.

Jododex, in the early 1970s (I 307), located lead-rich lenses and stringers in Ashburton Formation schists at Slate Bore in drilling a closely defined IP anomaly. Exploration by Austamax/BP Minerals (I 4156, 5038) for sedimentary-hosted targets in the Hardey Junction–Wyloo area was concentrated in the contact zone of the Ashburton Formation and Duck Creek Dolomite. Rock-chip assay data from gossan search revealed high values of lead (2.5%), zinc (0.4%), copper, arsenic, silver and gold. Two gossans were drilled with rather more modest results. Statistical analysis of the geochemical database suggested that metal enrichment in shale and dolomite, although suggestive in signature of sediment-hosted mineralization, was supergene. SIROTEM and IP surveys defined chargeable responses without outlining more discrete zones of possible massive sulfides.

Exploration in the 1980s had a gold focus, partially in response to work on the Mount Clement epithermal deposit.

Prospects

YARRALOOLA (Robe Hill)

Abandoned mine/prospect: Zn; Pb; Cu; Ag
Location: 21°35'40"S, 115°55'50"E; 6.9 km southeast of Yarraloola Homestead

Two coalescing zones (1 to 5 m wide) of silicified, ferruginous caprock trending at 200° and dipping 40–80° northwest, in pyrite–quartz–feldspar–mica–chlorite schist, are the surface expression of disseminated to massive sulfides in manganiferous banded chert and siliceous breccia within chloritic metasedimentary rocks of the Ashburton Formation. The two zones appear to reflect the limbs of a tight northwesterly plunging recumbent anticline. Basalt, dolerite, quartz–feldspar porphyry and dacite are recognized in drillcore. The more prospective southern end of the eastern zone of the stratiform mineralized body measured 100 by 13 m, reaches to 300 m in depth, and contains mainly cobalt-rich pyrite with minor associated iron-rich sphalerite, chalcopyrite and galena. This body is considered to be of possible distal volcanogenic origin in basalt, felsic pyroclastic rocks, volcaniclastic sedimentary rocks and chert. Lead:zinc and lead:silver ratios for Yarraloola resemble those in stratiform bodies rather than those in the vein-type deposits in the Wyloo Group (Doust, 1984).

The old workings consist of two 10 m shafts in the eastern zone from which a few tonnes of cupreous ore were produced in 1963. Between 1970 and 1982, WMC/Great Boulder Mines followed up costeaning and ground-magnetic surveys by drilling four shallow percussion and ten diamond holes in the main 100 m zone. The best intersections were 23.8 m at 0.75% Cu, 0.51% Pb, 0.41%

Zn and 20.1 g/t Ag, and 13 m at 1.92% Zn (including 2 m at 6% Zn), 0.67% Cu, 0.89% Pb and 28 g/t Ag. Average grades, however, were much lower. Further drilling to follow up IP surveys found only graphitic shale. Noranda (1983–84) conducted ground magnetic and EM surveys with negative results. In 1991, RGC carried out only limited rock-chip sampling before dropping the prospect.

As a result of his work with Great Boulder and Noranda, Doust (1984) interpreted the prospect as being within his Mount Stuart Formation. The unit containing sulfide mineralization provides the most consistent stratigraphic marker in drill profiles. Other lithologies are difficult to correlate. Slump structures and sedimentary breccias suggested an unstable sedimentary environment.

An area to the east of the prospect, though not the prospect itself, has recently been assessed by Normandy Poseidon (1991–94) for large-scale, clastic-hosted stratiform targets. The potential of the 'Mount Stuart BIF', at the base of the Ashburton Formation in the Wyloo Group, was examined and the unit interpreted as being at the interface between shelf and trough/basin facies and controlled by north-northwesterly trending growth faults at the margin of the Yarraloola Sub-basin. The company considered this unit to be of possible exhalative origin as the nearby Yarraloola prospect is also adjacent to a north-northwesterly trending linear feature. An intensive program of stream and soil geochemistry, supported by geomorphological and Thematic Mapper interpretation, failed to delineate any areas with potential for large deposits.

References: Marston (1979), Thorne and Seymour (1991), Doust (1984), GSWA-WAMEX - I 1700, I 3050, I 6564.

Mount Stuart 1

Abandoned mine/prospect: Pb; Cu
Location: 22°25'40S", 116°02'E; 2.4 km southwest of Mount Stuart

Stratiform lead and copper mineralization occurs over about 90 m of strike in an easterly trending bed of sheared conglomerate of the Ashburton Formation. A shaft 9 m deep is located about 60 m from the western end of the main lode. A dump sample gave 35.7% Pb, 0.01% Zn, 4.76% Cu and 83.97 g/t Ag in lead and copper carbonates. A second copper occurrence lies on strike about 170 m to the east, exposed in a costean. This apparently conformable mineralized zone may be of sedimentary–exhalative or distal volcanogenic origin.

References: Blockley (1971), Marston (1979), Thorne and Seymour (1991).

Mount Stuart 2

Prospect: Pb; Cu
Location: 22°24'11"S, 116°03'30"E; 6 km north-northeast of Mount Stuart Homestead

Base-metal anomalism is hosted by a west-northwesterly trending chert-rich felsic siltstone, lying between two banded iron-formation horizons, in a manganese-rich sequence of the Ashburton Formation (Mount Stuart Formation *of* Doust, 1984). The host unit is up to 57 m thick, extends over about 1 km of strike, and is interpreted by Doust to represent a shallow sub-basin localized by faulting. A maximum of 0.25% Pb was obtained in costeaning.

Great Boulder (1973–75) explored felsic-hosted VMS copper–lead–zinc targets and outlined an area of 'anomalous geochemistry' on a contact of felsic volcanic rocks with greywackes. Surface sampling gave up to 44.4% Pb and 4.5% Cu in schistose ore (after felsic volcanics) about 3.2 km north of Mount Stuart. These results are not mentioned by Doust (1984). Noranda (1976–82) carried out percussion drilling over a large geochemical copper–lead anomaly in siltstone associated with banded iron-formation, and obtained a maximum of 0.195% Cu, 0.11% Pb, 0.007% Zn and 2.8 g/t Ag in the oxidized zone. Follow-up IP and Turam surveys were negative. CRA (1980–82) explored on a more regional scale for stratabound, distal VMS but encountered no significant anomalism. Exploration by EZ (1982–83) for sediment-hosted base metals outlined a large zinc–copper(–lead) soil anomaly, east of Mount Stuart, with geochemical values similar to those obtained by Noranda. Percussion drilling found no sulfide mineralization in the underlying bedrock.

References: Doust (1984), GSWA-WAMEX - I 369, I 2565, I 1711, I 1712, I 1713.

Syftkog

Prospect: Pb; Zn; Ag
Location: 22°46'25"S, 115°21'30"E; 1 km north of Uaroo

Doust (1984) has interpreted this prospect as a stratiform pyritic lead–zinc–silver sulfide body hosted by graphitic shale of the Ashburton Formation (the Mount Stuart Formation *of* Doust, 1984). The prospect lies within a sequence of felsic gneiss, siliceous siltstone and minor micaceous, garnetiferous quartzite. A siliceous gossan about 120 m long by 10 m wide trends at 335°, in an area of poor outcrop, and is brecciated and quartz veined in places. The gossan takes the form of a series of pods and shows evidence of the presence of sulfides below the oxidized zone. Surface samples give up to 0.1% Cu, 2.95% Pb, 0.045% Zn, 18 g/t Ag and 0.5% As. Drilling yielded up to 2 m at 0.8% Pb and 0.43% Zn and 6 m at 0.1% Pb and 0.22% Zn with 6.2 g/t Ag.

The prospect was located and explored by Noranda (1977–84) to percussion drilling level. The reducing environment which produced the graphitic shale was seen to be limited laterally, and penecontemporaneous faulting was invoked to explain the rapid facies and thickness changes in the area. The faulting was also considered to have provided pathways for mineralizing fluids related to contemporaneous magmatic activity. The relatively high levels of zinc may be an indication of volcanogenic processes (Doust, 1984). Reporting by Noranda, however, maintained some doubt as to the origin of the mineraliz-

ation citing possible bedding-parallel, or shallow-angle quartz veining in the sedimentary sequence. The area is currently being explored by Aberfoyle.

Reference: GSWA-WAMEX - I 2278.

Potential

The tectonic and palaeogeographic setting and reconstruction of sedimentation in the Ashburton Basin has been summarized above. In relation to the tectonic–basinal settings proposed for sediment-hosted base-metal deposits, the Ashburton Basin would seem to most closely approximate the flysch-basin setting of Morganti (1980) and the continent-margin type of Maynard (*in* Force et al., 1991). As a foreland basin the regime is essentially compressional reflecting the collision of the Yilgarn and Pilbara Cratons. This is not directly favourable for the extensional rift-basin environment associated with many clastic-hosted lead–zinc–silver deposits. However, the subsidence which characterized the deposition of the Ashburton Formation may have been accompanied by some syndepositional faulting and creation of sub-basins. The rapid deepening of the basin and the volume of immature sandstone in the early Ashburton Formation, may well have provided a source and mechanism for metalliferous brines to be forced to the ocean floor during the deposition of the deeper water siltstone and shale.

The favourable chemical lithofacies of Doust's (1984) Mount Stuart Formation, while probably not representing a single coherent unit, seems to offer some potential for stratiform base-metal accumulations associated with deep-marine mudstone, minor felsic tuff, banded iron-formation and chert; particularly if they are partly exhalative. Doust (1984) suggests that metalliferous brines may have been fairly widely distributed and, in combination with pelagic sediments, produced ferruginous, manganiferous shale. Maynard (*in* Force et al., 1991) suggested that horizons favourable for lead–zinc exhalative mineralization may be identified by the wide dispersal of manganese. He also suggested that mineralization of this type in continent marginal basins will be barium rich and lead–zinc poor. The few apparently exhalative occurrences recognized to date in the Ashburton Basin, however, are relatively poor in barite.

On balance it seems that, despite the non-ideal tectonic setting of the Ashburton Basin for this target type, some potential does exist. Exploration would require careful mapping of lithological and synsedimentary structural features, to locate shelf-margin or sub-basin environments, combined with the search for chemical signatures suggestive of exhalative activity. The low success rate of exploration to date may indicate that the combination of required parameters may only be present in restricted areas, as appears to be the case in the Bangemall Basin.

Potential may also be present for carbonate-hosted base-metal mineralization. Duane and de Wit (1988) describe the formation of epigenetic and syngenetic deposits related to continental-scale fluid mixing and expulsion during continental collision in the northern Caledonides. Thrusting can focus brines through extensive sections of crust, where they may scavenge and redeposit metals, or may simply mobilize metalliferous fluids within a particular basin into suitable hosts, syn- or post-sedimentation. These sorts of mechanisms could apply to the clastic-hosted mineralization discussed above, but may be even more relevant to carbonate-hosted mineralization.

Thus the Duck Creek Dolomite could have potential for epigenetic mineralization whereas carbonates within the Ashburton Formation, mostly concentrated in the eastern part of the basin below the Bresnahan Group unconformity, might host mineralization similar to the Irish type. Carbonate units, however, form only 1% of the Ashburton Formation and tend to be thin.

Despite the presence of a small number of occurrences, potential for volcanogenic stratiform mineralization may be restricted due to limited felsic volcanism in the basin and the lack of a favourable arc or back-arc setting.

Vein-type lead–zinc deposits in the Ashburton Basin, are predominantly in veins cutting the Wyloo Group and associated with west-northwesterly to north-northwesterly trending dextral wrench faults (**Chapter 8**). These are too small to be economically viable and indicate metal mobility at too late a stage for syngenetic targets within the Wyloo Group. Some mobilization of metals in hydrothermal fluids during the deposition of the Ashburton Formation is indicated, however, by the stratabound, syngenetic, epithermal gold and silver deposit (with associated arsenic, copper, bismuth, antimony and lead) at Mount Clement. Davy et al. (1991) suggested that the mineralizing fluids were expelled from deeper in the basin during burial metamorphism and transported along major faults in processes analogous to those outlined by Duane and de Wit (1988). This type of deposit is therefore a third possibility for pre-D_1 mineralization in the Ashburton Basin. Exploration to date, following the discovery and elucidation of Mount Clement, has met with little success.

Nabberu Province

Geological framework

The geological framework of the Nabberu Province is detailed in the following chapter, and mineralization and potential are discussed at length there.

Of relevance to VMS potential is the tectonic setting of the Glengarry basins within the Capricorn Orogen on the northern margin of the Yilgarn Craton. Tyler (1991) and Thorne and Seymour (1991) have suggested that a subduction tectonic model most appropriate for this setting includes the development of an island arc and a marginal or back-arc rift basin on the northern margin of the Yilgarn Craton. Hynes and Gee (1986) pointed out that the resemblance of the Narracoota Volcanics to boninites suggested a subduction-related arc origin.

Prospects

Horseshoe Lights

Mine: Au; Cu; Ag; Pb; Zu
Location: 25°22'S, 118°37'E; 34 km north of Peak Hill

Copper and silver occur in association with gold in the supergene-enriched, stratabound, Kuroko-style volcanogenic sulfide deposit hosted in pyritic chert units and volcaniclastic rocks within quartz–chlorite, quartz–sericite(–muscovite–kaolin) schist, at Horseshoe Lights. The schists derive from felsic tuff and agglomerate of the Narracoota Formation of the Bryah Group (Pirajno and Occhipinti, 1995; Pirajno and Preston, 1998). The deposit, which lies below the oxidized zone, is composed of massive pyrite with subordinate chalcopyrite and is notably low in lead–zinc for VMS-style mineralization. This may relate to the temperature and chemical nature of the hydrothermal fluids (Huston and Large, 1989). Copper–gold stringer mineralization is found below the massive sulfides and hydrothermal alteration consists of chloritization, sericitization and possibly kaolinization. Groves et al. (1994) concluded that the lead-isotope compositions of the massive sulfides suggest, at least in part, a VMS deposit (~1.9 Ga) overprinted by later, structurally controlled lode-gold mineralization.

The deposit, discovered by a prospector in 1946, was mined as an openpit between 1949 and 1954 by Anglo-Westralian, and between 1957 and 1961 by J. Edwards. Electrolytic Zinc conducted geophysical and geochemical exploration from 1964 and established anomalism for lead, zinc, copper, nickel, and molybdenum. Further drilling and investigations were carried out between 1969 and 1977 by Plantagenet, Amax, Placer, Samantha and Homestake. Since 1979 mining has been carried out by Barrack Mines and Sabminco.

References: Gee (1987), Huston and Large (1989), Parker and Brown (1990), Groves et al. (1994).

Chapter 7

Sediment-hosted massive-sulfide deposits

Clastic-hosted type — summary of geology and mineralization

In the discussion of the classification of sediment-hosted deposits in **Chapter 4** it is pointed out that the main group of relevance to this Bulletin is the lead–zinc-dominant, sedimentary-exhalative, essentially syngenetic type associated with intracratonic and craton-margin rift basins and generally deep-water sediments. In the following examination of this type of deposit in Western Australia, however, there may be some environments and deposits that are ambiguous, suggesting lead–zinc associates of the copper-dominant, epigenetic group associated with more strictly cratonic, shallower water environments. This area of potential overlap, or confusion, in the description and discussion of specific deposits or occurrences, and in the evaluation of the potential of various basinal environments, will be acknowledged where appropriate and discussed in relation to the specific situation. Similar grey areas between clastic lead–zinc and Irish-type deposits, and between true MVT and Irish-type deposits, will also be dealt with where appropriate.

Distribution

Most deposits of this type are found, as might be expected, in dominantly sedimentary, rift-related basins of Proterozoic age; specifically in the Bangemall and Yeneena Basins, which contain twelve and eleven respectively (Figs 72 and 74). The potential of other possibly prospective sequences, such as those in the Rudall Complex, the Glengarry and Ashburton Basins of the Capricorn Orogen, the metasedimentary rocks of the Gascoyne and Northampton Complexes, and the Kimberley marginal basins of the Halls Creek and King Leopold Orogens, needs to be addressed.

Rudall Complex

Geological framework and mineralization

The Rudall Complex is made up of gneisses and schists representing granitic and sedimentary rocks deposited between 2.0 and 1.3 Ga and subsequently deformed and metamorphosed between 1.3 and 1.25 Ga.

On the basis of mapping in the BROADHURST 1:100 000 sheet (Hickman and Clarke, 1993) and RUDALL 1:100 000 sheet (Hickman and Bagas, 1996), the metasedimentary rocks in the Rudall Complex have been divided into five formations, which appear to broadly define two upward-fining turbidite–arenite–shale cycles (Fig. 75). The Larry Formation, Fingoon Quartzite and Yandagooge Formation make up the first cycle, while the Butler Creek and Poynton Formations are included in the second cycle. The sedimentary succession is considered to represent a siliciclastic shelf along an eastern continental margin with deeper water muds and turbidites thickening eastwards. In the lower fining-upward cycle a foreland basin is envisaged. Basin elongation was northerly or northwesterly. Volcanic rocks are rare although sandstones with a high feldspar content in the Yandagooge Formation, and possible metamorphosed felsic volcanic or volcaniclastic rocks in the Poynton Formation, may indicate erosion from an adjacent volcanic arc to the east or northeast.

In general, the fold-thrust belt tectonic environment of the Rudall Complex resembles that of other Proterozoic belts in Western Australia, for example the Capricorn Orogen, but differs from the intracontinental environments seen in central and eastern Australia. The Rudall 'basin' is therefore similar in its setting to the Ashburton Basin.

The contacts between the metasedimentary units are complex and often tectonized due to a number of deformation events. The main late structural event affecting the present disposition of the rocks in the complex is D_4 (0.8–0.7 Ga), associated with major, upright to overturned, tight to isoclinal, northwesterly trending folds which have formed in response to southwesterly directed compression. The southwest limbs of the anticlines are partly removed by thrusts, and lag faults occur on the northeastern limbs. Fold plunges are mostly shallow to the northwest. The dominant pre-Yeneena Group structural event, the Paterson Orogeny (D_2, 1.79–1.76 Ga) produced north-northeasterly trending shearing and folding. The succession has also been disrupted by intrusions of pre- to syntectonic granitoids (1.79–1.765 Ga), which are products of at least three episodes of felsic magmatism, and metamorphism has destroyed most primary fabrics. The granitoids are generally metamorphosed to orthogneiss, which makes up about 50% of the area of the complex.

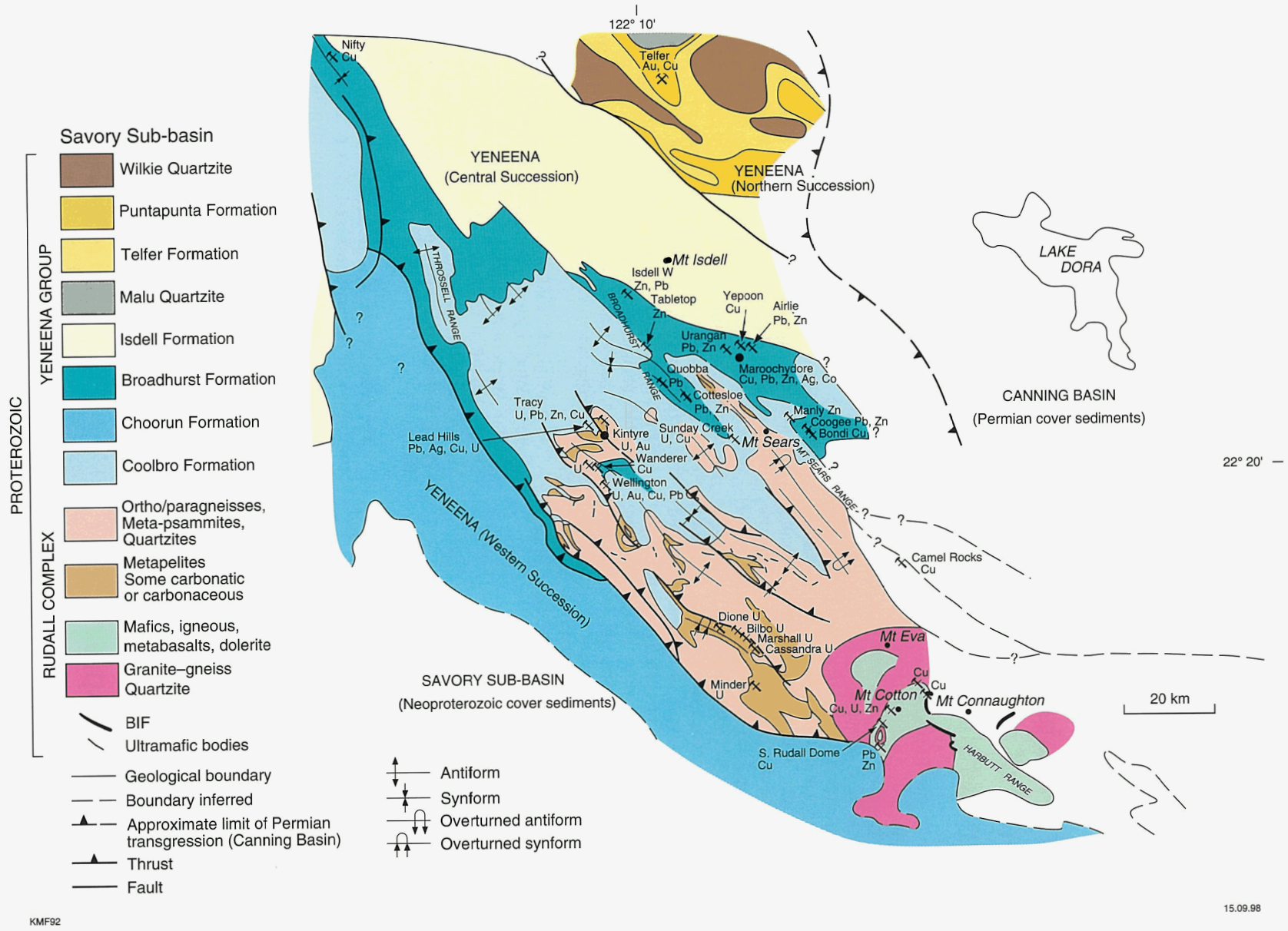


Figure 74. Paterson Orogen: geology, deposits and base-metal prospects

The Rudall Complex is considered (Hickman and Bagas, in prep.) to be the product of plate convergence, either in the form of continental collision, or as a result of ocean–continent collision.

In relation to base-metal potential the most significant unit in the Rudall Complex is the pelitic to semi-pelitic Yandagooge Formation, which contains laterally impersistent layers of banded iron-formation, chert, graphitic schist, carbonate rocks and biotite schist. The subsiding foreland basin setting, with probable rifting adjacent to a volcanic arc and marginal basin, suggests potential for clastic-hosted lead–zinc–silver. Potential also exists in the rifted shelf clastics of the Poynton Formation. The relative base-metal potential is hard to estimate, particularly since most recognized mineral occurrences are of the uranium-related unconformity type. To what extent this epigenetic mineralization may be a reworking of original syngenetic base-metal mineralization is not known. Copper, lead and zinc mineralization is present in stratabound form in similar pelitic lithologies within the complex. This style of mineralization is an element of the Tracy prospect, in the Yandagooge Formation, and is present in the South Rudall Dome, where it may be a category separate from that associated with unconformity-type uranium.

Potential for hydrothermal vein-type uranium mineralization, with associated gold, copper, lead, zinc and platinum-group elements, is also recognized in the pelitic, graphitic, chert and carbonate lithologies of the Yandagooge Formation, near the Yeneena Group unconformity, as seen at the Kintyre deposit and the Tracy and Lead Hills prospects described later. Most of the deposits in the Rudall Complex have an association with these lithologies and were formed in the same late-stage hydrothermal event. The importance of thrust faulting, associated with isoclinal folding (D_4 trend), to provide channels for mineralizing solutions, has also been recognized in relation to this target type. These faults, and minor north-northwesterly trending link structures, also bring suitably reactive host-rock types into juxtaposition. The almost ubiquitous nature of these structures, however, makes them a useful exploration tool only at a local level. If the Yeneena unconformity is considered to be a valid part of the genetic model, then its location only has limited application in defining prospectivity because of the structural complexity of the Rudall Complex. The possible presence of the unconformity close to, but above, the present erosion surface could be invoked almost anywhere.

Exploration

Since the uranium discoveries at Kintyre extensive exploration has been undertaken in the Rudall Complex, largely within the Rudall River National Park. Since 1985, CRA has held mining tenements over most of the complex southeast from Kintyre. About half of this tenement coverage is, or has been, in joint venture with PNC. Other explorers briefly involved include Esso, Pancontinental, Peko and Aquitaine. Idemitsu/Poseidon/Uranerz currently hold tenements over parts of the Rudall/Yeneena unconformity northeast of Kintyre.

Exploration by CRA has been predominantly for uranium and based mainly on the follow-up of a major regional airborne radiometric and magnetic survey of the whole complex. Several hundred radiometric and magnetic anomalies have been followed up, many to drilling level. Geological mapping and reinterpretation of the Rudall Complex has been aimed at defining parallels with other vein-type uranium provinces such as the East Alligator River area in the Northern Territory. Although other target types have been recognized the predominant uranium focus may possibly have been at the expense of meaningful examination of base-metal potential.

Graphitic, chloritic and garnetiferous units within this sequence have been termed the Graphite Valley sequence (GVS) by CRA/PNC, recognized within the Graphite Valley area and also considered the equivalent of the carbonaceous units at Kintyre, Tracy and Lead Hills; i.e. within the Yandagooge Formation. A number of vein-type prospects have been defined within the Graphite Valley area despite the complicating factor of intensive leaching of uranium from the GVS and subsequent enrichment in ferruginous cap rock. Vein-type uranium mineralization, with associated copper, lead, zinc, silver and gold, is recognized at the Cassandra and Minder prospects. The Dione and Bilbo prospects, while geochemically similar, are restricted to the regolith and may have precipitated from near-surface groundwater (Hickman and Bagas, in prep.).

In the 1970s, Otter (I 973) identified a copper-anomalous gossan to the southeast at Camel Rock in quartz–sericite schists (≤3500 ppm Cu) and examined a copper–zinc gossan in graphitic quartz–sericite schist at Mount Cotton. Follow-up drilling by Newmont (I 456) at Camel Rock in 1974 identified copper carbonates in quartzite–banded iron-formation. A maximum intersection of 2 m at 0.43% Cu was obtained with barium at up to 2% also present. Newmont delineated an aeromagnetic anomaly 8 km long around Camel Rock with ground follow-up suggesting two parallel magnetic horizons dipping southeast at a depth of about 50 m. Bagas and Smithies (in press) consider this area to be highly prospective for base-metal mineralization. At Mount Cotton significant copper–lead–zinc–uranium mineralization occurs in northeasterly trending quartz veins in schist and banded iron-formation. Limited work by AGIP (1981–84)(I 9031) indicated grades up to 2% Cu, 1.5% U and 0.6% Zn. At South Rudall Dome, Newmont (I 456) explored a domal structure with an amphibolite core surrounded by quartz–magnetite banded iron-formation and an outer partially graphitic and carbonate-rich schist. The schist was gossanous, in close association with the banded iron-formation, and contained pyrite, pyrrhotite and chalcopyrite with minor sphalerite and galena. Follow-up drilling gave only low base-metal values. AGIP (I 9031) explored the same area plus the Connaughton Structure in 1981–84. The domal structures and the plunging anticline that defines the Wells Structure are clearly outlined by marginal banded iron-formation and quartzite units. Drilling has been carried out by AGIP and by CRA, who farmed into the project in 1984. Anomalous platinum,

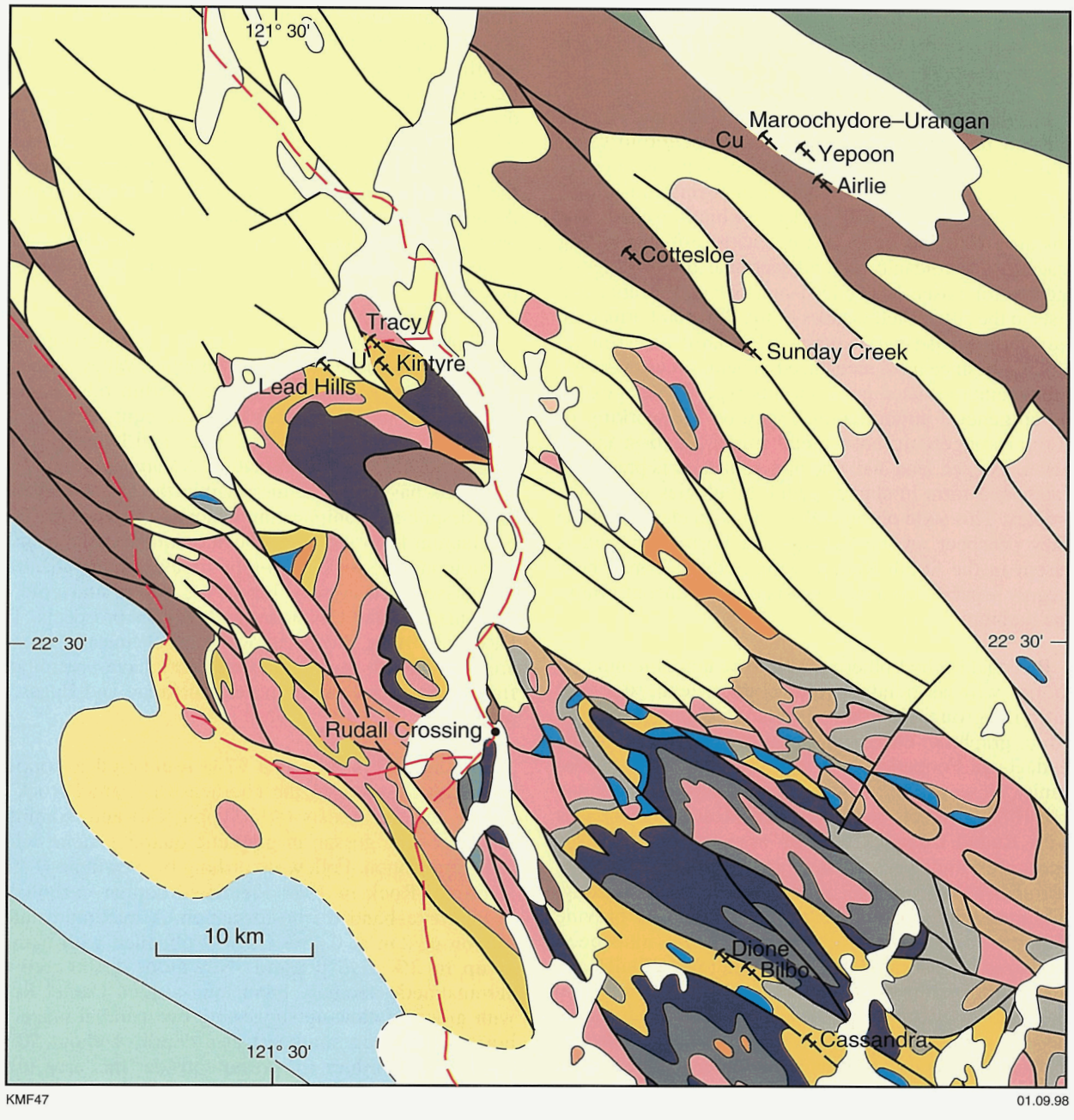
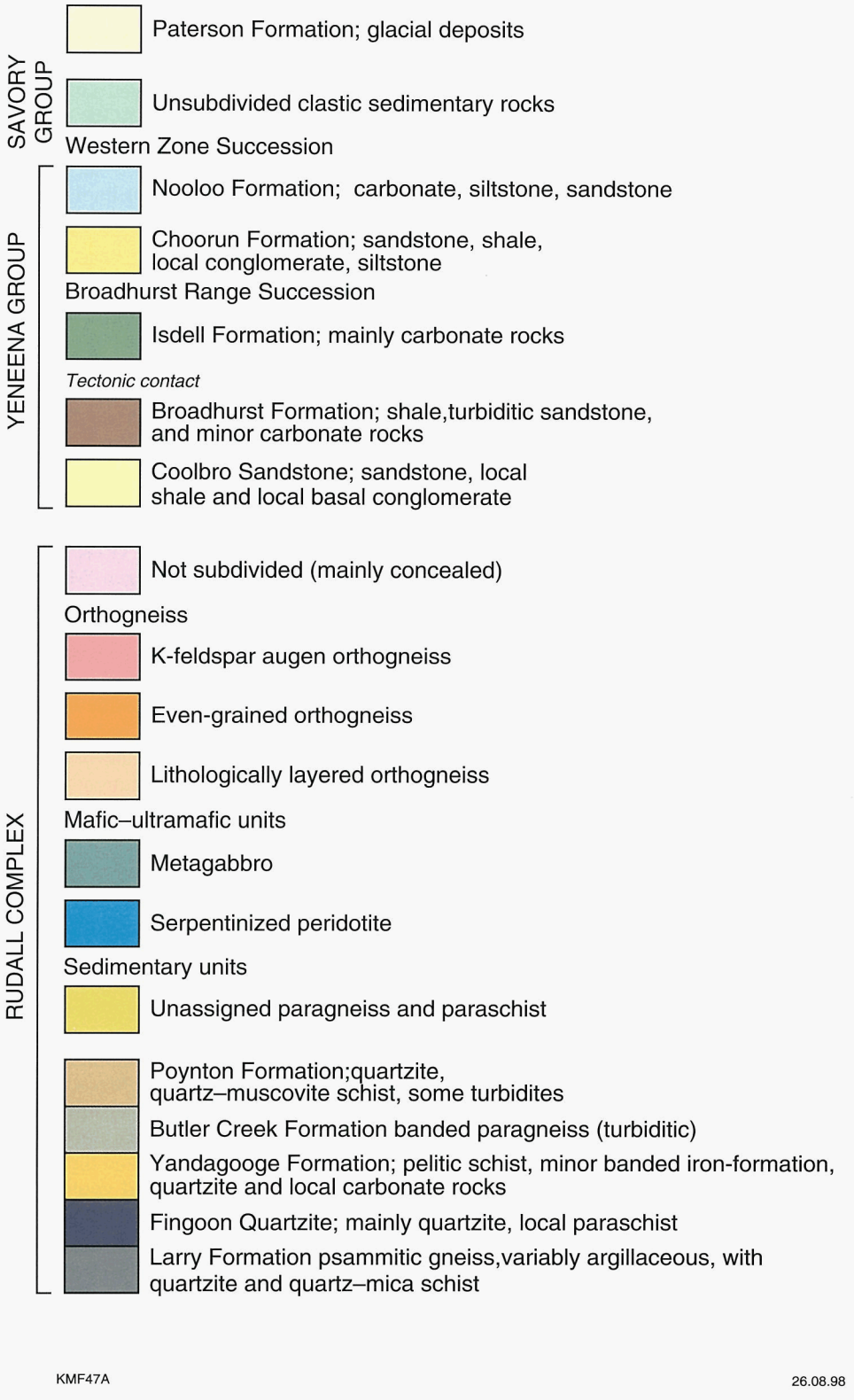


Figure 75. Telfer–Rudall area: geology and base-metal prospects (*after* Hickman, 1994)

palladium, manganese, cobalt, copper, zinc and lead were detected in the Connaughton Structure by CRA during stream-sediment sampling in 1986. Chip samples collected in this area by the GSWA (Bagas and Smithies, in press) gave up to 19.4% Cu and 2260 ppm Pb suggesting high potential for base-metal mineralization. Similar anomalism and potential exists in the vicinity of the Wells Structure. This area fell within the Exploration Exclusion Zone around Rudall National Park, and no further exploration has been carried out since 1987.

Preliminary mapping by GSWA (Bagas, L., 1995, pers. comm.) suggests that the Rudall Complex sequence in this area is significantly different from that farther northwest. It more closely resembles a typical Archaean greenstone sequence and may be basal to that which makes up the northwestern half of the complex. There are also some broad similarities with the Late Archaean–Early Proterozoic Mount Bruce Supergroup. Mafic and ultramafic volcanic and intrusive rocks in association with banded iron-formation suggest potential for VMS copper–zinc–lead, epigenetic gold, and layered ultramafic platinum-group elements and nickel.

Immediately southeast of the Mount Cotton–Connaughton area, in the Harbutt Range, a granite–gneiss



dome lies to the northeast of a series of pelitic/graphitic metasedimentary rocks, carbonate rock and banded iron-formation. This association suggested to CRA that the area was analogous to Rum Jungle in the Northern Territory, a supposition supported by radiometric and stream-sediment anomalies. After drill testing most of the prospects, however, the company dropped the majority of its tenements in 1993, retaining only the western area, which abuts the Connaughton Dome and is within the Exploration Exclusion Zone.

Deposits, prospects and occurrences

Tracy (Yandagooge)

Prospect: Pb; U; Cu; Zn
Location: 22°19'20"S, 122°04'10"E; 1.5 km north-northwest of Kintyre

The Tracy prospect consists of stratabound sulfides that follow the folded contact of graphitic quartz–sericite schist and quartz–biotite–sericite schist within the Yandagooge Formation. Surface gossans overlie pyrite-rich zones and pass along strike into ankerite–siderite–quartz 'iron-formation' and goethitic chert. These occur over a 3 km strike length, trending east-northeast and dipping north. The prospect lies about 300 m east of a northwesterly trending shear zone which separates the metamorphic rocks of the Yandagooge Inlier from the unconformably overlying Coolbro Sandstone of the Yeneena Group. At depth the sulfide zones are up to 20–30 m wide and include thin layers of massive pyrite with finely disseminated chalcopyrite, galena and sphalerite. Sulfide veinlets containing galena indicate some secondary remobilization. Rock-chip samples showed up to 1.2% Pb, 0.35% Cu and 0.25% Zn, and a diamond-drill intersection included 2 m at 4.2% Pb and 11 g/t Ag in pyritic, graphitic quartz–sericite–biotite schist.

Otter (1971–79) identified copper–zinc–lead in the Yandagooge Inlier, at what was initially named the Yandagooge prospect, during a regional helicopter-borne sampling program in 1971. Further exploration during the 1970s identified a number of gossans in this area, with base-metal levels of around 1000 ppm, associated with the stratabound pyritic zone and graphitic schists. Diamond drilling was carried out in 1978 by Getty Oil in partnership with Otter. Follow-up of radiometric anomalies in this area by CRA in the early 1980s (Jackson and Andrew, 1990) led to the recognition of the association of uranium with the base metals at Tracy and Lead Hills, and with gold, silver and platinum-group elements at nearby Kintyre.

References: Marston (1979), Jackson and Andrew (1990), Hickman and Clarke (1993), GSWA-WAMEX - I 973.

South Rudall Dome

Prospect: Cu; Zn
Location: 22°50'10"S, 122°34'40"E; 17 km west-southwest of Mount Connaughton

At this prospect concordant gossans, anomalous in copper, zinc and silver, occur in a small lens on the northeast flank of a small northerly trending dome in quartz–magnetite schist interbedded with banded iron-formation. The banded iron-formation horizon marks a break in the stratigraphy between underlying amphibolite in the core of the dome, and an overlying schist–gneiss sequence. The mineralized lenses dip at 30–50° to the northwest. Graphite, sericite, chlorite, quartz, magnetite and carbonate are associated with boxworks after pyrite, pyrrhotite and chalcopyrite with traces of galena and sphalerite. In the southern part of the dome chrysocolla, galena and minor malachite have been found in silicified carbonate veins in graphitic and micaceous schist, associated with extensive silica, sericite, carbonate and chlorite alteration.

Newmont (1974–75) located and explored the northern prospect, and follow-up by AGIP (1981–84) located up to 1500 ppm Cu in rock-chip samples. Costeaning by AGIP in the southern prospect showed up to 11.4% Cu, 46 ppm Ag and 2.60% Pb. Drillhole assays showed 1.8% Cu, 1.6% Pb, 1.1% Zn and 27 ppm Ag (Bagas and Smithies, in press).

References: Marston (1979), Bagas and Smithies (in press), GSWA-WAMEX - I 456, I 911.

Potential

Bagas and Smithies (in press) point out that in the last 20 years of exploration, '. . . numerous subeconomic and rare economic, stratabound and fault-controlled, vein-type mineral deposits, including gold, base metals, uranium and platinum-group elements (PGE), have been found throughout the Paterson Orogen. Many of the deposits in the Rudall Complex occur in carbonaceous or sulfidic schist, are hydrothermal in origin, late in the history of the complex, and supergene-enriched to varying degrees . . . economic concentrations of gold, silver, base-metals and/or uranium occur at South Rudall Dome, Mount Cotton, Wells Structure, Connaughton Structure and Camel Rock. The full potential of this area can only be assessed with detailed exploration.'

Nabberu Province

Geological framework

The Palaeoproterozoic Nabberu Province is part of the extensive Proterozoic Capricorn Orogen, lying between the Pilbara and Yilgarn Cratons. It lies on the northern margin of the Yilgarn Craton and is overlain to the north by sedimentary rocks of the Mesoproterozoic Bangemall Basin. As defined by Gee (1990) and Gee and Grey (1993), the Nabberu Province comprised the Glengarry Basin, the Earaheedy Basin, and the Marymia and Goodin Inliers. More recent detailed geological mapping, with associated petrological and geochemical studies and Landsat and aeromagnetic image interpretations, in the western part of the Province, has led to a reappraisal of the tectono-stratigraphic framework of the Glengarry Basin (Pirajno, et al., 1996). This has now been redefined and subdivided into three separate basins, the Yerrida, Bryah and Padbury Basins (Fig. 76).

The interpretation of Hynes and Gee (1986), Gee (1990), and Gee and Grey (1993) suggested an ensialic or intracontinental basinal setting for the Glengarry basins, with shelf and extensional rift-basin components. Tyler and Thorne (1990) placed the basins in the context of south-dipping subduction between the converging Pilbara and Yilgarn Cratons with, in part, a back-arc basinal setting. Pirajno (1996) has suggested that the three lithostratigraphic successions of the Bryah, Padbury and

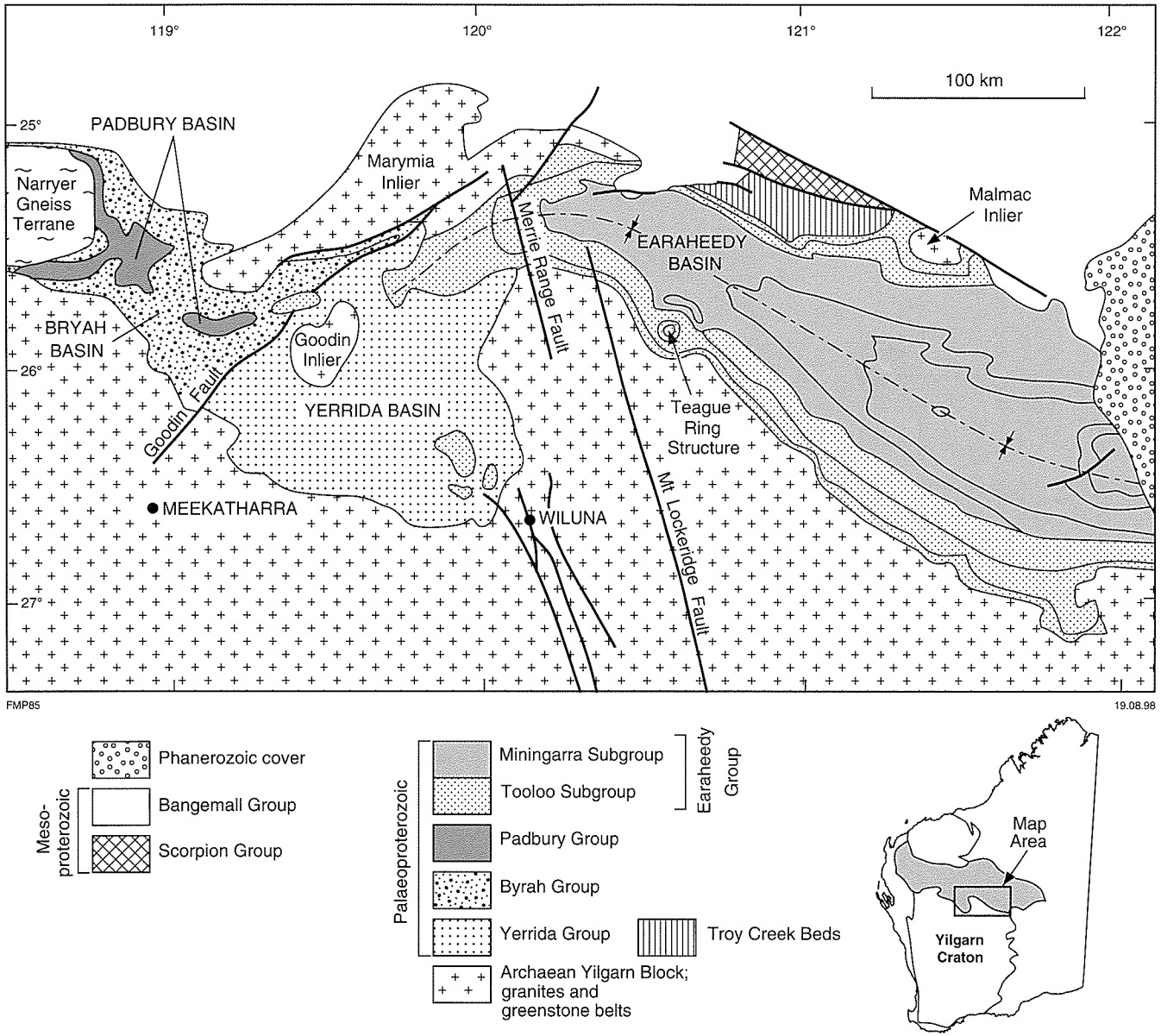


Figure 76. Nabberu Province: regional geological features (*after* Pirajno, 1997)

Yerrida Basins formed either in a back-arc setting or as a series of pull-apart openings during oblique convergence and collision between the Yilgarn and Pilbara Cratons.

The redefined Yerrida Basin (Table 16 and Figure 77) comprises the earlier, undeformed, predominantly shallow-water Windplain Subgroup, developed in an extensional sag basin, and the later, deformed Mooloogool Subgroup formed in a rift basin (Pirajno and Occhipinti, 1995).

The Windplain Subgroup, consists of unmetamorphosed and little-deformed siliciclastic, carbonate and evaporitic sedimentary rocks, on the southern margins of the basin, and deformed, metamorphosed siliciclastics on the northern margin (Fig. 78). They include the arenitic Juderina Formation and the more carbonate-dominated Johnson Cairn Formation. The rift-basin succession of the Mooloogool Subgroup developed with continuing extension and contains two distinct depositional domains. The northern domain, which forms a northeasterly trending zone around the Goodin Dome, contains deeper water turbiditic wackes and arkoses of the Doolgunna and Thaduna Formations deposited in a horst-and-graben structure during continuing tectonic instability. The southern domain contains the black shales, siltstones and carbonates of the Maraloou Formation conformably overlying mafic volcanic and intrusive rocks of the Killara Formation. These interfinger with the Doolgunna and Thaduna Formations to the north. The Killara mafic rocks have REE abundances and trace-element chemistry suggestive of an intracontinental tectonic setting (Pirajno et al., 1996).

The Bryah Basin rift succession lies to the northwest of the Yerrida Basin and is everywhere in fault contact with the Yerrida succession along the major, northeasterly trending Goodin Fault. The Bryah Basin consists of the clastic Karalundi Formation, mafic and ultramafic rocks of the Narracoota Formation, turbidites of the Ravelstone Formation and banded iron-formation and clastics of the Horseshoe Formation. Trace- and major-element data for

Table 16. Stratigraphy of the Yerrida, Bryah and Padbury Basins (after **Pirajno et al., 1996**)

Basin/group	*Subgroup*	*Formation*	*Rock type*
PADBURY (peripheral foreland basin)			
Padbury Group		Millidie	sericitic siltstone, chlorite siltstone, BIF, dolomitic arenite
		Robinson Range	ferruginous shale, BIF
		Wilthorpe (Beatty Park and Heines members)	quartz-pebble conglomerate, (mafic wacke, and polymictic conglomerate, respectively)
		Labouchere	turbidite sequence (quartz wacke, siltstone)
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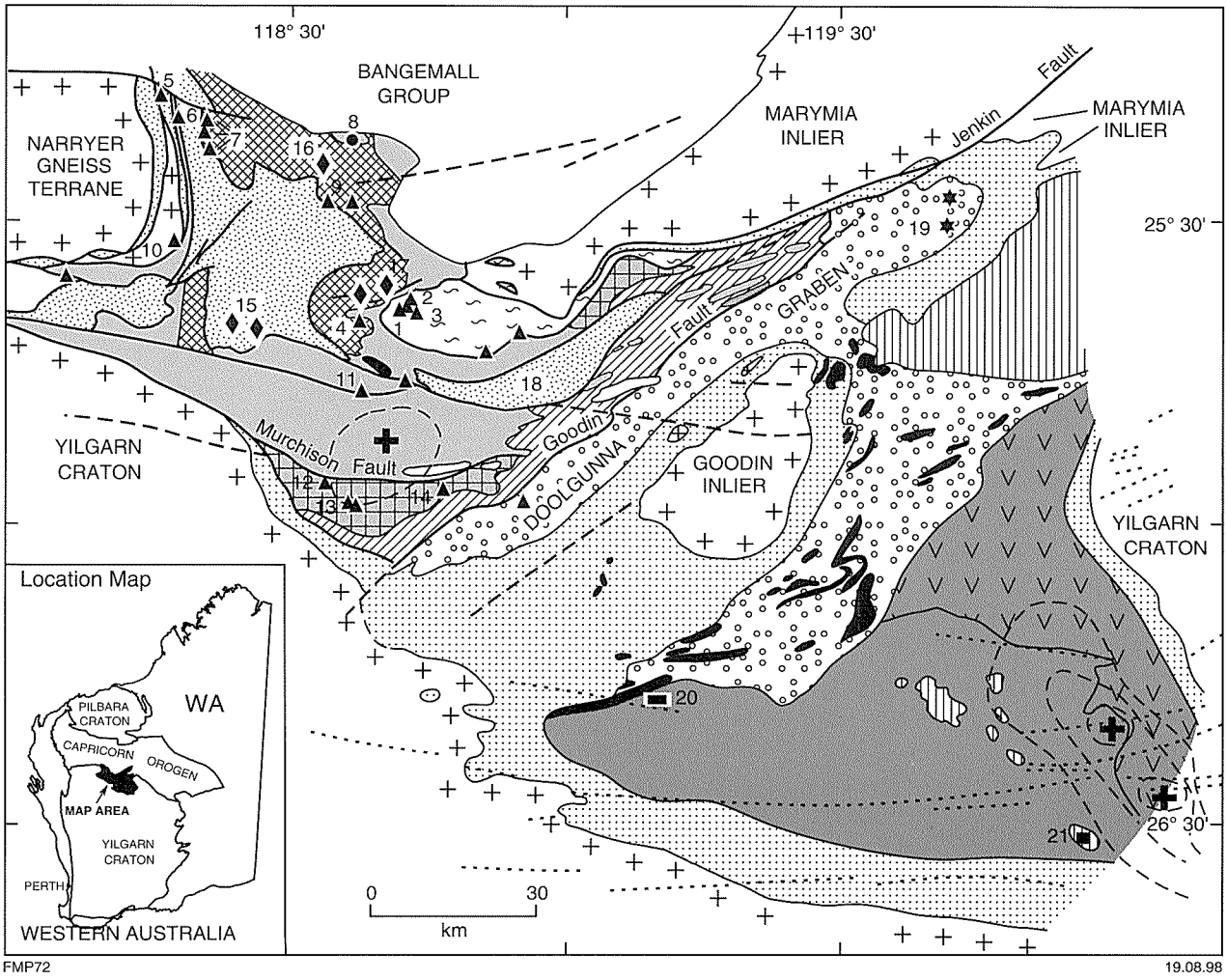

EARAHEEDY GROUP

PADBURY GROUP

BRYAH GROUP
- Horseshoe and Ravelstone Formations
- Narracoota Formation: mafic–ultramafic schist/ metabasaltic hyaloclastite
- Karalundi Formation

YERRIDA GROUP
- Mooloogool Subgroup
  - DOOLGUNNA–THADUNA DOMAIN with intercalated mafic sills and lavas
  - MARALOOU–KILLARA DOMAIN mafic extrusives and intrusives
- Windplain Subgroup
  - Siliciclastic, evaporite, shale

Peak Hill Schist

Archaean basement

Fault
Aeromagnetic lineament
Geological boundary
Microgabbro dyke
Mesothermal Au, Au–Cu
Shear-one hosted Cu
Epigenetic Pb
Volcanogenic massive sulfide
Supergene Mn
Shale-hosted stratabound sulfides
Bouguer gravity anomaly

1. Peak Hill
2. Jubilee
3. Mount Pleasant
4. Harmony (New Baxters Find)
5. Labouchere
6. Nathans–Deep South
7. Fortnum group
8. Horseshoe Lights
9. Horseshoe gold
10. Wilthorpe
11. Wembley
12. Mikhaburra
13. Cashman
14. Ruby Well
15. Mount Padbury–Mount Fraser group (including Elsa)
16. Horseshoe magnagese
17. Ravelstone
18. Robinson Range BIF (no specific locality)
19. Thaduna
20. PGE-bearing gossan
21. Magellan

Figure 77. Glengarry region: stratigraphic and structural interpretation (*after* Pirajno and Preston, 1998)

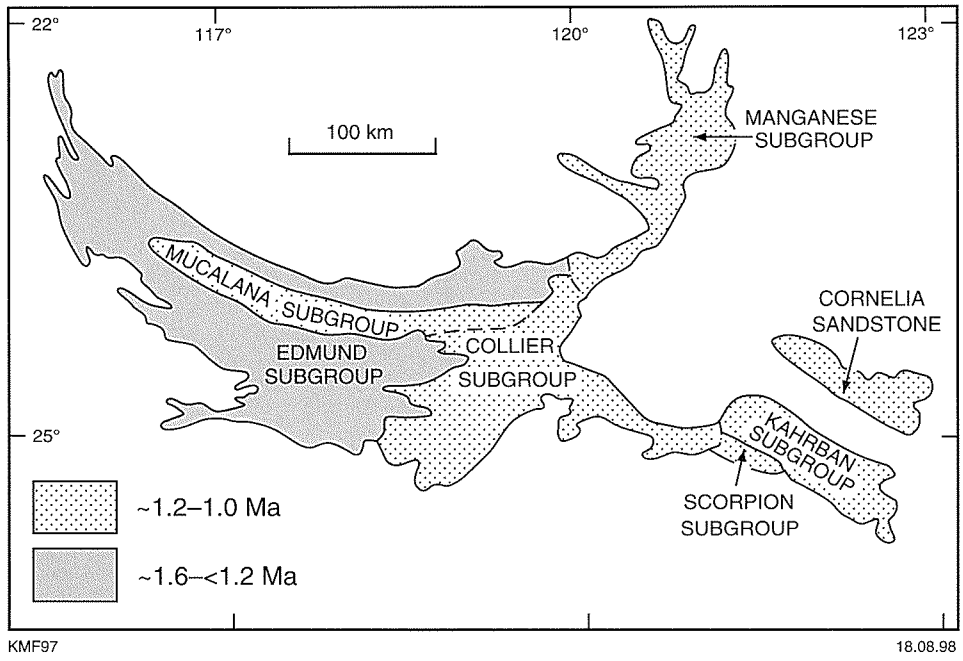

Figure 78. Bangemall Basin: subdivision of Bangemall Group (*after* Williams, 1990b)

the subalkaline mafic and ultramafic rocks of the Narracoota Formation (Pirajno and Davy, 1996), suggest mixed MORB to oceanic-island chemical signatures.

The intensely deformed Bryah Group is unconformably overlain by the predominantly turbiditic, clastic and chemical sedimentary rocks of the Padbury Basin succession, which is considered to have been deposited in a peripheral foreland basin during early deformation of the Bryah Basin. No volcanic rocks are present in the Padbury Basin succession although complex tectonic interleaving of Bryah Group volcanic rocks with the Padbury sedimentary rocks has occurred in response to thrusting and convergence from the north.

The Earaheedy Basin occupies the eastern part of the Nabberu Province and unconformably overlies the Yerrida Basin in the west. It is dominated by marine-platform clastics, carbonate and cherty iron formations of the Earaheedy Group (Fig. 76). The stratigraphy reflects two transgressive–regressive cycles, represented by the Tooloo and Miningarra Subgroups (Table 17). The Earaheedy Group is folded into a broad, asymmetrical synclinorium on an east-southeast trend. North of the axis the rocks are deformed, have slaty cleavage and are affected by folding.

Gee (1990) notes that the basal unit of the Earaheedy Basin, the Yelma Formation, reflects progressive shallowing of the basin to the southwest indicating northeast to southwest trangression on an extensive marine shelf. Outliers of the clastic Yelma Formation, overlie the Maraloou Formation within the Yerrida Basin, in a northerly trending syncline. They consist of intercalations of stromatolitic cherty carbonate with calcareous silty sandstone, underlain by a basal thin sandstone–conglomerate unit.

The Yerrida, Bryah and Padbury Groups are dated at approximately 2.258, 1.92 and 2.0–1.9 Ga, respectively (Pirajno et al., 1996)

Mineralization

The tectonic evolution of the Yerrida and Bryah Basins, with volcanic-arc and back-arc affinities, and the development of continent-marginal rift-bounded troughs, might suggest potential for both volcanogenic and sedimentary stratiform exhalative base-metal mineralization. Extensive shelf carbonates might also host epigenetic mineralization.

The discoveries of the Magellan deposit (Fig. 77), and other prospects, by RGC in base-metal exploration for sediment-hosted targets confirms potential for the epigenetic style. Carbonate rocks occur both in the Maraloou Formation and in the margins and outliers of the Earaheedy Basin which overlie the Yerrida and Bryah Basins. Some corroborative evidence for this (Le Blanc Smith et al., 1995) can be seen in the presence of coalified hydrocarbon residues within thick black carbonaceous shale and carbonate breccia units (Maraloou Formation and overlying Frere Formation) in the Mount Bartle area of the Paroo Platform. These hydrocarbons are possibly sourced from stromatolitic units and black shale and indicate the migration of potentially mineralizing fluids in the sequence. Anomalous copper, zinc and mercury are present in the black shale. Hydrocarbon residues are reported in association with base-metal mineralization in the Transvaal Sequence in South Africa and in the McArthur Basin. Le Blanc Smith et al. (1995) also report chert breccia and hydraulic fracturing in laminated carbonate–stromatolite units, which are locally silicified.

Table 17. Stratigraphy of the Earaheedy Group (after **Bunting, 1986**)

Sub-group	*Formation and map symbol*	*Lithology*	*Approximate thickness (m)*	*Deposition environment*
MININGARRA	Mulgarra Sandstone *PEm*	Medium-grained quartz arenite; minor shale and limestone in middle section	100	Shallow marine
	Kulele Limestone *PEk*	Limestone, which is variously oolitic, pisolitic, stromatolitic and brecciated, interbedded with calcarenite, sandstone, shale and rare dolomite	300	Cyclical, from shallow marine (subtidal) to tidal mudflats or lagoons
	Wongawol Formation *PEo*	Arkosic and lithic sandstone, shale, with minor carbonate in upper part (Sholl Creek Member)	1 500	Very shallow water, non-tidal (lagoon or partly enclosed sea)
	Princess Ranges *PEp*	White orthoquartzite, kaolinitic siltstone and silty sandstone	280–600	Shallow marine, tidal; localized deltaic and shoreline facies. Regressive
	Wandiwarra Formation *PEw*	Ferruginous quartz arenite and shale	0–1 500	Shallow marine, becoming deeper above stratigraphic level of Windidda disconformity. Transgressive
TOOLOO	Windidda Formation *PEd*	Laminated or stromatolitic dolomite and limestone interbedded with mudstone and shale	300–800	Barred basin or lagoon. Regressive
	Frere Formation *PEf*	Granular and banded iron-formation, shale, chert, minor carbonate	1 200	Shallow marine. Transgressive
	Yelma Formation *PEy*	Quartz arenite, shale, minor carbonate, chert and conglomerate	5–1 500	Shallow marine, local fluvial near base. Transgressive

These suggest processes of silicification and subsequent hydraulic fracturing with implications for the genesis of hydrothermal base-metal accumulation.

Gee and Grey (1993) discuss the presence of high supratidal sabkhas in the evaporitic rocks of the Juderina Formation (Bubble Well Member), and point out their similarity to those reported from the McArthur Group in the Northern Territory and at Mount Isa, which may have been a source of sulfate in metalliferous brines in those areas.

The biggest known base-metal deposits in the Yerrida Basin are the Thaduna copper deposits (Fig. 77), which are located within metagreywacke and slate of the Mooloogool rift sequence. They consist of enriched oxidized zones over north-northwesterly and easterly trending, shear-controlled quartz-vein systems. These, like the shear zone-hosted gold and copper–gold mineralization in the Bryah and Padbury Basins, are presumably the result of hydrothermal activity in association with the collision-related intense deformation and medium-grade metamorphism in this area.

Copper and silver occur in association with gold in the Horseshoe Lights massive-sulfide deposit, hosted in pyritic chert units and volcaniclastic rocks within quartz–chlorite, quartz–sericite(–muscovite–kaolin) schist of the Narracoota Formation (Bryah Group) (**Chapter 6**). This is considered to be a VMS deposit overprinted by structurally controlled lode-gold mineralization (Groves et al., 1994). Pirajno and Preston (1998) consider this deposit to be synvolcanic and pre-orogenic. Its presence lends support to the concept of a volcanic island arc and back-arc basin, subduction-related tectonic setting on the northern margin of the Yilgarn Craton during the latter part of the Palaeoproterozoic.

Pirajno and Occhipinti (1995) suggest that in the Bryah rift basin, continental rifting advanced to form oceanic crust and oceanic islands. They also suggest that crustal thinning and stretching in the Mooloogool rift sub-basin produced only small areas of oceanic crust. Parallels with the tectonic setting of the Matchless Belt in the Damara Orogen in Namibia may indicate potential for Besshi-type volcanogenic Cu–Zn sulfide deposits in the Killara Formation.

Exploration

Most of the base-metal exploration in the Bryah, Yerrida and Earaheedy Basins in the 1960s and early 1970s was copper-oriented and related to Thaduna-style and Horseshoe/Labouchere-style targets.

Among those who began searching for stratabound targets in the mid-1970s, Samantha (I 3004) obtained up to 2000 ppm Cu and 2950 ppm Zn in gossan samples at Twelve Mile Pool in the southeast Paroo Platform in Finlayson Sandstone. Samples showed the presence of sphalerite and galena. Exploration in the Killara area, detailed below, also began at this time. In 1980–82, Chevron (I 2490) explored for stratabound targets in the rift-facies sedimentary rocks and volcanic rocks north of the Goodin Inlier. Aeromagnetic anomalies were checked on the ground with soil sampling and shallow drilling. Minor anomalies were associated only with arkosic sedimentary rocks. At about the same time Esso (I 2020) assessed the potential of a postulated sub-basin at Lake Gregory following more regional mapping, gravity and RAB geochemical studies. Percussion-drilling results did not confirm a favourable tectonic environment. Drilling by CRA in 1982–83 (I 3102) beneath a gossan in basalt, tuff and tuffaceous shale at Karalundi, near the southwest margin of the basin, failed to locate significant mineralization.

The first significant study of the Maraloou Formation on the Paroo Platform was by ACM/Esso from 1982–86 (I 3101). Prior to this Chevron had located low-order base-metal anomalies in the Diamond Well area during uranium exploration (I 1252) and Noranda, also at Diamond Well (I 571), found anomalous surface enrichment of zinc, nickel and cobalt in black manganiferous shale (Maraloou Formation). ACM targeted Kupferschiefer and McArthur River mineralization types. The apparent structural and lithological uniformity of the Maraloou Formation, and lack of surface mineralization, led to an examination of the Maraloou rocks at greater depth, initially in a gravity survey. This indicated a feature interpreted as a deepening of the basin between two Archaean greenstone palaeo-highs. Despite drilling to nearly 400 m in carbonaceous black shale of the middle to upper Maraloou Formation, little lithofacies variation was encountered and base-metal contents were low (≤10 m at 0.29% Cu). Anomalous gold, silver, titanium and barium were recorded. Potentially favourable lithologies in the rift-facies units (Mooloogool Subgroup) were considered to be at too great a depth to warrant further exploration.

Follow-up work by Mitchell Exploration in 1986–89 (I 3800 and 4579) in part of this area at Mount Bartle and in the Finlayson Range and Twelve Mile Bore areas, recognized the structural complexity and surface anomalism of the area but involved only mapping and surface sampling. Assays of Maraloou sedimentary rocks (interpreted as felsic lava, tuff and tuffaceous material) at Mount Bartle, and a fine carbonate unit interpreted as an altered tuff, gave up to 0.62% Zn and 10 ppb Au. Silver up to 76 g/t and anomalous phosphorus and fluorine were also recorded.

Between 1977 and 1980, BHP examined possible stratabound carbonate or clastic-hosted base metals in the Frere and Yelma Formations (dolomite and sandstone–shale) at Sweetwaters Well in the Earaheedy Group, in the eastern part of the Nabberu Province (I 2181). Galena and pyrite stringers, and up to 6% Pb, was found in outcrop of dolomite, and up to 0.5% Pb and Zn in ironstone. Shallow drilling indicated lead, interpreted as surface enrichment, up to 7000 ppm, in the 'lake sediments' of Lake Nabberu and in weathered Yelma Formation.

Exploration for base metals in the Troy Creek Inlier, on the northern margin of the Earaheedy basin (Fig. 76), has targeted the Troy Creek Beds (possible Yerrida correlative), made up of phyllitic shale, chloritic schist, quartz sandstone, chert dolomite, banded iron-formation and felsic tuff. CSR/Pacminex in 1977–79 (I 2038) explored in the eastern part of the Inlier, initially for VMS targets based on the possible presence of felsic volcanic rocks in the sequence. Follow-up work included aeromagnetic and radiometric surveys, geological mapping and ironstone search and sampling. No significant anomalies or indications of sulfide mineralization were located (≤1050 ppm Pb and 700 ppm Zn). The ?felsic sequence included a significant proportion of felsic porphyry and ironstone, which appear to be associated with regional faults. No shallow magnetic features were located in the ?felsic rocks. Recent GSWA mapping has found no trace of felsic volcanic rocks in this area (Pirajno, F., 1998, pers. comm.).

In 1982–83, Amax (I 3196) explored in the western part of the Troy Creek outcrop area for sediment-hosted base metals. Carbonaceous siltstone and shale occupy the lowest part of the sequence in this area with rapid coarsening upwards. The proximity of the major Salvation Fault, and the association with supposed heat-producing acid volcanism, were considered prospective features. Ironstone geochemistry, however, suggested that the ironstones represent bedded pyrite rather than base-metal sulfides.

Exploration by Geopeko (1983–84) included stratiform base-metal models in a review of the potential of this area. Only restricted chip sampling was carried out. An assay of 2350 ppm Pb from an old WMC uranium-exploration percussion hole was considered significant. However, no follow-up ensued. A discussion of these targets is given in the section on the Bangemall Basin in this chapter.

In 1984–86, CRA (I 3238) located magnetite in carbonate-cemented siltstone in the Salvation Fault zone while drilling a 'bullseye' magnetic anomaly. No significant base metals were related to this, although 'traces of chalcopyrite and galena were observed'.

Normandy Poseidon/Sons of Gwalia explored for gold, base metals and diamonds in the Troy Creek area in the early 1990s, locating some gold and copper anomalism.

RGC began exploring for base metals in the Nabberu province in 1990 (McQuitty, 1997). The Magellan lead deposit was discovered in 1991 during RAB drilling follow-up of anomalous chip sampling. The recognition of the Yelma Formation of the Earaheedy Group as the principal host for this mineralization led to regional follow up of that unit, using the broad-spaced pattern drilling typical of MVT mineralization, and the discovery of further prospects at Iroquois and Navajo. RGC explored almost the whole 300 km southern margin of the Earaheedy Basin and discovered a further six significant

prospects. Most are near the west end of the basin, west of the Shoemaker Impact Structure (formerly Teague Ring Structure). These are described as consisting of zinc- and/or lead-rich sulfide mineralization with base-metal oxides in the weathered updip portion (McQuitty, 1997).

Deposits, prospects and occurrences

MAGELLAN

Prospect: Pb
Location: 26°31'15"S, 119°57'15"E; 31 km southeast of Yandal Homestead.

In their 1993 Annual Report, RGC announced that within its 4500 km^2 of tenements in the Nabberu Province, work on the Magellan prospect had outlined lead mineralization over an area 5 by 2.5 km, in the Yerrida Basin. The deposit contains a total resource of 210 Mt at 1.8% Pb, with defined zones at 2% cutoff containing an indicated resource of 5.5 Mt at 7.1% Pb (McQuitty, 1997) and an inferred resource of 7.09 Mt at 4% Pb (Rennison Goldfields Consolidated, 1995). Several other anomalous areas with potential for base-metal sulfides have been detected.

The mineralization is hosted by silicified immature wacke and stromatolitic carbonate units in outliers of the Yelma Formation of the Earaheedy Group overlying Maraloou Formation black shales of the Yerrida Basin (Pirajno and Preston, 1998). McQuitty (1997) describes the Yelma Formation in the vicinity of Magellan as consisting of a basal sandstone unit fining upwards into siltstone and claystone and overlain by a quartz-breccia unit. In this area it forms a gentle syncline on a northwest axis. The lead minerals occur as matrix replacement, predominantly in the quartz–clay breccia. The breccia is made up of fragments of silicified stromatolitic carbonate, chert, siltstone, vuggy euhedral crustiform quartz and colloform banded quartz. Lead levels are low, however, in the silica cap over the quartz-breccia unit, which effectively masks the deposit except at breakaways.

Lead ore minerals include cerrusite, anglesite, plattnerite, and pyromorphite. Pirajno et al. (1995) report a Pb–Pb model age of 1650 Ma for the cerrusite which is clearly the dominant mineral. An anglesite-dominant zone occurs above the thickest parts of the deposit. Anomalous abundances of Ba (1000–1828 ppm), Mn (1900–3672 ppm) and Cu (257–400 ppm) are indicated but no sulfides or other metals are present. Zinc levels are low but increase towards the base of oxidation. Maraloou Formation carbonaceous shales below the deposit, however, contain up to 0.5% zinc (McQuitty, 1997).

RGC interpret the deposit as the residue from a primary carbonate-hosted lead sulfide deposit following weathering-related solution collapse after formation. Thus, volume reduction and leaching of zinc could have been instrumental in converting a moderate-grade carbonate-hosted lead–zinc sulfide deposit into a higher grade lead deposit.

References: Rennison Goldfields Consolidated (1993), McQuitty (1997), Pirajno et al. (1995), Pirajno and Preston (1998).

KILLARA (Westralian, Gee-Bunting)

Prospects: Pb; Zn; Cu
Location: 26°15'40"S, 119°06'30"E; 20 km east-northeast of Killara Homestead

These prospects occur in two east-northeasterly striking ironstone bands within carbonaceous shale of the Johnson Cairn Formation, intruded by dolerite sills. Levels of up to 5.05% Pb and 0.283% Zn have been recorded in chip sampling. Most geological and geochemical evidence suggests that this is a surface enrichment. Drilling of the Westralian Gossan gave a best intersection of 1 m at 2230 ppm Zn. Some drill targets produced by the exploration summarized below remain untested.

The CSIRO (1976–78) carried out rock-chip sampling of cupriferous ironstone overlying carbonaceous shale in the vicinity of Killara Homestead, obtaining up to 0.181% Cu and 660 ppm Zn. The highest copper value in percussion drilling to fresh rock was 190 ppm. As a result of petrological and geochemical studies, CSIRO concluded that, owing to contrasting Eh and pH during oxidation, surface enrichment of base metals occurred at shale–dolerite boundaries.

Following this finding, Pacminex and EZ briefly explored in the area. CEC (1983–84) combined regional and detailed mapping with BMR aeromagnetic and gravity data to propose that the Maraloou Formation in this area (Johnson Cairn Formation — Pirajno, F., 1998, pers. comm.), rather than being a shelf facies equivalent of the Glengarry Group, was of possible Middle Proterozoic age, was unconformably overlying the Glengarry Group, and had been deposited in a proposed intracratonic Killara Basin. They interpreted this age as suggesting a higher prospectivity for McArthur River-style stratiform base metals. Shallow-water sedimentation with basal coarse arenites also suggested prospectivity for Zambian-style copper. Regional stream-sediment geochemistry, detailed aeromagnetics, gravity and Sirotem plus rock, soil and RAB geochemistry led to the drilling of three prospects. Surface sampling gave maxima of 2830 ppm Zn and 2260 ppm Pb in ironstones. In the Westralian Gossan prospect a maximum of 1 m at 2230 ppm Zn was obtained at a depth of 141 m on a carbonaceous shale/dolerite contact associated with alteration and bleaching.

CRA (1985) joined CEC in the project and drilled a gravity anomaly considered to have similarities with that at McArthur River. No anomalous base metals were encountered.

Recent mapping by GSWA has recognized scattered outliers of Earaheedy Group sedimentary rocks unconformably overlying the Yerrida Group in the east of the Yerrida Basin. It is possible that the unconformable sedimentary rocks described above are part of this association.

ACM/Poseidon (1989–92) obtained up to 5.05% Pb in ironstone sampling in the same general area. A soil and RAB geochemical anomaly was identified which yielded two conductors in TEM and ground magnetics. Drilling indicated that the conductors were due to graphitic shale units and returned a maximum of 620 ppm Pb and 780 ppm Zn.

Most recently Geopeko (1992–93) carried out further reconnaissance mapping and chip and stream-sediment geochemistry in the area and obtained only weakly anomalous results. They concluded that the area covers a transition zone between shelf facies and trough facies environments in the Yerrida Basin and does not have high potential.

References: GSWA-WAMEX - I 642, I 1247, I 2017, I 3232, I 6759, I 8613.

Potential

The information presented above indicates potential for several types of base-metal mineralization in the Nabberu Province, including clastic and carbonate-hosted epigenetic types and syngenetic volcanic-hosted mineralization.

Although an evaluation of the potential of the Nabberu Province for lead–zinc–silver mineralization must take into account the still-evolving understanding of the detailed nature of events and settings within the framework of the Capricorn Orogen, and more specifically in the Yerrida, Bryah, Padbury, and Earaheedy Basins, much progress has been made due to recent mapping and tectonic–basinal studies

Geological mapping by GSWA at the 1:100 000 scale has confirmed the complexity of syn-sedimentary tectonics related to the extensional rift phase and to the onset of compression in the Bryah and Yerrida Basins. Although intracratonic and craton-margin rift settings exist in the Yerrida and Bryah Basins, there is no evidence for syngenetic, clastic-hosted lead–zinc mineralization. Extension and subsequent limited compression in the Yerrida Basin, with the combination of arenaceous basal sedimentary rocks of the Finlayson Member and overlying tholeiitic basalt (Killara Formation), black shales, siltstones and carbonate of the Maraloou Formation, might suggest potential for this type of mineralization. However, the basin is relatively shallow and it is hard to visualise a large enough basin-dewatering system that could focus a sufficient volume of metal-bearing fluids into the potential host lithologies.

The synsedimentary onset of compression, related to the presence and distribution of carbonate lithologies in the Yerrida Basin may, however, provide potential for both the mixed syngenetic and epigenetic Irish-type mineralization, and for more typical, stratabound carbonate-hosted mineralization in more distal settings. The features related to hydrocarbon mobility and hydraulic fracturing in chert breccias, described by Le Blanc Smith et al. (1995), support this.

Pirajno and Occhipinti (1995) highlight the potential for syngenetic sulfides associated with a sabkha environment in the Bubble Well Formation on the southeast margin of the Yerrida Basin. Hematitic units of the Finlayson Member could provide a metal source with sulfides being precipitated in a marginal-marine sabkha.

The interpretation of volcanic-arc and back-arc settings on the Yilgarn continental margin, reflected in the ocean-island chemical signature of the Narracoota Formation, suggests the potential for volcanogenic base-metal mineralization in felsic volcanic rocks. The quartz–muscovite–chlorite schist seen at Horseshoe Lights is considered to be after felsic tuff and agglomerate (Gee, 1987), and contains massive and stringer copper–gold mineralization, interpreted as Kuroko-style volcanogenic (Parker and Brown, 1990; Pirajno and Preston, 1998) (**Chapter 6**). Unfortunately, mafic and ultramafic lithologies dominate most of the outcrop areas of the Narracoota Formation. Areas with potential for further volcanogenic base-metal mineralization are probably largely concealed beneath sedimentary rocks of the Bangemall Basin.

Bangemall Basin

Geological framework

The relatively undisturbed sedimentary rocks of the Bangemall Basin (1.6 to 0.75 Ga) unconformably overlie the deformed and metamorphosed elements of the Capricorn Orogen (2.0 to 1.7 Ga), the Gascoyne Complex, and the Nabberu and Ashburton Basins (Fig. 72). The Bangemall sedimentary rocks obscure the suture zone between the Pilbara and Yilgarn Cratons and form an eastward-plunging synclinorium (Muhling and Brakel, 1985; Williams, 1990b).

The dominant lithologies are sandstone, shale and carbonate intruded by abundant dolerite sills. The western part of the basin predominantly comprises the older (1.6 to 1.2 Ga) Edmund Subgroup (Figs 78 and 79; Tables 18 and 19). Early sedimentation in this area reflected localized erosion and deposition in relation to south-easterly to east-northeasterly trending horst blocks and growth fault basins in the underlying basement, considered to have formed in a period of crustal extension. The Mount Augustus Formation and Tringadee Sandstone show wedges of coarse, poorly sorted terrestrial detritus indicating a provenance to the south. There is some evidence for volcanic activity related to the extensional tectonics in localized felsic volcanic activity in the Coobarra Dome area (Tangadee Rhyolite) and dolerite sills in the Ullawarra Formation and the Fords Creek Shale. Also developing was a shallow-marine, lagoonal facies along the western and northern margins of the basin. The dolomitic Irregully and Cheyne Springs Formations and the clastic–dolomitic Kiangi Creek and Jillawarra Formations indicate an interfingering of lagoonal and open-marine shelf facies in a complex, transgressive linear-shoreline phase. The marine facies reflected a transgression from the south which began in a

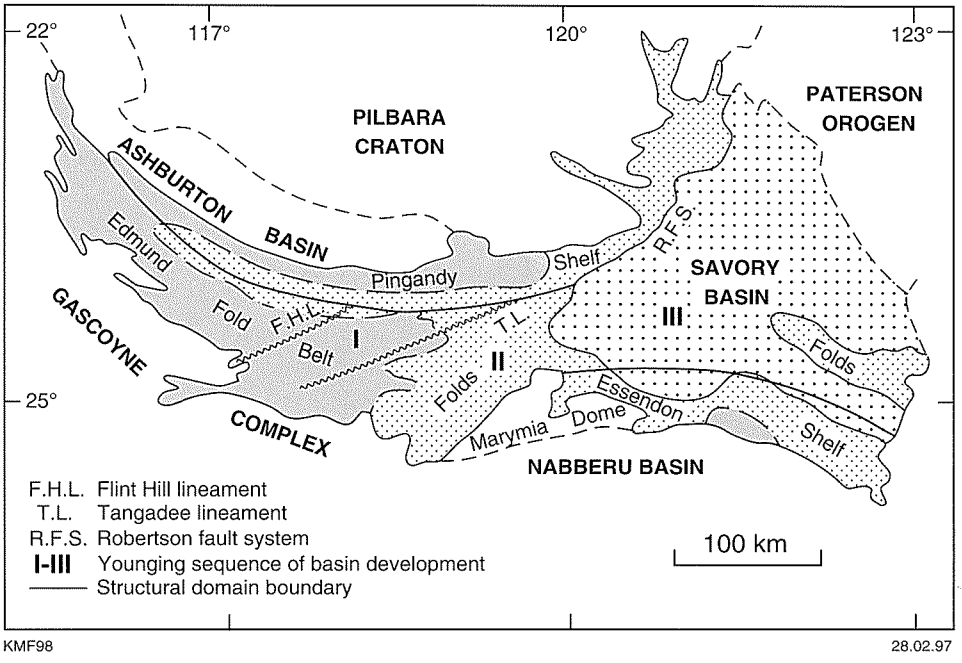

Figure 79. Bangemall Basin: major structural elements (*after* Williams, 1990b)

complex graben situated between the northeasterly trending Flint Hill and Tangadee Lineaments. Sandy influxes on the northern margin are represented by the Gooragoora Sandstone and Prairie Downs Formation. The widespread Discovery Chert marks the end of this phase of sedimentation and is a key marker horizon which formed by the precipitation of a silica gel beneath the wave base, under reducing conditions and low pH, in a barred basin.

The overlying dolomitic Devil Creek Formation marks a return to shallow-marine shelf to basin conditions. There is very little clastic input at this stage apart from quartz arenites on the southern margin represented by the Nanular Sandstone. A thick sequence of greenish shales and siltstones overlies both of these units and may represent either a shallow platform or deeper basin plain. This is overlain by two related elements of a prodelta facies; the proximal, near-shore turbidites of the Coodardoo Formation, and the distal-shelf black shales and siltstones of the Curran Formation.

Of economic importance is the part of this subgroup which occupies the central part of the Bangemall Basin. The discovery of stratabound base metals at Abra has led to more detailed studies in this area (Vogt and Stumpfl, 1987; Boddington, 1987; Vogt, 1995) that have defined an easterly trending fault-bounded graben identified as the Jillawarra sub-basin. Mapping at 1:250 000 scale by GSWA has identified lithologies in this area as continuous

Table 18. Stratigraphic subdivision of the Bangemall Group (after **Williams, 1990b**)

					[a]1.0
Mucalana Subgroup	Collier Subgroup	Manganese Subgroup	Kahrban Subgroup	Cornelia Sandstone	1.1
					1.2
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Table 19. Stratigraphic subdivision of the western Bangemall Basin (after **Williams, 1990b**)

Unit	*Lithology*	*Thickness (m)*	*Stratigraphic relationships*	*Depositional setting*
Mucalana Subgroup				
Kurabuka Formation	Shale, mudstone, chert; minor limestone, calcareous siltstone	990	Eroded top of unit; conformable on Mount Vernon Sandstone	Shallow-water suspension deposition in marine lagoons or small sub-basins, sub-wave base
Mount Vernon Sandstone	Fine- to medium-grained arenite; rare conglomerate; local interbedded siltstone, shale, and glauconitic sandstone	~225	Conformable between Kurabuka Formation and Fords Creek Shale	Shoreline barrier bar, tide-swept shelf
Fords Creek Shale	Greenish shale, mudstone; lesser arenite, wacke, dolomite, chert	~1 740	Apparently conformable on Coodardoo and Curran Formations	Marine shelf; sub-wave base, distal turbidites
Jeeaila Sandstone Member	Medium-grained arenite	≤80	Member of Fords Creek Shale	Shallow-marine turbidites, partly reworked by bottom currents
Edmund Subgroup				
Coodardoo Formation	Arenite, wacke; minor siltstone, shale, aphanitic mudstone	≤370	Lenticular unit, conformable on Curran Formation	Near-shore proximal turbidites
Curran Formation	Grey to black shale, mudstone; very minor chert, limestone, dolomite, fine-grained sandstone	100–250	Lenticular unit, conformable on Ullawarra Formation	Distal pro-delta shelf, shallow-water turbites
Ullawarra Formation	Shale, siltstone, fine-grained arenite; minor interbeds of wacke, claystone, dolomite, chert	1 500–2 500 (difficult to measure)	Conformably overlies Devil Creek Formation	Shallow-marine platform, sand and silt shoals, turbidity currents
Nanular Sandstone	Medium- to fine-grained quartz arenite, coarse grained quartz siltstone, interbeds shale, wacke	2 200	Conformable on Devil Creek Formation, lenticular; relationship to Backdoor Formation not clear	Barrier-bar system; possible delta front
Devil Creek Formation	Dolomite, shale; very minor siltstone, fine-grained sandstone, breccia, chert	30–800	Conformably overlies Discovery Chert	Sub-wave marine platform, tidal flat, estuaries, shoals of carbonate sand
Discovery Chert	Massive, laminated, or fissile chert, local shale	50–80	Conformable on Jillawarra and Kiangi Creek Formations	Sub-wave-base marine, hypersaline, restricted circulation
Jillawarra Formation	Shale, siltstone; minor claystone, chert, dolomite, sandstone	60–1 020	Conformable on, and lateral equivalent in part to, Kiangi Creek Formation	Open-marine shelf becoming restricted and hypersaline
Kiangi Creek Formation	Quartz arenite, shale, siltstone; minor dolomite, conglomerate	700–2 000	Conformable on Cheyne Springs Formation and Irregully Formation	High-energy barrier bar or beach; delta-front marine

Table 19.(continued)

Unit	*Lithology*	*Thickness (m)*	*Stratigraphic relationships*	*Depositional setting*
Coobarra Formation	Sandstone, conglomerate; minor siltstone, shale, small plugs of rhyolite	~500	Nonconformable on Coobarra Dome granitic inlier; relationship to Backdoor Formation not exposed	Alluvial fan
Cheyne Springs Formation	Dolomite, dololutite, dolomitic breccia; minor mudstone, sandstone, siltstone	200–700	Conformable on Gooragoora Sandstone where present	Shallow-water shelf; shelf edge and slope
Gooragoora Sandstone	Medium-grained sandstone; some shale, conglomerate	10–250	Lenticular units, conformable on Irregully Formation	Alluvial fan, fan delta, marine
Irregully Formation	Dolomite shale, siltstone; minor sandstone	≤1 300	Conformable on Tringadee Formation; unconformable basal unit on Ashburton Basin and Gascoyne Complex	Fringing coastal lagoon system, tidal flats, shoals, washover fans
Tringadee Formation	Sandstone, pebbly sandstone, conglomerate; minor siltstone, dolomite	≤1 100	Lenticular basal unit, restricted to southern margin overlying Gascoyne Complex	Alluvial fans, fan deltas
Mount Augustus Sandstone	Coarse-grained sandstone, scattered pebbles; minor conglomerate	200–400	Basal unit, restricted area; unconformable on Gascoyne Complex	Alluvial fans
Top Camp Formation	Dolomite, limestone, shale, dolomitic shale, chert, quartz arenite, breccia; minor conglomerate	900–2 500	Unconformable on Ashburton Basin and Bresnahan Basin; conformably overlain by Fords Creek Shale	

with the Irregully and Kiangi Creek Formations farther west. Vogt and Stumpfl (1987) and Vogt (1995), however, have suggested that the graben represents an initial zone of rifting in the Bangemall Basin and have established a separate sequence within it. Within the sub-basin are ~1000 m of thinly bedded dolomitic siltstone, shale and arkose with minor massive dolomite of the subtidal, supratidal Gap Well Formation overlain by ~1000 m of the nearshore, shallow-marine, siliciclastic arenaceous turbidites of the West Creek Formation.

The upper part of the western sequence, the Mucalana Subgroup (~1.2 to 1.1 Ga), conformably overlies the Edmund Subgroup and comprises the Fords Creek Shale, the Mount Vernon Sandstone and the Kurabuka Formation. These are interpreted as a regressive, linear-shoreline sequence, reversing the transgressive sequence seen in the Edmund Subgroup. This is the lateral equivalent of the Collier Subgroup, which is the dominant sequence in the eastern part of the basin. The three main units, the Backdoor Formation, the Calyie Shale and the Ilgarari Formation, directly correlate with the Fords Creek, Mount Vernon and Kurabuka units respectively. The Collier Subgroup unconformably overlies the Scorpion Subgroup (~1.6–1.2 Ga), a 10 km-thick clastic–carbonate equivalent of the Edmund Subgroup, in the southeast. To the northeast the Collier equivalent is the dominantly marine Manganese Subgroup, which occupies a linear zone marginal to the southeastern edge of the Pilbara Craton. In some contrast to the previously reported ~1.05 Ga age for the Manganese Group (Williams, 1990b), recent unpublished Rb–Sr data (J. de Laeter, *cited by* Williams, 1992) suggest a range of 1.33 to 1.26 Ga for the Manganese Subgroup. This would make it equivalent to the upper part of the Edmund and Scorpion Subgroups.

Extensional tectonics continued throughout the deposition of the Bangemall Group affecting the development of the Jillawarra sub-basin, and the related base-metal mineralization, and the widespread emplacement of dolerite sills into the Ullawarra Formation and Fords Creek Shale. Continuous tectonism in the basement produced the post-depositional Edmund Fold Belt in the Bangemall Group. The elongate steeply dipping fold axes change direction across the major Flint Hill Lineament. Later tight folding was produced by a change to compressional tectonics as the Gascoyne Complex moved north towards the Pilbara Craton. Growth faults and shear zones in the basement were reactivated with resulting thrusting of rocks northwards against the Pingandy Shelf. A number of outliers of the Edmund Subgroup are located in preserved synclinal keels within the Gascoyne Complex west and south of the Bangemall Basin.

Mineralization

Lead–zinc mineralization in the Bangemall Basin is found predominantly in minor vein-type occurrences such as Maroonah, Teano Range and Keep It Dark. Most of these are small quartz veins in the Irregully Formation within the western facies of the basin (**Chapter 8**).

Stratabound copper–zinc mineralization in the Bangemall Basin is commonly associated with shallow-marine carbonaceous, pyritic shale–dolomite–chert lithologies in various units of the western facies, notably the Irregully, Kiangi Creek and Devil Creek Formations, and the Discovery Chert.

In a study of stratabound mineralization at Mount Vernon, Mount Palgrave and Quartzite Well, Davy (1980) concluded that the mineralization was syngenetic and formed in unconsolidated sediments in a strongly reducing environment. At the first two prospects, the black shale was considered to have formed in shallow-marine conditions on a continental shelf, whereas at Quartzite Well (in the Jillawarra sub-basin) the more carbonatic siltstone was deposited in a restricted basin or lagoon. Sphalerite is the main economic mineral, with minor covellite. Pyrite and sphalerite were remobilized into veins during diagenesis. No volcanic units are associated with these occurrences and the source of sulfides was assumed to be connate water. Reducing conditions and organic matter were considered to have played a major part in the precipitation of base-metals at Mount Vernon and Mount Palgrave. This conclusion would probably apply for most of the prospects detailed below, except those of the Jillawarra sub-basin. In a study of possible McArthur River–HYC analogues, Marshall (1968) commented on the large areal extent and strong stratigraphic control of the Bangemall copper–zinc mineralization as a confirmation of its syngenetic origin. He also suggested that the close areal and temporal relations of the Mount Palgrave and Mount Vernon prospects with a bed of pure alunite and a lens of altered dolomite might indicate a submarine exhalative source for the metals.

Muhling and Brakel (1985) pointed out that most of the known copper–zinc occurrences lay close to boundaries between structural provinces, coinciding with sedimentary hinge lines and related to emergent basement. They considered this to have produced areas of enhanced reducing potential and fixing of copper and zinc.

The carbonaceous, pyritic shale units of the Discovery Chert, Jillawarra Formation and Kiangi Creek Formation have been found to be regionally anomalous in zinc, copper and lead in extensive stream-sediment and soil sampling surveys carried out by various exploration companies. Smith and Davy (1979) reported the validation of stream-sediment geochemistry in base-metal exploration in the Bangemall Basin by Union Miniere and Westfield Minerals.

Marston (1979) pointed out that exploration in the Bangemall Basin for stratiform copper, zinc and lead had commonly shown levels of up to several percent at the surface but that drilling rarely encountered levels above 0.1%. Marshall (1968), however, demonstrated that megascopic recognition of the depth limit of weathering, particularly in black shale and mudstone in this area, was unreliable. An idealized profile of the Mount Vernon–Mount Palgrave areas shows depressed copper and zinc to depths of over 150 m. In detail the picture is more complicated with both depletion and enrichment occurring within the thick weathered zone.

In discussing the base-metal potential of the Bangemall Group, Chuck (1984) examines the potential for both

carbonate-hosted and clastic-hosted deposits. Carbonate-hosted occurrences and prospects in the basin are all of subeconomic grade and are predominantly in the Irregully Formation lying in the Pingandy Shelf and the more stable marginal parts of the Edmund Fold Belt. The associated lithologies are dolomitic and tend to lack significant interbedded terrigenous sedimentary units. The dolomite horizons are silicified and commonly resemble cherts. Dark-grey areas possibly contain unoxidized organic carbon. They are of shallow-marine origin showing shallow subtidal to intertidal shelf features. A major negative feature for this deposit type, however, may be the general absence of significant zones of either primary or secondary porosity in the host sequences.

Clastic-hosted occurrences and prospects are in pyritic shale at several levels in the units mentioned above. These have formed in low-energy, reducing environments at subtidal levels. Chuck (1984) has pointed out the regional association (within 20 km) of this mineralization type with growth faults in the basin. He suggested that the major growth faults are the Lofty Range–Mount Vernon Fault, parts or all of the Tangadee Lineament, and the unexposed 'northern margin fault' (Fig. 80). Smaller scale growth faulting is inferred at Irregully Creek, Mount Genoa and in the Ti Tree Syncline and Chuck (1984) suggested that most of the structural sub-basins and synclines may have developed initially as fault-bounded basins. These occurrences are also generally within the folded parts of the basin, in the Edmund Fold Belt.

In the Jillawarra sub-basin (Fig. 81), the main prospect at Abra is a zoned stratabound sedimentary–exhalative lead–silver–copper–gold–barium deposit with an upper layered ('stratiform') zone overlying a 'stringer' feeder vein zone. This deposit has developed in the clastic and carbonate sedimentary rocks of the uppermost Gap Well Formation and it is overlain by clastic rocks of the West Creek Formation. These two formations have been identified as probable time equivalents of the Irregully and Kiangi Creek Formations respectively. The location of the deposit is considered to have been determined by a small fault-controlled sub-basin and to lie beneath one of a series of domes produced by intersecting fold trends (Boddington, 1990). During a rise in the geothermal gradient, inferred from felsic igneous activity, mineralizing fluids containing metals, possibly scavenged from basal Bangemall Group arenites or related to the felsic igneous activity, have ascended along a fault-controlled feeder zone (Vogt, 1995).

The clastic-hosted prospects of the Bangemall Basin, including Abra, show some similarities to the setting of the base-metal mineralization of the Mount Isa Inlier and the MacArthur River Basin proposed by Etheridge et al. (1987). That setting is of an intracratonic basin developed over an older orogen. The analogies to Phanerozoic deposits suggested by Myers and Barley (1992) are also applicable. Such deposits form in a foreland or epicratonic basin during the late stages of orogeny, where basin inversion and dewatering are the result of transfer of strain from a convergent plate margin, or during the early stages of continental rifting. The importance of fault-controlled synsedimentary sub-basins within the first-order basin is borne out by the evidence from Abra. Figure 80 (*after* Chuck, 1984) summarizes the favourable lithological and structural associations for this deposit type in the Bangemall Basin.

Exploration

The geochemical data discussed above result from exploration in the late 1960s and early 1970s for stratiform base metals in the Bangemall Basin by Union Miniere, Westfield Minerals, and Amax.

Between 1961 and 1967, Westfield (I 3227) carried out reconnaissance in the northwest of the State based on regional geophysical and geochemical surveys. The Bangemall Basin was included in this work, which identified three stratabound prospects (Mount Vernon, Mount Palgrave, and Thomas River) that required follow-up detailed sampling and/or drilling. Percussion drilling at Mounts Palgrave and Vernon gave only moderate grades. Further investigation by Amax (I 245) in the Mount Vernon syncline involved regional rock-chip sampling, which produced some encouragement but was not followed up. Union Oil (I 1052) carried out regional stream-sediment sampling in the EDMUND 1:250 000 sheet area in 1973.

Stream-sediment geochemistry by Unimin in the Irregully Creek area on the northern margin of the basin delineated extensive lead and zinc anomalies. Follow-up work by Alcoa (I 1469) in the early 1980s recognized the importance of fault-controlled subsidence in the deposition of the Irregully Formation dolomite in this area. Anomalous base-metal values were found to extend for over 50 km along strike. In the domal area, percussion drilling gave a best intersection of 24 m at 0.26% Pb in a zone about 12 km long and 80 m thick that averaged about 500 ppm Pb. Low zinc suggested that the mineralization was atypical of Mississippi Valley type and an early diagenetic origin was proposed. Similar results were obtained in the Mount Genoa area (Chapter 8). Anaconda (1966–67) (I 37) delineated some stream-sediment base-metal anomalies over the Irregully and Jillawarra Formations on the Pingandy Shelf along the northern margin of the basin. These were not followed up. CRA (1981–82)(I 2569) targeted the Irregully Formation in part of this area for McArthur River-type mineralization, and regional SIROTEM surveys located highly conductive sedimentary rocks at the base of the Bangemall Group. Again, there was no immediate follow-up work; however, Newcrest and Pasminco commenced base-metal exploration in this area in 1990.

In 1982, Alcoa (I 2051) drilled a diamond hole 5 km east-southeast of the Ilgarari fault-hosted copper mineralization, which was sporadically mined this century at grades of between 12% and 34% Cu. The drilling was designed to test the concept of the copper mineralization representing a feeder zone for an exhalative mineralizing system that might have produced stratiform lead–zinc down slope. No stratiform mineralization was encountered.

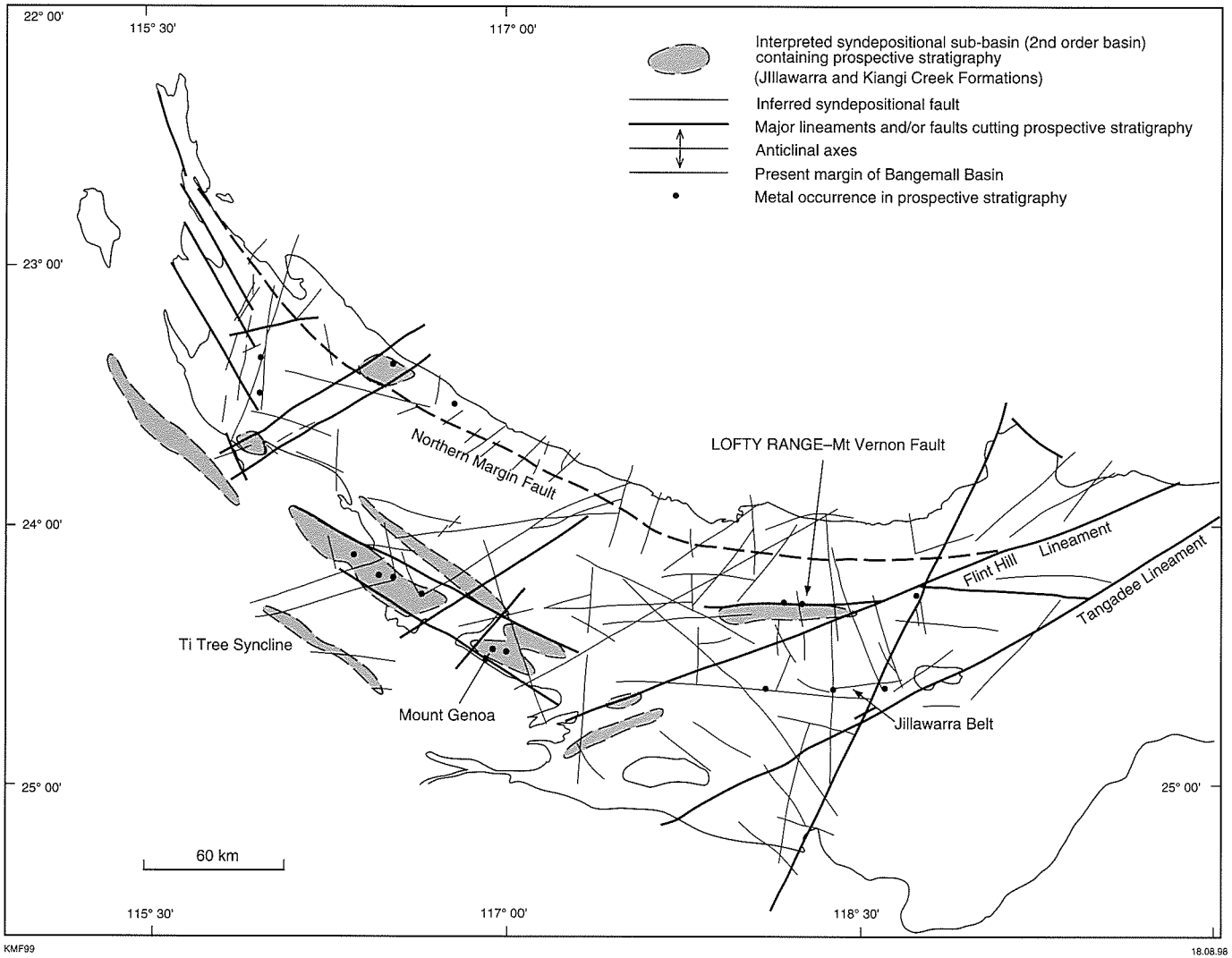
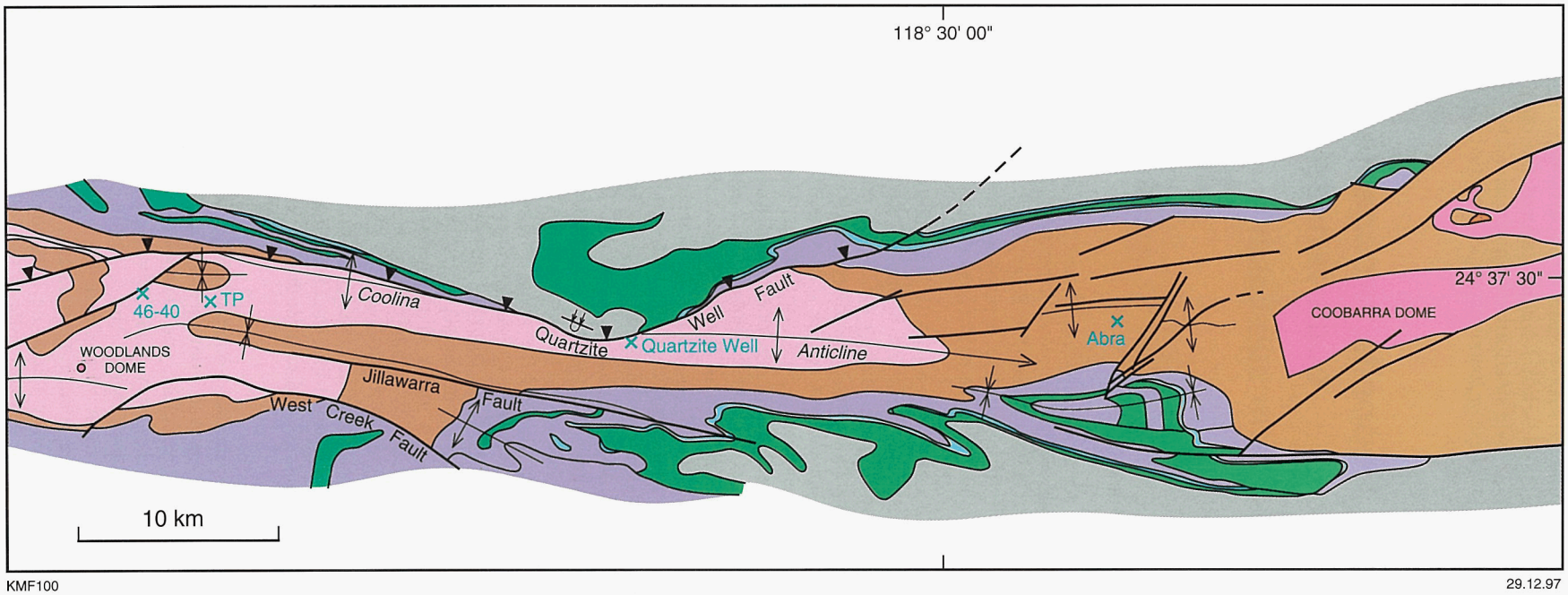


Figure 80. Bangemall Basin: favourable parameters for clastic-hosted base-metal mineralization (*after* Chuck, 1984)



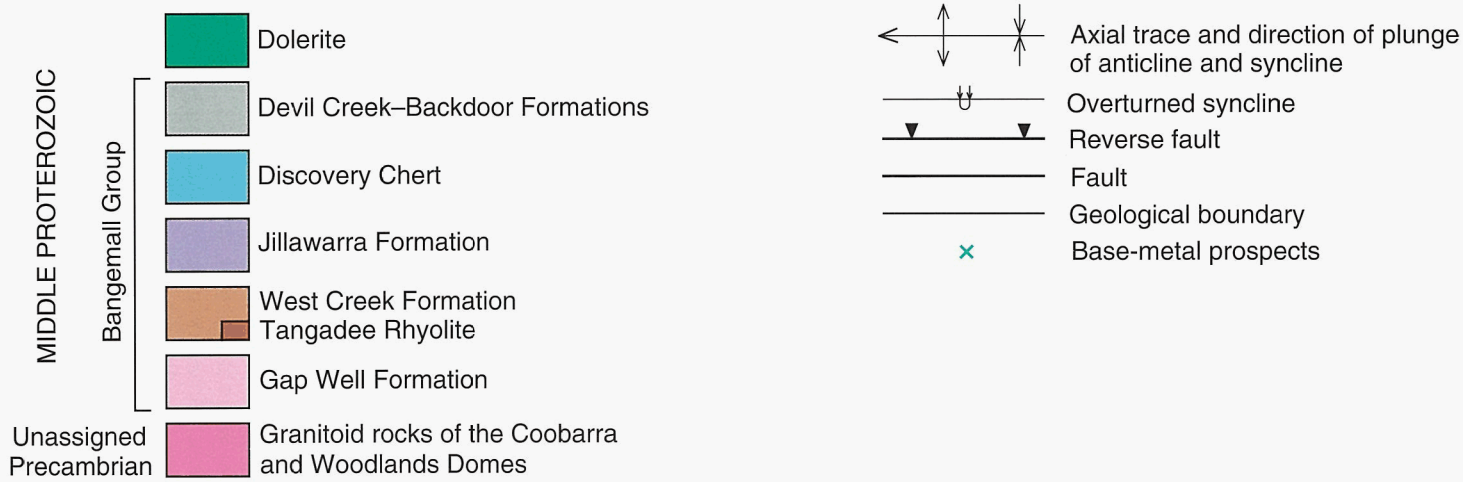


Figure 81. Jillawarra mineralized belt: geology and base-metal prospects (*after* Boddington, 1990)

In 1974 (I 4644) Amoco commenced a search for McArthur River-style mineralization in the Jillawarra sub-basin. Anomalous surface geochemistry led to the location of a number of prospects of which only Quartzite Well was significantly lead–zinc rich. Aeromagnetic surveys in 1977 successfully defined several anomalies, one of which (a 'bullseye' anomaly) in the east of the sub-basin was later tested by JV partner Geopeko by diamond drilling to reveal the concealed Abra stratabound copper–lead–silver–barium deposit. The similar, but much smaller '46–40' copper–lead–barium prospect in the west of the sub-basin was also identified. Other anomalies were found to represent copper–barium, copper, and copper–manganese occurrences, all of which are associated with magnetite and pyrite.

Abra mineralization was first intersected in September 1981, and it may be significant that at least half of the exploration programs for copper–lead–zinc in the Bangemall Basin recorded in the GSWA WAMEX system commenced in the 1980s, when companies began to target sedimentary rocks marginal to regional faults (growth faults) and associated with basement highs. Major companies such as CRA also considered parallels with the Yeneena Group in the Paterson Orogen, following the discovery of the Nifty copper deposit by WMC.

RGC (1991–92)(I 6563) examined the Jillawarra Formation in the Sawback Range on the southern margin of the western Bangemall Basin and located a gossan (3.2 km in length) with anomalous zinc values (≤0.298% Zn) in siliceous siltstone. This was interpreted as a mineralized bedding-plane thrust which may have reworked a syngenetic sulfide zone.

More recent regional exploration carried out in the southeast of the Bangemall Basin by Geopeko (I 5199) illustrates some of the possibilities for mineralization in the Bangemall Basin and at its margins. The area explored lies along the Salvation Fault, a major growth fault which separates the Troy Creek Beds of the Nabberu Basin in the south from three younger Bangemall sequences to the north. These include the Scorpion Subgroup shallow-water stromatolitic carbonate, the overlying Western Bangemall Group arenite, and the Eastern Bangemall Group consisting of sedimentary rocks extensively intruded by dolerite sills. These are informal names applied by Geopeko. The Eastern Group may belong to the Savory Sub-basin. The Troy Creek Beds have been correlated with the Yerrida Group farther west.

Two models were considered to have potential in the area. The Jillawarra model, based on the Abra and '46–40' bodies, relates to stratiform and stringer sulfide mineralization at a disconformity between a dolomite–shale sequence and an overlying arenite siltstone, associated with active faulting during deposition. Fumarolic activity related to faulting, and possible sub-aerial exposure of the mineralization are indicated. Both the disconformity between the Scorpion Group carbonate and the Western Bangemall arenites, and growth faulting associated with the Salvation Fault, provide an analogy.

The second model, based on the relationship between the thick arenite wedge of the Western Bangemall Group formed north of the active Salvation Fault, and a possible transition to low-energy, carbonate-rich black shale within a rapidly subsiding basin across a faulted 'hinge zone' north of the clastic wedge, offered the possibility of Zambian-style stratiform mineralization at the hinge zone. Despite these encouraging analogies little exploration has taken place.

Deposits, prospects and occurrences

Jillawarra sub-basin

Abra

Deposit: Pb; Ag; Cu; Au
Location: 24°38'45"S, 118°35'E; 170 km southwest of Newman

The Abra deposit (Figs 81 and 82), located towards the eastern end of the easterly trending Jillawarra sub-basin, in the central Bangemall Basin, is a structurally localized complex exhalative deposit in clastic and carbonate sedimentary rocks of the Upper Gap Well Formation.

The 80 km-long by 10 km-wide sub-basin has been interpreted (Vogt and Stumpfl, 1987; Vogt, 1995) as a graben formed during the initial phase of rifting that ultimately produced the Bangemall Basin. The clastic and carbonate rocks of the Gap Well Formation and the overlying clastic rocks of the West Creek Formation are interpreted as being local equivalents of the Irregully, Kiangi Creek and Coobarra Formations seen in the broader Bangemall Basin. The easterly trending normal faults that initially defined the graben (the Quartzite Well Fault to the north and the Jillawarra Fault to the south) have been reversed during the later, compressional tectonic phase that produced the Coolina Anticline, which dominates the central part of the Bangemall Basin. As a result, the Gap Well Formation has been overturned and thrust north over the Jillawarra Formation, Discovery Chert, and Devil Creek Formation along the Quartzite Well reverse fault. Thrusting from the south-southwest has produced a minimum displacement of 3.4 km. The eastern and western limits of the graben are defined by the Coobarra and Woodlands Domes respectively. Collins and McDonald (1994) report a U–Pb zircon age of about 1.78 Ga for tonalite in drillcore from the Coobarra Dome, which is younger than the Gascoyne and Ashburton rocks that are presumed to form the bulk of the basement to the basin.

The Abra mineralization is located in the upper part of the Gap Well Formation, on the southern limb of the Coolina Anticline, one kilometre south of the axis and about 10 km west of the subcropping granitoid rocks of the Coobarra Dome. The mineralization is overlain by 200–500 m of West Creek Formation clastics. In this location the containing strata dip at about 25° to the south and are gently folded on a northeast to east-northeast axis which in places offsets the anticlinal axis, creating a number of domes and basins. Abra is located beneath one of these domes. Three main fault trends are present

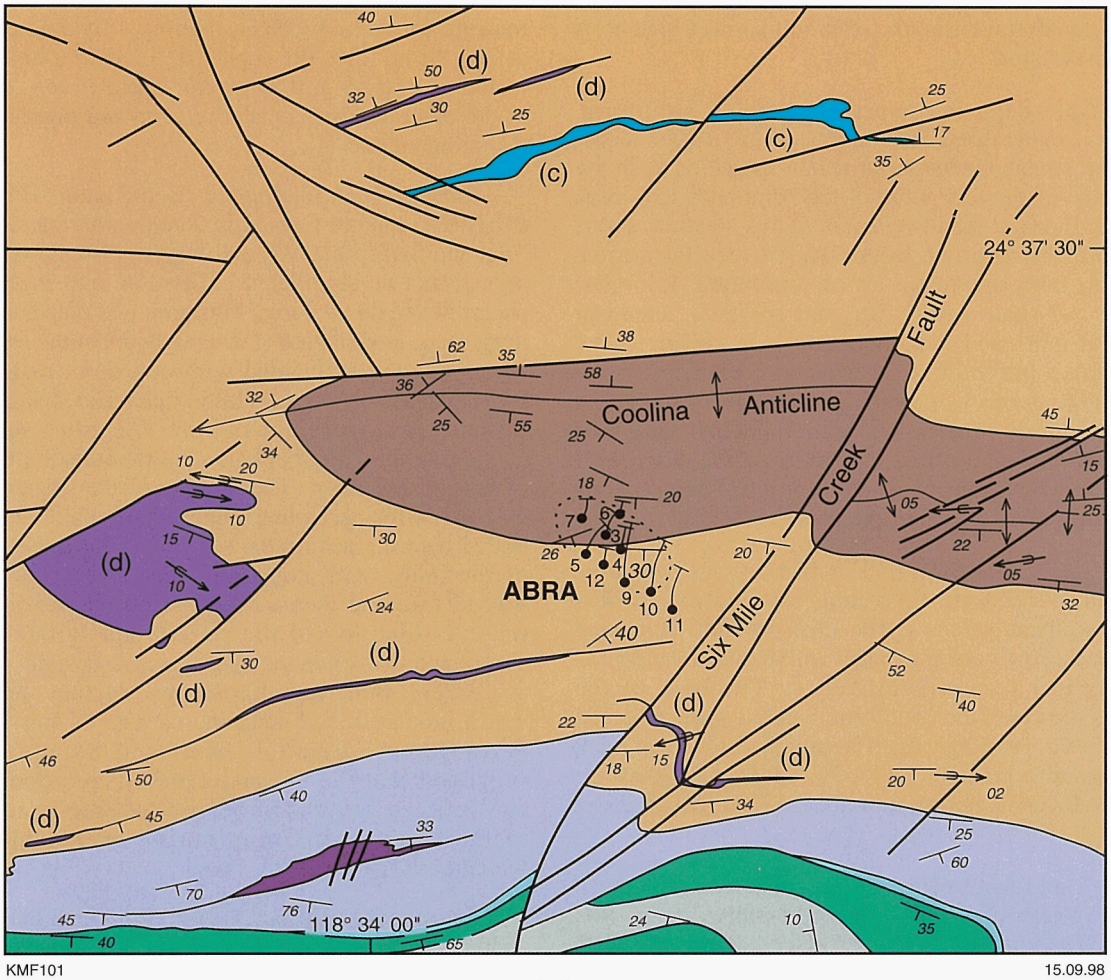


Figure 82. Abra deposit: local geology and drillhole locations (*after* Boddington, 1990)

in the vicinity; easterly, approximately northeasterly, and northwesterly. There is a major displacement of 700 m horizontally and up to 300 m vertically in the northeast-trending Six Mile Creek fault just east of the mineralized zone (Fig. 82). The faulting in this area has defined a small sub-basin (the Abra sub-basin) which hosts the mineralization.

The Abra deposit comprises an upper stratiform, exhalative, mineralized zone and a lower stringer feeder zone. The stratabound/stratiform mineralization is in the lower three of the four units of the Abra beds that mark the top of the Gap Well Formation in this location, and is disconformably overlain by the West Creek Formation. The Abra beds are made up of laminated dolomitic siltstone and shale with biostromal dolomite, abundant microbial mats and syndiagenetic iron sulfides. The deposit takes the form of an inverted cone tilted to the south, the lower part of which is a stringer zone hosted within dolomitic siltstone and coarse-grained sandstone with minor stromatolitic dolomite of the Gap Well Formation, whereas the upper stratiform part has a saucer-shaped form lying on top of the cone.

Unit 1 is a colloform rock with bands of hematite–barite–silica–carbonate alternating with those of barite–carbonate–silica(–galena–pyrite–chalcopyrite). Veins and local breccia zones are associated with barite and galena(–chalcopyrite) vein mineralization. The bulk of the mineralization is in the colloform material with up to 2 m at 26.75% Pb and 50 g/t Ag. The unit is about 23 m thick with an average grade of 2.51% Pb, 6.9 g/t Ag, 0.09% Cu and 6.7% Ba and a potential of about 13 Mt (Boddington, 1987.)

Units 2 and 3 are made up of distinctive red, banded to massive jaspilite with variable hematite, magnetite, barite, carbonate and silica, in places associated with banded and disseminated galena, chalcopyrite and pyrite. Both primary stratabound and secondary vein-type mineralization in this zone are associated with colloform banding. Thin ferruginous clastic beds are present in the upper part of the body and lutite intercalations, partly replaced by carbonate and silica, occur in the southeast of the body associated with disseminated to massive galena. This whole zone is extensively veined and to some extent brecciated with a system of barite–carbonate–quartz–hematite–magnetite–jaspilite with some galena–pyrite and chalcopyrite veins. Mineralization is erratic but locally high grade; up to 13 m at 10.68% Pb, 15.2 g/t Ag, 0.22% Cu and 18% Ba.

The Abra deposit is 'capped' by a local conglomerate which contains clasts of jaspilite and barite from the underlying 'red' sequence (units 2 and 3).

The basal stringer zone comprises a large network of veins, breccias and replacement zones and extends over an apparent thickness of 350 m down to a 'root' zone of dilational fractures that have acted as conduits for mineralizing fluids. It has been pervasively chloritized with local silicification, carbonatization and baritization. The extensive veining and brecciation is associated with vein galena–barite and chalcopyrite–magnetite mineralization, both with local gold and scheelite. Galena and barite are also found as fine-grained stratabound disseminations in coarser clastics. An approximate tonnage of 144–196 Mt has been inferred for this zone (Boddington, 1987) with average grades of 0.19% Cu, 1.45% Pb, 0.13 g/t Au and 3.85 g/t Ag. The total potential tonnage for Abra has been inferred (Boddington, 1987) at 200 Mt at 1.8% Pb, 6 g/t Ag, 0.18% Cu and 6% Ba, including 150 Mt at 0.13 g/t Au. There is very little zinc in the Abra deposit; sphalerite veins are present only in the stringer zone.

Abra has been interpreted (Boddington, 1990) as an exhalative deposit formed in shallow-marine sediments. Vogt and Stumpfl (1987) and Vogt (1995), however, have argued that no significant exhalation onto the sea floor occurred and that the mineralization was emplaced during diagenesis. Boddington (1990) argued that the lead–barite mineralization associated with colloform material and interbedded with coarse, clastic, intertidal sediments was formed by surface exhalation. The Abra sub-basin, containing the Abra beds, is considered to be the result of tensional faulting. The doming of the sequence acted as a locus for ascending mineralizing solutions, which boiled before reaching the sea floor. The crude zonation of the body, with copper in the lower zones giving way to lead and then to barite, is an expression of the relative solubility of the sulfide and sulfate species. The mineralization in the upper parts is partially oxidized, a process that was halted by further tectonism which produced the blanketing clastics of unit 4 and the West Creek Formation. Vogt and Stumpfl (1987) suggested that the unusual metal distribution at Abra may reflect a derivation from red-bed arkoses at the base of the Bangemall Group during greenschist-grade metamorphism.

Collins and McDonald (1994) considered the mineralization to represent the upper parts of a mid-Proterozoic sediment-hosted epithermal system active during the deposition of the upper Gap Well Formation in a subaerial, subtidal–intertidal environment. They quote a 1.64 Ga date for galena from Abra (Richards, J. R., 1994, pers. comm.) correlating with a U–Pb zircon age of 1.63 Ga for the Tangadee rhyolite (Nelson, D. R., and Nutman, A., 1994, pers. comm.) within the Coobarra Formation, 15 km east of Abra (Fig. 81). Collins and McDonald (1994) suggested that a deep-seated felsic intrusive, beneath Abra and related to the Tangadee volcanism, may have driven the convective hydrothermal system. There is no evidence yet, however, for the presence of felsic intrusives to drive similar hydrothermal systems at the TP, 46–40, and Quartzite Well prospects discussed below.

The association of this mineralization within a specific magma-driven epithermal system may help to explain some differences (for example the lack of zinc) between Abra and more conventional basin-margin hydrothermal sedex-type deposits.

Amoco/Geopeko have explored the prospect since 1977, and the deposit was located by drilling in 1981 after Amoco aeromagnetic data were remodelled by Geopeko to determine the target depth of the magnetic source. Geopeko drilled eight diamond holes between 1981 and 1983, following gravity confirmation of the distinctive

'bullseye' anomaly, and defined a large, subeconomic body 260 m below the surface. Subsequent low-level aeromagnetics helped define the structural elements while SIROTEM and EM-37 surveys detected the body from the surface.

References: Boddington (1987, 1990), Vogt and Stumpfl (1987), Collins and McDonald (1994), Vogt (1995), GSWA-WAMEX - I 4641.

46–40

Prospect: Pb; Cu; Ba; Au
Location: 24°37'30"S, 118°06'E; 20 km north of Woodlands Homestead

Amoco drilled four diamond holes in 1977–78 to test a bullseye magnetic anomaly referred to as '46–40' and intersected a small copper–lead–barium deposit in the western Jillawarra sub-basin (Fig. 81). The best intersections were 5.5 m at 2.09% Pb, 14 m at 1.1% Pb and 6 m at 1.04% Cu. One hole intersected 1 m of 5.5 g/t Au and 2.5% Cu. In 1980 Geopeko drilled another two diamond holes with the best intersection of 2 m at 1.29% Pb and 7.5 g/t Ag.

Reference: GSWA-WAMEX - I 4641.

TP

Prospect: Pb; Ag; Ba
Location: 24°38'S, 118°09'E; 18 km north-northeast of Woodlands Homestead

The TP prospect is named for the distinctive 'thumbprint' shape of a large (5 km diameter) magnetic anomaly prominent in the western part of the Jillawarra sub-basin (Fig. 81). In 1978 Amoco drilled a hole to 724 m in an attempt to identify the magnetic source, which was postulated to be an 'Olympic Dam' type of polymetallic deposit. Although the magnetic target was not reached, the hole intersected a narrow zone of lead–silver mineralization, with 4 m at 1.56% Pb and 17.6 g/t Ag. In 1981 Geopeko drilled a deeper hole to 1200 m and intersected the probable source: a broad zone of magnetite veining and chloritization (from 970–1200 m) in massive and brecciated dolomite. Higher in the hole narrow zones of lead–silver–barium were intersected, with 5 m at 2.94% Pb, 11 g/t Ag, and 10.92% Ba; and 2 m at 4.7% Pb, 19 g/t Ag, and 9.9% Ba.

Reference: GSWA-WAMEX - I 4641.

Quartzite Well

Prospect: Zn; Cu; Ag
Location: 24°39'50"S, 118°20'30"E; 25 km northwest of Mulgul Homestead

Stratabound zinc–copper occurs close to the top of the Jillawarra Formation and Gap Well Formation in carbonaceous siltstone and carbonate siltstone within a broad fault zone in the overturned north limb of the Coolina Anticline (Fig. 81). The sediments are interpreted as having been laid down in a shallow-marine basin or restricted lagoon. In drillcore the grey siltstone is sheared, quartz veined, and partly to wholly recrystallized. Siderite is present in the reconstituted sediment matrix and also in the veins. Stratigraphically controlled massive and disseminated pyrite contains sphalerite and minor traces of chalcopyrite, covellite and chalcocite, but galena is not present. The primary mineralization is interpreted as being syngenetic, modified on compaction to give sphalerite and pyrite in veins. Recrystallization of clay, microfaulting and minor veining are also the result of diagenesis on compaction (Davy, 1980). Davy (1980, p. 5) also interprets the fault zone mineralization as being derived from remobilization of the stratabound mineralization.

Amoco/Geopeko (1974–1981) tested the prospect to drilling level.

References: Marston (1979), Muhling and Brakel (1985), Davy (1980), GSWA-WAMEX - I 4641.

Other prospects

Mount Vernon

Prospects: Zn; Cu; Ni
Location: 24°15'S, 118°10'E; 9.6 km south of Mount Vernon Homestead

Efflorescent zinc sulfate (goslarite) coats outcrops of pyritic, graphitic shale along 4.8 km of strike in the Glen Ross Shale Member of the Kiangi Creek Formation. The primary sulfides are pyrite, sphalerite and covellite. Four lithological zones are recognized in diamond drillcore (Davy, 1980):

- Highly weathered (oxidized) near-surface shale and quartzite
- Partially altered shale and siltstone
- Fresh black shale and siltstone
- Grey carbonate, siltstone and shale

The black shale and siltstone are similar to those at Mount Palgrave. Pyrite and copper minerals are present throughout the black shale but sphalerite is restricted to zone 3 in the cores. In one hole the mineralized zone is heavily veined with sparry quartz and subordinate siderite, sphalerite and/or goethite. There are no sulfides in zone 4.

Westfield (1961–67) discovered the occurrence following up a regional stream-sediment survey which gave strong zinc–copper anomalies over 3 km on the north limb of the Mount Vernon Syncline. No other anomalism was encountered on surveying the graphitic shale unit around the whole syncline rim. The company obtained an average of 3.8% Zn and 0.48% Cu and up to 7.2% Zn with 0.96% Cu in surface rock-chip samples at the prospect. Subsequent drilling of three diamond holes established a true thickness of about 100 m of shale and gave a best intersection of 11 m at 1.2% Zn and 0.1% Cu. Amax (1974–78) carried regional rock-chip sampling over the syncline. Individual samples gave up to 7.25% Cu and 1.05% Zn, and a 20 m zone of 0.15% Cu was located in gossan, all within a 5 km strike length on the western end of the northern limb of the syncline. WMC (1989–91)

located low-level deflation lag anomalies for copper, zinc, lead and arsenic but did not consider the results as indicating any potential for primary sulfide mineralization.

References: Blockley (1971), Marston (1979), Chuck (1984), Marshall (1968), Muhling and Brakel (1985), Davy (1980), GSWA-WAMEX - I 245, I 3227, I 5335, I 5965.

Dunnice Well

Occurrence: Cu; Zn
Location: 24°16'20"S, 116°38'E; 4 km west of Dunnice Well

Another minor occurrence of disseminated pyrite, chalcopyrite and sphalerite in weathered and bleached black shales of the upper Irregully Formation has been noted at Dunnice Well.

Reference: Williams et al. (1983).

Deep Frederick Well

Occurrence: Pb; Zn; Cu
Location: 24°05'S, 116°54'E; 26 km north of Mount Augustus

A carbonate outcrop 2–5 km long and 1.5 km wide, dipping northeast at 10°, contains disseminated galena–sphalerite mineralization. This occurs in crystals and veinlets within a manganese-rich silty horizon in dolomite. Malachite and hydrozincite are found at the surface. BHP (1984–86) collected rock-chip samples with up to 1.74% Pb and 0.17% Cu, with 1.03% Zn in a separate sample.

Reference: GSWA-WAMEX - I 4401.

Mount Palgrave 2

Prospects: Zn; Cu
Location: **'a'** 23°31'50"S, 115°57'30"E; 2 km west-northwest of Mount Phillips Homestead
'b' 23°24'30"S, 115°55'E; 7 km southwest of Mount Phillips Homestead

Sedimentary stratiform zinc–copper mineralization occurs in black carbonaceous, pyritic shale of the Discovery Chert in two prospects, **'a'** and **'b'**, located in a syncline of Jillawarra Formation. Gossans contain chrysocolla, malachite and goslarite. In drillcore, sphalerite and covellite are the main sulfides of interest in the generally pyritic shale and siltstone. Both sphalerite and covellite occur in the matrix of the rock, but most sphalerite is contained, with pyrite, in late-stage siliceous veins. Traces of chalcopyrite, chalcocite and galena are also present.

Westfield (1961–67) conducted regional exploration in the area. At Mount Palgrave, percussion drilling at prospect **'a'** gave a maximum of 3% Cu and 2.4% Zn. Mineralization was in three stratabound zones, each 3 m thick. At prospect **'b'**, drilling intersected 0.67% Cu and 1.3% Zn, both over 1.8 m in separate holes. BHP (1971–74) carried out exploration using a Zambian or Kupferschiefer model. Follow-up of malachite float in a stream led to percussion and diamond drilling and detection of copper up to 0.5% in shales of the Jillawarra Formation.

References: Blockley (1971), Marshall (1968), Marston (1979), Muhling and Brakel (1985), Davy (1980), Chuck (1984), GSWA-WAMEX - I 1108, I 3227.

High Range (Two Peaks)

Occurrence: Cu; Zn; U
Location: 23°40'30"S, 115°39'E; 24 km southeast of Maroonah Homestead

Stratiform copper, zinc and uranium in black, pyritic shale, stromatolitic dolomite, and chert of the Discovery Chert was reported by Daniels (1966) in an outlier of the Bangemall Basin within the Gascoyne Complex. Surface samples with 0.56% Cu, 0.01% Pb, 0.02% Ni, 0.01% uranium and 0.05% Zn were recorded.

Uranerz (1973–80) examined copper and uranium in a shear zone in the Irregully Formation. Uranium was in veinlets but the copper, up to 0.32%, was separate. Endeavour Oil (1972) also tested the High Range prospect, reporting anomalous zinc most strongly associated with carbonate-rich sedimentary rocks of the Kiangi Creek Formation. Australian Anglo (1978–82) attributed anomalism in the Irregully Formation to surface scavenging.

References: Blockley (1971), Daniels (1966), Marston (1979), GSWA-WAMEX - I 656, I 2039, I 2524, I 2553.

Coria Springs

Prospect: Pb; Zn
Location: 23°31'S, 115°27'E; 24 km northeast of Lyndon Homestead

Zones of lead–zinc anomalism in Irregully Formation carbonate and ironstones, and in Kiangi Creek Formation shale is found 22 km to the northwest of the High Range occurrence within the same synclinal outlier of the Bangemall Basin. Exploration by Australian Anglo (1978–82) obtained maximum values of 1.05% Pb in a 12 m channel sample in Kiangi Creek Formation, and 1% Zn in an ironstone grab sample. Follow-up drilling of five diamond holes found no significant mineralization. Surface scavenging by carbonaceous black shale was invoked.

References: GSWA-WAMEX - I 2039, I 2553.

Ti Tree (Ti Tree Well)

Prospect: Cu; Zn; Pb
Reference: 24°21'S, 116°03'E; 27 km west-northwest of Mount Phillips Homestead

Exploration by Alcoa (1979–83) for stratiform, sedimentary exhalative mineralization in deep-water, manganese-rich argillite of the Irregully Formation in the Ti Tree Syncline (an outlier of the Bangemall Basin within the Gascoyne Complex) detected up to 2.8% Cu, 0.8% Pb and 1% Zn in ironstones generally associated with arenites. Levels in the host sediments were lower and manganese

scavenging of base-metals was suspected. Nearby (6 km to the east), pyrite with minor chalcopyrite, molybdenite and galena was located by Australian Minerals Inc (1972–73) in east to east-southeasterly trending shears in granodiorite.

Unimin/Carr Boyd (1972) located anomalous zinc (≤0.86%), copper, lead, cadmium and cobalt in discontinuous gossanous outcrops in the contact zone between dolomites and overlying argillite. Percussion and diamond drilling gave poor results.

References: Marston (1979), Williams et al. (1983), GSWA-WAMEX - I 172, I 2062, I 2258.

Gillie Well

Prospect: Zn
Location: 24°35'45"S, 116°25'E; 25 km southeast of Mount Phillips Homestead

Exploration for unconformity-type uranium by Nord (1973–83) in the Ti Tree Syncline, where Bangemall Group sedimentary rocks unconformably overlie Lower Proterozoic metamorphic rocks of the Gascoyne Complex, located anomalous zinc in carbonaceous slate of the Discovery Chert in a synclinal keel. Percussion drilling gave zinc levels commonly in the range of 0.1–0.7%, and up to 4 m at 1.3% Zn at 60 m depth. Gossan search failed to locate evidence for massive-sulfide deposits.

Reference: GSWA-WAMEX - I 2242.

Thomas River

Occurrence: Zn
Location: 24°35'S, 116°25'E; 29 km east of Yinnetharra Homestead

Ashburton/Westfield, during regional exploration in 1961–67, located zinc (≤0.16%) in Discovery Chert at the southeastern end of the Ti Tree Syncline.

References: Blockley (1971), GSWA-WAMEX - I 3227.

Potential

The setting of the Bangemall Basin in the suture zone between the Yilgarn and Pilbara Cratons, and its syndepositional extensional tectonic regime, combined with shelf to marine sandstone and shale-dominant lithologies, suggest high potential for clastic-hosted lead–zinc mineralization. This is borne out in part by the discovery of the Abra deposit. Despite this, in the late 1980s base-metal exploration moved elsewhere in the State to areas that were perceived as more obvious and less costly targets such as the Rudall area.

The comprehensive review by Chuck (1984) has highlighted the association of known mineral occurrences with recognized major and minor growth faults (Fig. 80). He suggests that most of the structural sub-basins are within the Edmund Fold Belt. He nominates the Cobra, Ti Tree, Kurabuka, Mount Vernon and Mangaroon Synclines and the Mount Resolution Synclinorium, as probable sub-basins, along with structures in the Mount Genoa and Needle Hill areas. He also selects the Irregully Creek area, on the Pingandy Shelf, as having potential on the basis of growth faults. All these areas also show some traces of base metals in previous exploration. The problem of deep weathering and possible leaching of base metals to 150 m is probably a significant factor in the lack of success of at least the early exploration.

The chemical and mineralogical study of Davy (1980) confirms the favourable shallow-marine shelf setting of the black shale in this area. He recognizes appreciable chemical differences between the mineralized siltstone at Quartzite Well in the Jillawarra sub-basin, and black shale at Mounts Vernon and Palgrave, reflecting differences in the environment of deposition. The diversity of these chemical associations is taken to indicate the difficulties of establishing consistent indicator elements for use in exploration. The most promising is copper, with lead, zinc, nickel, silver and barium all of possible use.

In the particularly favourable lithological/structural setting of the Jillawarra sub-basin, the main deposit at Abra was located by magnetics and drilling, lying between 300 and 500 m below the surface. A significant negative feature of all the stratabound mineralization that has been located in the Bangemall Basin, even at Abra, is the low grade of sulfide minerals. It may be that only in very favourable locations will large, high-grade deposits be found.

It is worth noting that in 1970s/80s the prime exploration tool was aeromagnetics, because of its ability to locate sulfide bodies associated with large amounts of magnetite. However, there may be other very large deposits that contain very little magnetite and these may only show as very weak aeromagnetic anomalies. These may be more susceptible to electromagnetic methods such as the recently introduced airborne 'deep GEOTEM'.

A combination of exploration techniques is required to test the full potential of the Bangemall Basin for stratabound base metals. Regional and detailed mapping are necessary to define possible growth faults, grabens and sub-basins and the distribution of favourable host lithologies. Signs should be sought of silicification, chloritization, manganese enrichment, iron enrichment and the presence of pyrite and/or the possible indicator elements suggested above, and magnetic and EM responses measured in the favourable areas.

The interpretation of Abra as an epithermal deposit driven by a felsic intrusive episode needs to be considered in the regional context, in relation to known felsic magmatism, and to the setting of other known base-metal prospects in the Jillawarra sub-basin.

The potential of the Bangemall Basin for carbonate-hosted base metals appears to be low despite the post-depositional onset of compressional tectonics (producing the Edmund Fold Belt and reversing the normal subsidence-related faulting) that could have mobilized metalliferous brines upwards and towards the margins of the basin. Occurrences and prospects are low grade and are mostly within dolomitic lithologies of the

Irregully Formation on the Pingandy Shelf and in the more stable marginal parts of the Edmund Fold Belt. The dolomite units are silicified and show few signs of the primary or secondary porosity required for fluid pathways or sulfide precipitation.

In the eastern part of the basin (Table 18), the 10 km-thick clastic–carbonate sequence of the Scorpion Subgroup is roughly equivalent to the Edmund Group in the west, but is poorly known in detail. Exploration by Geopeko (*see above*) has given some indication of potential for Jillawarra-style and Zambian-style mineralization. Dolomitic sedimentary rocks, some stromatolitic, also suggest potential for carbonate-hosted target types. Williams (1990b) has described the basin margin in this area, east of the Marymia Inlier, as a faulted unconformity with basins and domes formed adjacent to growth faults. The combination of a thick accumulation of clastic–carbonate sedimentary rocks, possible extensional tectonics, and an age comparable with the Edmund Group and with major clastic-hosted deposits in eastern Australia and overseas, suggests significant, untested potential for a variety of sediment-hosted target types.

The Manganese Subgroup, which occupies a north-easterly trending linear zone on the southeast margin of the Pilbara Craton, is made up predominantly of shallow marine-shelf sandstone, siltstone, shale, chert and dolomite. Recent data suggest that this unit may be equivalent to the upper parts of the Edmund and Scorpion Subgroups (Williams, 1992). Williams (1990b) considered the craton margin north of the Sylvania Inlier to have been faulted into a series of horsts and grabens, which produced an environment of active growth faulting during deposition of the Manganese Subgroup. This is reflected in a series of faulted domes and basins, similar to those described above on the southeast margin of the Bangemall Basin.

No lead–zinc prospects are known in these marginal parts of the east Bangemall Basin but exploration has been limited. Some potential may exist in the extensional tectonic environment for syngenetic lead–zinc, though this would depend on the depth of subsidence, thickness of the sedimentary pile, availability of suitably immature arenite to act as metal sources, and the presence of anoxic shale or rapidly buried dolomitic shale (as at Abra) to host mineralization.

Yeneena Basin

Geological framework

The Yeneena Basin, along with the Rudall Complex, has recently been mapped by GSWA at 1:100 000 scale to clarify its metallogenesis and mineral potential. Williams (1990a) summarized the geology of the basin prior to this work. The recent study includes results from 1:250 000-scale mapping on Balfour Downs (Williams, 1989). Hickman and Clarke (1993), Hickman and Bagas (in prep.) and Bagas and Smithies (in press) have detailed the stratigraphy in the Broadhurst, Rudall and Connaughton 1:100 000 sheet areas. Material has also recently become available on the WAMEX open-file system covering the exploration of the Nifty area by WMC (I 6882).

The gneissic Rudall Complex (~2.0 Ga) is unconformably overlain by the deformed sandstone, siltstone, shale and carbonate rock of the Yeneena Group (1.1–0.85 Ga), considered to have been deposited in fluviatile to shallow shelf environments. There is little evidence for deeper water marine environments, suggesting that sedimentation kept pace with subsidence of the basin. Hickman and Bagas (in prep.) have defined separate areas within the Yeneena succession, as indicated in Figure 74. These areas, which more or less correlate with the western, central and northeastern successions of Williams (1990a), are separated by broad, sand-covered corridors aligned along major fault zones. These probably reflect original growth faults in the basin that were reactivated contemporaneously with the prominent southeast-trending isoclinal folding and thrusting that transported the basin rocks westwards in response to plate collision events which also affected the Rudall Complex (*see above*). It is suggested (Hickman and Bagas, in prep.) that the plate convergence was significantly retarded following the major collision of D_2. Further subduction was impeded, and continued crustal shortening was accommodated by strike-slip faulting so that the Yeneena Basin developed as a strike-slip basin, or a series of such basins.

The rocks of the Yeneena Group are predominantly metamorphosed to greenschist facies, but in the northeast their grade increases to lower amphibolite facies. In the Telfer area the Yeneena Group is intruded by post-tectonic (0.7 Ga) granitoids.

Hickman and Bagas (in prep.) point out that lateral variations in the Yeneena Group are not completely understood, mainly due to exposure gaps in key areas. In general, however, the succession indicates sedimentation from a source to the southwest, beginning with a basal conglomerate in most areas followed, in the Broadhurst (or Central) succession, by the Coolbro Formation. This unit is absent in the Western succession, possibly indicating that the boundary between the Western and Broadhurst successions, the Southwestern Thrust (Fig. 74), may have been an active growth fault at this stage. The Coolbro Sandstone, a wedge-shaped, poorly bedded fluviatile sandstone passing upwards into shallow-marine sandstone and siltstone, passes transitionally up into the dominantly pelagic Broadhurst Formation, which is composed mainly of siltstone and shale with local sandstone, dolomite and dolomitic shale. The siltstone is generally carbonaceous and may contain up to 10% pyrite, indicating anoxic conditions. Stratabound lead, copper and zinc mineralization is associated with this unit. Occasional incursions of sand and mud in the Broadhurst Formation were carried in from the basin margin by turbidity currents.

The rest of the Western succession, to the top of the Choorun Formation, is correlated with the Broadhurst Formation in the Central succession but was formed in a shallow-water, near-shore environment. These temporally equivalent successions are each between 1000 and 2000 m thick. The Choorun Formation forms a cyclic sequence of conglomerate, sandstone, siltstone and shale deposited on an unstable marine shelf. No black sulfidic shale or

turbidite have been recorded. The contact between the Choorun and Isdell Formations in the Western succession is unconformable, whereas that between the Broadhurst and Isdell Formations, northeast of the Broadhurst Range, is not exposed but is probably tectonized.

The Isdell Formation, east of the Broadhurst Range is composed of dark-grey sulfidic limestone and dolostone, with subordinate, silty, pale grey-cream carbonate and shale. These rocks indicate a relatively deep water environment. In the Western succession, however, the Isdell Formation forms a mixed sequence of stromatolitic carbonate and clastic rocks indicating a shallow-water environment. In the subsequent, largely conformable succession, the Malu Quartzite and Telfer Formations represent alternations between cycles of turbidite deposition in submarine fans, and cycles of laterally extensive siliciclastic units. The Puntapunta Formation of calcareous sandstone and massive clastic carbonate, lacks algal deposits and stromatolites, suggesting a deeper water environment, whereas the parallel-bedded, sandstone-dominant Wilkie Quartzite represents a shallow-marine basin environment.

Overall, the lithological evidence, in the form of palaeocurrent data and lateral facies changes, suggests a continental margin setting for the Yeneena Group, with the landmass to the southwest (Hickman and Bagas, in prep.). The general succession of basal channel-fill conglomerate and overlying fluviodeltaic clastics (Coolbro Formation) suggests a continental environment in the early stages with later progression to a deltaic shallow-shelf environment. Farther from the landmass, to the north and east, the Broadhurst and Isdell Formations, however, indicate anoxic, progressively deeper water environments.

Although palaeocurrent data indicate relatively constant northerly and northeasterly flow in the Yeneena Group, there is evidence in the Coolbro Formation of syndepositional faulting that created a horst and graben environment. In the strike-slip regime, this would have produced lenticular, northwest-elongate blocks, which may explain evidence of instability seen in slump folding, graded turbidites and variable thickness in the Broadhurst Formation. Hickman and Bagas (in prep.) suggest that the northern side of the Broadhurst Range may represent the deeper, north and northeast side of such a strike-slip basin.

Mineralization

Within the Yeneena Group the Broadhurst Formation has potential for stratabound and stratiform copper, lead and zinc mineralization. The copper-dominant deposit at Maroochydore is essentially similar to that at Nifty (reserves of 5.6 Mt at 3.2% Cu in the oxide zone and of 23 Mt at 3.4% Cu in the sulfide zone), about 90 km to the northwest, and at the same stratigraphic level in graphitic and carbonate-rich shales and siltstone. There are other prospects in this formation, some lead–zinc dominant, from which analogies with both Mount Isa and Zambian deposits can be drawn. In some cases faulting and brecciation are clearly related to mineralization, suggesting a combination of syngenetic and epigenetic mineralizing processes. Myers and Barley (1992) have suggested that the situation of the Nifty deposit parallels that of Phanerozoic mineralization related to dewatering of a foreland basin as a result of strain transfer at a convergent plate margin in the late stages of orogeny.

Potential for base metals and gold is present in formations stratigraphically above the Broadhurst Formation in the Yeneena Group. In the Isdell Formation dolomites and dolomitic siltstones may host stratabound lead, zinc and copper, either clastic-hosted or carbonate-hosted, and gold has been reported at one dolerite–carbonate contact. Newmont and MIM have explored (?epigenetic) copper and gold targets in the Isdell Formation at Hasties, southeast of Telfer. Potential analogues of the Telfer epigenetic gold mineralization may be present in the Telfer Formation if suitable combinations of stratigraphy and domal structures, with associated granite intrusions, are present at shallow depth beneath Permian cover. The Telfer Formation, if present, may also be prospective for gold–copper skarn-type mineralization, as at Minyari Hill.

Exploration

The discovery of gold in gossan sampling by Day Dawn Mines and Newmont geologists, searching for Zambian-style copper in the Yeneena Group, led to the pegging of Telfer by Newmont in 1972. Subsequent exploration in the Yeneena Group was directed mostly at gold, but WMC (I 6882) shifted its emphasis to copper following reappraisal of the geological environment in relation to sediment-hosted deposits. In 1980, as a result of a lag-sampling program, WMC discovered copper mineralization at Nifty.

The discoveries of stratiform/stratabound copper (with lead–zinc) mineralization in the Broadhurst Formation at Nifty and at Maroochydore (discovered by Esso in 1984), which may be partly syngenetic and partly epigenetic, have further enhanced the prospectivity of the Yeneena Group, particularly the graphitic/sulfidic, carbonate-rich facies of the Broadhurst Formation. The deposits at Nifty and Maroochydore, which are predominantly supergene in terms of their defined resources, lie at about the same stratigraphic level. Other prospects, such as Warrabarty, may be more specifically related to faulting and breccia zones that have provided pathways for mineralizing fluids.

Haynes et al. (1993) described the successful exploration strategies adopted by WMC, which led to the discovery of the Nifty deposit and to other adjacent zinc–lead deposits, such as Warrabarty. These strategies involved following a conceptual model for stratiform copper mineralization emphasizing the basal arenaceous Coolbro Sandstone as a possible source rock, and the thinly bedded, pyritic dolomitic siltstone and shale of the Broadhurst Formation as a potential host rock. The deformational style of the basin was considered similar to that of the Katanga 'Series' in the central African copperbelt. Potential was also seen in the basin for zinc–copper–lead pipes, analogous to the Kipushi deposit in Zaire.

Of the two copper discoveries located by WMC, Rainbow was considered to be of the model target type. Nifty, however, is considered by Haynes et al. (1993) to be a new type of sediment-hosted copper deposit with similarities to stratiform lead–zinc deposits. They note the occurrence of chalcopyrite near a synsedimentary fault and in the footwall of a stratiform pyrite–sphalerite–galena bed.

Later exploration for base metals in the Yeneena Group has been carried out mainly by MIM, following up earlier work by Amax (I 1115) and Esso. CRA (I 3419) and Idemitsu/Poseidon/ Uranerz have also been involved. Amax drilled the Eva Well gossan (later Cottesloe) in the late 1970s and at the same time Occidental (I 1694) examined uranium/copper veining in Coolbro Formation quartz sandstone at Sunday Creek. Occidental obtained up to 3.6% U_3O_8 in surface samples but drilling results were disappointing. More recent examination of the Sunday Creek mineralization (≤2.88% U_3O_8) by CRA/PNC suggests that it is controlled by a shear zone which cuts both metamorphic rocks and the Yeneena Group near the unconformity.

CRA (I 3419) examined the Broadhurst Formation for stratabound base metals in 1984, prior to the Kintyre uranium discovery. Over 20 000 m of RC drilling was carried out but no significant intersections were found. MIM has further defined the Maroochydore mineralization, which is in part lead–zinc rich (Urangan) and extends to depth following the carbonate lithology in the keel of a syncline. Other related copper (lead–zinc) prospects in the Maroochydore area, originally defined by Esso, are Airlie and Yepoon, while Bondi (copper) and Manly (lead–zinc) lie farther to the southeast, in the Mount Sears Range. The Poseidon/Idemitsu/Uranerz JV in the Broadhurst Formation, northwest to north-northwest of Maroochydore, has recognized the geochemically anomalous calcareous upper Broadhurst Formation on a regional scale. Drilling (RAB) in the Tabletop area has confirmed anomalies of up to 0.22% Zn. Drilling at Isdell West, approximately on strike with Maroochydore, has given up to 0.6% Zn.

Sampling of gossans in the Broadhurst Formation by GSWA during the mapping of the PATERSON RANGE 1:250 000 sheet and the BROADHURST 1:100 000 sheet (Chin et al., 1982; Hickman and Clarke, 1993) indicate the general prospectivity of this formation.

Deposits, prospects and occurrences

NIFTY

Mine: Cu; (Pb; Zn)
Location: 21°39'32"S, 121°34'10"E; 70 km west of Telfer

This is a stratabound deposit, with an enriched supergene zone, hosted by the Broadhurst Formation. The main orebody consists of secondary cuprite and malachite in a discordant, subhorizontal zone between 40 and 80 m below surface. The body is over 1.5 km by 0.2 km at the surface and overlies the axis of the asymmetrical, overturned, southeasterly plunging Nifty Syncline within carbonaceous and dolomitic shale at approximately the same stratigraphic level as the Cottesloe and Maroochydore prospects. Intersections in the oxidized zone include 35.9 m at 2.14% Cu and 14.9 m at 4.71% Cu.

The primary mineralization is in the form of a high-grade chalcopyrite core which follows the keel of the syncline. The main host is a carbonate member between footwall and hangingwall shales. Intersections in this zone are up to 48.5 m at 11.95% Cu. Silicification, dolomitization and chloritization are associated with the mineralization. A thin pyrite marker horizon containing stratiform sphalerite and galena lies above the hangingwall within the keel and contains 5.3 m at 2.26% Pb and 0.85% Zn. Haynes et al. (1993) consider that a local basin existed during deposition of the Nifty carbonate member and was transected by a synsedimentary fault at its eastern end. Chalcopyrite and pyrite are considered to have replaced the algal-laminated carbonate in the basin prior to the initial phase of early diagenetic open folding. The pyrite–sphalerite–galena bed is interpreted as forming before chalcopyrite. A poorly constrained Pb model age of 850 to 900 Ma, reported by Norris (1987), was determined (Fletcher, I. R., 1986, pers. comm.) on samples given to GSWA by WMC.

WMC has been exploring in the Paterson Orogen since 1971. The mining tenements in the Nifty area were acquired in 1979 and Nifty was discovered during intensive geochemical sampling in 1980. The secondary copper mineralization was intersected in percussion drilling in 1981 and primary ore located in 1983, defining a high-grade deposit. Exploration since 1979 has consisted of regional and detailed lag and ironstone geochemistry, aeromagnetic, radiometric and INPUT surveys, ground magnetics, TEM, IP and gravity surveys followed by RC and diamond drilling. Geological interpretation has been greatly aided by the regional use of TEM surveys, that have clearly identified the potential carbonaceous and pyritic host sequences that tend to swamp individual deposit and prospect response.

Reserves for Nifty are calculated as 23 Mt at 3.4% Cu in sulfide ore (indicated/in situ) and 5.6 Mt at 3.2% Cu in oxide (indicated/mineable). Mining commenced in mid-1993. During the first three quarters to March 1994, 447 866 t of ore grading 4.16% Cu was mined and 449 153 t treated to produce 2640 t of copper cathode.

References: Norris (1987), Davies and Blockley (1990), Blockley and Myers (1990), Hickman and Clarke (1993), WMC Notice 3/9/92, GSWA-WAMEX - I 6882.

RAINBOW 1

Prospect: Cu
Location: 21°25'46", 121°25'17"; 26 km north-northwest of Nifty

A stratiform copper occurrence, close to the western margin of the Yeneena Basin, is in the form of a thin, sheet-like body of disseminated and massive chalcopyrite with some bornite, in two layers within laminated chert and

chloritic silty shale. They are at the base of a thick sequence of carbonaceous sedimentary rocks and lie above a pink quartz arenite.

The combined thickness of the mineralized layers is 1 m or less and has been intersected in several drillholes over 4 km.

References: Haynes et al. (1993). Williams and Trendall (in press, a), GSWA-WAMEX - I 6882.

Warrabarty

Prospect: Zn; Pb
Location: 21°11'S, 121°23'30"E; 55 km north of Nifty

Fault-bound and stratabound epigenetic, zinc and lead mineralization occurs in a sequence of massive crystalline dolomite, interbedded dolomite and carbonaceous siltstone. Mineralization is in a flat-lying sequence on the east limb of an anticline and in a north-northwesterly trending fault zone. The fault-bound mineralization is contained in a steep zone of intense solution breccia, dolomite-vein breccias, and dolomitization. Zinc occurs as sphalerite on the margins of dolomite breccia veinlets, and lead is present as galena in the vein breccia and in late-stage, steeply dipping dolomite veins. The stratabound mineralization is sphalerite dominated and lies in dolomite beds and shale units beneath crystalline dolomite. Minor disseminated to massive-sulfide mineralization forms stratiform and crosscutting zones. Zinc contents are generally less than 4% and diminish to the northeast, downdip from the fault.

Three phases of dolomite formation are indicated; one as a replacement prior to mineralization, a void-filling phase probably synchronous with mineralization, and a post-sphalerite void-filling phase. Smith and Gemmell (1994) outlined a preliminary genetic model describing a complex sequence of epigenetic dolomitization of host rocks followed by carbonate dissolution, brecciation, mineralization and hydrothermal dolomitization. The prospect is overlain by 80 to 150 m of Permian and Tertiary rocks. Galena samples from the deposit recorded rounded lead ages of about 0.9 Ga (Fletcher, I. R., 1986, pers. comm.).

Warrabarty was discovered by WMC in 1984 during reconnaissance stratigraphic percussion drilling in an area defined by airborne magnetic and EM surveys, and anomalous surface geochemistry. The best intersection found up until 1991, in 114 percussion holes and 256 diamond holes, was 28 m at 3.67% Zn and 1.43% Pb. Other intersections include 14 m at 7.46% Zn and 1.3% Pb. Percussion drilling has defined an anomalous zone extending over an area of 4.5 km^2.

References: WMC Annual Report-1991, GSWA-WAMEX - I 6882.

Baton

Prospect: Pb; Zn; Cu
Location: 20°52'44"S, 121°12'47"; 90 km north of Nifty

Anomalous lead and zinc, with sporadic copper, located by reconnaissance and follow-up drilling by WMC, is coincident with two shallow northeasterly dipping conductors, interpreted as carbonaceous sediments. Zinc and lead are preferentially concentrated in crystalline carbonate and in a ferruginous and manganiferous zone. The mineralization is coincident with a major fault contact between carbonaceous siltstones and crystalline carbonate.

References: Williams and Trendall (in press, b), GSWA-WAMEX - I 6882.

Moses Chair

Prospect: Zn; Pb
Location: 21°58'S, 121°51'E; 45 km southeast of Nifty

This stratabound base-metal prospect lies in the Broadhurst Formation and at the time of writing is under tenement to CRA. WMC defined zinc and lead anomalism in percussion drilling of major TEM anomalies.

Reference: GSWA-WAMEX - I 6882

Maroochydore–Urangan

Deposit/prospect: Cu; Pb; Zn; Ag; Co
Location: 22°11'45"S, 122°18'10"E; 60 km south of Telfer (Maroochydore)
22°10'30"S, 122°17'36"E; Urangan

The Maroochydore deposit lies beneath a 20–100 m cover of Permian fluvioglacial sedimentary material. Primary stratabound copper and lead–zinc mineralization occurs in dolomitic and pyritic carbonaceous shale and siltstone in the upper part of the Broadhurst Formation at a similar stratigraphic position to the Nifty mine. Within the deposit the occurrence of various sulfides is lithologically controlled. The mineralized sequence includes a lead–zinc anomalous hangingwall horizon, a copper mineralized horizon and a lead–zinc anomalous footwall horizon (Urangan — described below).

The copper horizon is about 70 m thick and contains chalcopyrite as fine 'bedded' material and also in quartz–dolomite veinlets. The fine 'bedded' chalcopyrite is in thin dolarenite beds, commonly just above a diagenetic framboidal pyritic bed. These contain up to 30% of interstitial chalcopyrite, suggesting that mineralization may be related to rock porosity. The copper-rich veinlets are preferentially concentrated within the dolomitic siltstone. Diagenetic bedded framboidal pyrite is present throughout the copper horizon. Higher grade copper (≤3.8%) occurs as irregular clots (≤0.02 m diameter) of chalcopyrite in a coarse dolarenite unit, and is associated with minor pervasive silicification. The copper horizon is anomalous in cobalt and silver and also contains gypsum pseudomorphs suggesting a sabkha depositional environment (Robinson et al., 1993). The hangingwall horizon is made up of carbonaceous shale with thin beds of dolomitic siltstone with common framboidal pyrite. In both the copper and hangingwall horizons the bulk of the mineralization is associated with silica dolomite veinlets, suggesting a remobilized origin. Pyrite is associated with subordinate galena and sphalerite.

The principal copper resource is located updip in the oxidized zone (14 Mt at 1.6% Cu, using a 1% Cu cut off,

and 0.07% cobalt) that extends over an area of 1 km by 300 m. The copper occurs mainly as chalcocite. An intersection of 8 m at 3.82% Cu (?oxidized zone) has been recorded. McKnight (1992) records a Pb model age of 820 ± 40 Ma from galena and a K–Ar model age on alteration-related mica of 753 ± 10 Ma. Groves et al. (1994) suggested analogies with the mineralization of the Zambian Copperbelt.

The Urangan prospect is a strike extension of the footwall lead–zinc horizon within a chloritized mudstone with subordinate thin dolomite beds. Pyrrhotite is the main sulfide (3–10%) with lesser pyrite and minor galena and sphalerite, mainly occurring in thin quartz carbonate veinlets. At outcrop the prospect is represented by a geochemically anomalous ferruginous siltstone about 1 km west of Maroochydore and, owing to its magnetic signature, the siltstone is a useful marker unit. Cerussite has been identified in shallow drilling over a stratigraphic thickness of up to 60 m. Drillcore has given samples of about 1 m thickness containing up to 3% Pb and a few thousand ppm of zinc.

Exploration by Esso/Barrack/City Res and, most recently, MIM (1984 on) in the Eva Well area, led to the discovery of Maroochydore in 1984 by Esso, who were following a Zambian Copperbelt model. Drilling (RAB) established the stratigraphy and led to the location of copper anomalies greater than 1%. Subsequent RC drilling led to the further definition of the prospect. MIM entered the joint venture in 1991 and compiled and reinterpreted all data. This led to the recognition of primary mineralization, and established that the copper horizon extended over 9 km of strike and several hundred metres downdip. Metallurgical studies on the secondary mineralization show variable, but generally subeconomic, leachability and flotation characteristics.

References: Hickman and Clarke (1993), Louthean (1987), West Australian 2/8/91, McKnight (1992), Groves et al. (1994), Robinson et al. (1993), Robinson (1994).

Airlie

Prospect: Cu; Pb; Zn; (Ni; Co)
Location: 22°12'45"S, 122°21'50"E; 5 km east-southeast of Maroochydore

Stratabound sulfides in the Broadhurst Formation at Airlie give up to 0.3% Zn in drillhole intervals of up to 2 m. The prospect is presently being explored by the MIM joint venture (1984 on).

Reference: Hickman and Clarke (1993).

Coogee

Prospect: Pb; Zn
Location: 22°22'24"S, 122°30'30"E; 49 km east-southeast of Sunday Creek

Galena and traces of sphalerite occur in veins of coarse 'sparry' dolomite and quartz in an outcrop of massive micritic dolomite with a minor clastic component. The prospect was identified by Esso in the mid-1980s but no drilling has been carried out by the MIM joint venture (1984 on).

Reference: Robinson (1994).

Yepoon

Prospect: Cu; Pb; Zn
Location: 22°11'55"S, 122°20'25"E; 2.7 km east of Maroohydore

Stratabound sulfides in the Broadhurst Formation 2.7 km east of Maroochydore have been explored by Esso/City Res/Barrack/MIM (1984 on).

Reference: Hickman and Clarke (1993).

Cottesloe (Eva Well)

Prospect: Pb; Ag; Zn; Cu
Location: 22°16'20"S, 122°13'40"E; 120 km south of Telfer

Stratiform sulfide mineralization occurs in the Broadhurst Formation at the southeast closure of a basin-shaped syncline. Gossanous ironstone outcrop is associated with a shale–carbonate unit (siltstone and dolomitic siltstone) that is 6 m thick, traceable for 12 km along strike, and dips at 15° to the northwest. Amax obtained up to 3.8% Pb and 80 g/t Ag in chip samples from the gossan. Zinc values are generally less than 1000 ppm. A GSWA gossan sample 5 km northwest of Cottesloe, but in the same horizon, returned 1.44% Pb, 412 ppm Zn, 22 g/t Ag and 28 ppm U. Cerussite has been identified in RAB and percussion cuttings. Below the base of oxidation only trace amounts of galena and sphalerite have been identified in a weakly pyritic shale unit.

The prospect has been drilled by Amax (1974–80) and Esso/MIM (1984–). A total of 28 percussion holes, 4 diamond holes and numerous RAB holes have been completed. The highest assays reported from drill cuttings are 5% Pb and 100 g/t Ag (MIM).

References: Hickman and Clarke (1993), Robinson (1994), GSWA-WAMEX I 1115.

Sunday Creek

Prospect: U; Cu; Pb
Location: 22°20'30"S, 122°19'35"E; 26 km east of Kintyre

Stratabound mineralization occurs in pyritic black shale of the Broadhurst Formation and underlying black pyritic feldspathic quartzite of the Coolbro Formation, close to the axis of a northwesterly trending syncline. The narrow mineralized zone (1–2 m wide and up to 800 m long) contains disseminated pitchblende, torbernite, covellite, and chalcopyrite. Surface sampling by Occidental gives up to 7% uranium, 1.12% Pb and 0.85% Cu. More recent exploration by Uranerz/Idemitsu suggests that the mineralization is structurally controlled and unconformity related.

The prospect was found by Occidental Minerals (1978–81) who considered it to have similarities with Zambian uranium–copper mineralization; i.e. located at the first sandstone/slate transition above felsic, crystalline basement. Drilling gave up to 1.3 m of 0.6% U with minor base-metals remobilized in quartz–carbonate veins. Mineralization was seen to be zoned vertically; U–Cu–Pb/Zn–Fe, upwards. Occidental suggested remobilization of the syngenetic protore in a local deformation zone. The prospect is currently being explored for uranium by the Uranerz/Idemitsu JV (1987–94). Reverse circulation and diamond drilling outlined a 400 by 800 m zone of intense chlorite–sericite alteration with associated subeconomic mineralization, one of three prospects over a strike length of 8 km. Mineralization is in a mylonitic shear zone and is cross-cutting carbonate–pyrite veins.

References: Hickman and Clarke (1993), Louthean (1993), GSWA-WAMEX - I 1694.

Potential

Within the Yeneena Group, base-metal potential is considered to be fairly clearly defined, with a maximum in the middle to upper Broadhurst Formation, in sulfidic and carbonate-rich shale units that host the Nifty and Maroochydore deposits. The underlying Coolbro Sandstone seems to have little potential except as a host for isolated vein-style mineralization, particularly gold.

Exploration to date and mining-tenement distribution reflect the known and projected extent of the Broadhurst Formation. The position of the margin of the Rudall Complex, and the distribution of the Broadhurst Formation, are not clear to the east of the Mount Sears Range, north and east of Camel Rocks. Magnetic signatures in this area are equivocal. East-southeast of Maroochydore, the Broadhurst and Coolbro Formations seem to be folded into a poorly exposed set of east-southeasterly trending anticlines and synclines. A strong magnetic ridge east of this may indicate Broadhurst Formation beneath sand cover. Northwest of the Rudall Complex, the distribution of the Broadhurst Formation, largely interpreted from aeromagnetic data, is shown in Figure 74. On the southwestern side of the complex the Yeneena Group is represented by the Choorun Formation, a unit composed chiefly of interbedded sandstone, micaceous siltstone and quartz pebble conglomerate with minor shale, similar to the lower part of the Broadhurst Formation. This assemblage is considered to have limited potential for base metals.

The Isdell Formation consists of carbonate rocks with relatively thin interbeds of calcareous siltstone and shale. To date no significant deposits are known in this unit though GSWA mapping detected some minor base-metal anomalies in gossans and there are indications from Uranerz drilling, near the Broadhurst Formation – Isdell Formation contact, of stratiform zinc mineralization. The combination of carbonate lithologies and convergent tectonics in the Isdell Formation, east of the Broadhurst Range, may be favourable for the more intermediate, epigenetic/syngenetic Irish-type of carbonate-hosted lead zinc mineralization. A critical element here would be the presence (or absence) of syndepositional faulting to provide channelways for mineralizing brines. On present evidence the Isdell Formation shows little sign of sub-basin development. The tectonized Broadhurst Formation – Isdell Formation contact, however, could have been a growth fault at the time of Isdell sedimentation.

Bagas and Smithies (in press) have indicated the potential of the little-explored Pungkuli Formation of the Tarcunyah Subgroup of the Yeneena Group, in the southern part of the CONNAUGHTON 1:100 000 sheet area. This formation contains locally sulfidic gossanous shale and carbonate.

The distribution of favourable host lithologies is critical to an assessment of the potential for syngenetic stratabound and stratiform base-metal mineralization in the Yeneena Group sedimentary rocks particularly those representing anoxic conditions, and the nature and extent of synsedimentary faulting in the sequence. Synsedimentary faulting is suggested in the Coolbro Formation (Hickman and Bagas, in press), but considered less likely in the Broadhurst and Isdell Formations. It is possible, however, that growth faults in the Coolbro Formation could have acted as conduits providing access for mineralizing brines to the Broadhurst Formation.

An alternative, epigenetic model for the Nifty and Maroochydore mineralization, based on that proposed by Unrug (1988) for the Zambian copper belt, envisages the possibility that metalliferous brines, mobilized from elsewhere in the basin during the main post-Yeneena D_4 deformation, could have been introduced into the pyrite-rich host stratigraphy along thrust faults produced by reactivation of original growth faults. This could explain the structural control of mineralization at Nifty and the copper–cobalt association at both deposits.

Exploration for these targets will need to be based upon all available detailed lithological and structural information to help define areas of high potential. Given the generally poor outcrop of the Broadhurst and Isdell Formations, detailed magnetics may be the most useful tool for this purpose.

Savory Sub-basin

Geological framework and potential

The Savory Sub-basin of the Officer Basin evolved between 0.9 and 0.6 Ga and overlies the eastern parts of the Bangemall Basin and the western margin of the Yeneena Basin. The sedimentary rocks are predominantly arenaceous but the basin also contains a glacigenic sequence and stromatolitic dolomites (Williams, 1992). The basin was initiated by renewed instability following the uplift and erosion of the Bangemall Basin. This movement is attributed to further adjustments in the positioning of the Pilbara and Yilgarn Cratons. The Bangemall Basin (and, to some extent, the Paterson

Orogen) was the main provenance for Savory Sub-basin sedimentary succession. The basal units of the basin sequence reflect block faulting and subsidence in an environment similar to that occupied by the early sedimentary rocks of the Edmund Subgroup in the Bangemall Basin, producing predominantly clastic rocks on a shallow-marine shelf. Early growth faulting was largely confined to the southern margin of the basin (Williams, 1992). In a second phase of sedimentation, listric growth faulting occurred along the northwestern margin of the basin. A marginal-sag basin developed and was filled with shallow-marine clastic and minor carbonate rocks. Following uplift and some folding, a third major phase of clastic sedimentation took place in a foreland environment in the northeastern part of the basin, reflecting uplift of the adjacent Paterson Orogen during the early stages of the Paterson Orogeny at 0.62–0.60 Ga.

The tectonic setting of the basin during the first and second phases of clastic sedimentation, suggests some potential for clastic-hosted base-metals. However, the predominance of arenaceous lithologies and shallow-marine settings provide some limitations. Suitable host lithologies are present in more restricted areas of the second phase, in the shale and siltstone (in part glauconitic) of the Watch Hill Formation, on the northeastern boundary of the basin, and in the dolomite, chert, siltstone and shale of the Skates Hills Formation. Halite and anhydrite pseudomorphs in the coeval Mundadjini and the Skates Hills Formations suggest possible sabkha environments (Williams, 1992) which may be favourable for base-metal deposits.

During the 1980s, several companies carried out regional and more-detailed aerial and ground magnetic surveys in the basin with follow-up surface geochemistry targeting base metals, gold, platinum-group metals and uranium. No significant anomalies were recognized.

Other possible clastic-hosted deposits

Pilbara Craton

Coondamar Creek (Mount Hay)

Prospect: Cu; Pb; Zn; Ag
Location: 21°55'50"S, 120°39'50"E; 58 km east of Nullagine

Two gossans, 500 m apart, are present in metasedimentary and felsic volcanic rocks of the ?Mosquito Creek Formation in the core of a tight, north-northwesterly trending syncline between two northerly trending faults. The southern gossan covers an area of 3 by 20 m and contains malachite, azurite, chrysocolla, cuprite, hydrozincite, smithsonite and cerussite, with up to 27% Cu in surface samples. Primary mineralization consists of short intervals of pyrite, chalcopyrite, sphalerite and galena in quartz–chlorite–sericite–feldspar schists in the southern gossan. The northern gossan is largely pyritic at depth.

Diamond drilling by CEC (1974–75) beneath the southern gossan gave intersections of 1.8 m of 1.1% Cu, 2.51% Zn and 3.5 m of 3.9% Cu, 2.89% Pb, 3.12% Zn and 189g/t Ag.

References: Marston (1979), GSWA-WAMEX - I 308.

Yilgarn Craton – Southern Cross Province

Diemals (Diemals Find)

Prospect: Cu; Zn
Location: 29°36'S, 119°09'E

A small siliceous copper gossan and other ferruginous zones are located in a 150 m-thick unit of pelitic metasedimentary rocks within a north-striking mafic sequence on a contact of graphitic slate and metabasalt. This possibly represents supergene enrichment of iron sulfides in the slate and may include copper leached from the metabasalt.

Exploration by WMC (1966–71) includes a best percussion-hole intersection of 4.57 m at 4.23% Cu and 1.3% Zn.

References: Marston (1979), GSWA-WAMEX - I 374.

Yilgarn Craton – East Yilgarn/Albany–Fraser Orogen

Beete (Lake Gilmore)

Occurrence: Zn; Pb
Location: 32°44'S, 121°42'E; 42 km south-southwest of Norseman

Zinc and lead mineralization in interbedded quartzites, carbonaceous shale and siltstone within the Norseman Greenstone Belt (east of Lake Gilmore) extends over 1.6 km along strike and is largely contained within the quartzites.

Percussion and diamond drilling by Newmont (1965–72) obtained a best result of 1.82 m at 4.7% Zn and 0.5% Pb. On the basis of five diamond holes, a resource of 43 000 t at 1.2% Zn and 0.2% Pb was inferred. Auselec (1973–75) re-examined Newmont's work and concluded that the mineralization was subeconomic.

References: Doepel (1973), GSWA-WAMEX - I 365, I 1429.

Hamersley Basin

Wanna-Munna (Wonmunna)

Deposit: Cu; Ag; Zn
Location: 23°06'30"S, 119°08'20"E; 25 km east-southeast of Mount Robinson

The Wanna–Munna deposit is one of a number of copper occurrences in the Jeerinah Formation of the Hamersley

Basin, but in this case with some associated zinc enrichment. Weak, thin mineralization occurs over 300 m strike length in steeply southdipping, interbedded dark-grey shale, pisolitic carbonate and silicified shale in the upper part of the Jeerinah Formation in the uppermost Fortescue Group. Horizons of limonite nodules after pyrite are seen at the surface and carbonaceous shale contains finely disseminated malachite.

Minor copper production took place in 1953. WMC (1967–75) drilled three lines of rotary holes with a best intersection of 3 m at 2.9% Cu. Zinc was detected up to 0.4% and silver-rich veinlets recorded in some holes.

Reference: Marston (1979).

Gascoyne Complex

Mount Alexander

Prospect: Zn; Pb
Location: 22°41'S, 115°31'30"E; 4 km southwest of Mount Alexander

Apparently stratabound base-metal sulfides occur as gossans in a sequence of amphibolite, schist, dolomite, banded iron-formation, slate and quartzite of the Morrissey Metamorphic Suite. The sequence is draped around a northeasterly trending anticline with amphibolite in the core. The mineralization occurs in a dolomitic unit lying between the mafic amphibolite and banded iron-formation, and comprises galena and sphalerite with lesser chalcopyrite, arsenopyrite, pyrite and pyrrhotite. Malachite and brochantite are present in the gossans. The sequence is frequently intruded by granite which has produced metasomatic effects, local hornfelsing, and garnet and epidote skarns. Possibly the sulfides have been remobilized in skarns and quartz veins during metamorphism/metasomatism marginal to granite intrusions.

Exploration by Esso (1977) concentrated on uranium targets. Amax/Amoco (1980–86) encountered up to 4% Pb and 4.2% Zn in rock-chip samples. Cyprus (1985–88) in RC drilling of the gossan zones obtained intersections of 12 m at 1.6% Zn, 8 m at 2.38% Zn, 6 m at 4.7% Cu and 126 g/t Ag, and 6 m at 1.3% Pb. Cyprus considered the mineralization to be syngenetic, on petrographic evidence, but at least partially remobilized in skarns and quartz veins. Exploration by MIM (1989–94) suggested that the mineralization is indeed in skarns.

References: GSWA-WAMEX - I 664, I 3671, I 4645.

Gifford Creek (Yangibana)

Prospect: Pb; Zn; REE
Location: 23°53'45"S, 116°09'30"E; 15 km south-southeast of Edmund Homestead

Gossanous ironstones occur at two stratigraphic levels over an approximate strike length of 14 km within paraschist of the Morrissey Metamorphics, close to a granite–granodiorite contact. Four main ironstones have been located. They represent quartz–magnesite–magnetite banded iron-formation with variable amounts of feldspar, garnet, apatite, ilmenite, epidote, pyrolusite, pyrite and pyrrhotite. The sequence is thought to be of carbonatitic affinity. Galena, sphalerite and chalcopyrite are located in stratabound anomalous zones, which contain up to 3% Pb and 0.92% Zn, with associated silver, gold, uranium, barium (≤3%) and rare-earth elements (≤1.5%) in rock-chip samples.

Newmont (1974–75), operating on a Broken Hill exploration model, tested the prospect to drilling level, obtaining best grades of 0.55% Pb and 0.65% Zn, but still within the oxidized zone. Cliffs (1981–84) carried out rock-chip sampling and interpreted the ironstones as representing quartz–carbonate–iron–manganese–barite–garnet-rich metasedimentary rocks of possible volcanic origin, and also considered the results to favour a Broken Hill model. K. W. Wolzak (1986–90) explored the rare-earth elements but obtained rock-chip results up to 3% Pb and 1% Zn. The Yangibana prospect has been explored by Newcrest in joint venture with Grenfell Minerals. An inferred resource figure of 3.5 Mt at 1.7% rare earths has been quoted.

References: GSWA-WAMEX - I 364, I 4471, I 5240, I 5271.

Ashburton Basin

Slate Bore (South Hardey River)

Abandoned workings/prospect: Pb; (Sb; As; Cu; Zn)
Location: 22°58'S, 116°36'10"E; 48 km southeast of Wyloo

Stratabound mineralization occurs in tightly folded quartz–sericite schist and quartzite (metamorphosed mudstone, siltstone and sandstone) of the Ashburton Formation on the south limb of an easterly trending anticline. Galena with associated sulfides (pyrite, arsenopyrite, chalcopyrite, covellite, sphalerite, bornite, digenite, chalcocite, marcasite, cubanite and stibnite with anglesite, hindalsite, mansfieldite and malachite present in the oxidized zone) occurs in stringer zones, massive lenses and later cross-cutting quartz/carbonate veins. These are confined to a concordant carbonate-bearing, brecciated, tourmalinized and kaolinized metasiltstone unit. The lenses may be associated with bedding-parallel shears with sedimentation having taken place in a restricted basin. Up to 2.5% Pb has been found in rock-chip samples. Diamond drilling gave a best intersection of 6.7 m at 2.28% Pb in massive sulfide/quartz breccia within 16 m of 1.24% Pb. All other holes include 1.5 m of Pb values in excess of 1%.

A few pits indicate early small-scale mining. Mallina/Newmont (1980 on) explored around the old workings for Mount Clement-style gold; grab samples gave up to 2.6% Pb. Geophysical data of Jododex (1971–75), who also drilled the diamond holes, are not encouraging in terms of potential.

References: Blockley (1971), Marston (1979), Thorne et al. (1991).

Halls Creek Orogen

The Osmond Range succession

Along the eastern margin of the Lamboo Complex and east of the Halls Creek Fault, a number of deformed and varied sedimentary sequences are exposed in structurally separated settings (Griffin and Grey, 1990). The Osmond Range lies in the centre of this belt. Dow and Gemuts (1969) recognized a number of conformable and unconformable units in this area; Table 20 summarizes some of them. Unconformably underlying the Osmond Range succession are the Red Rock Beds, intruded by the Fish Hole Dolerite, both of which belong to the Kimberley Basin succession.

The Mount Parker Sandstone, Bungle Bungle Dolomite and Wade Creek Sandstone are considered to have been deposited in a shallow marine-shelf environment. The Mount John Shale Member and Helicopter Siltstone represent deposition in a fault-bounded downwarp farther east.

Osmond Range (Trend, Paradise Creek)

Prospects: Pb; Zn; Cu
Location: 17°16'40"S, 128°26'20"E; 34 km east-southeast of Turkey Creek (Trend)
17°13'10"S, 128°21'E; Paradise Creek

Stratiform lead, zinc and copper mineralization is located within the Bungle Bungle Dolomite on the north and south limbs of a shallowly east-northeasterly plunging anticline. The dolomite contains stromatolitic chert, pyrite and manganese-rich shale and thin rhyolitic tuff. Copper occurs over 25 km of strike in the basal chert, zinc–manganese mineralization in the shale, and lead in the overlying dolomite. Anomalies are associated with the thickest sections of the units and may be related to fault-scarp subsidence in a restricted basin.

The Trend gossan, a dolomite breccia impregnated with iron and manganese oxide, extends about 2.3 km along strike just south of the nose of the anticline and is up to 12 m wide. It has been variously interpreted as a collapse/oxidation breccia or an east-dipping fault zone. A large outcrop about 200 m long at the southern end, carries an average of 1.5% Pb (≤3% Pb) and 0.2% Zn in surface samples. Galena has been recognized among exotic iron and manganese oxides at the surface. Other, thinner gossans occur in the area at different levels in the dolomite. The Paradise Creek gossan lies on the northern limb of the anticline in two horizons of a stromatolitic dolomite unit separated by a high-energy detrital unit. Galena is present within the stromatolites, in carbonaceous laminae and in solution lines in the lower unit. In the upper unit it is associated with a black chert cap.

The Trend gossan was explored by Trend Exploration P/L (1973) using gossan sampling and shallow diamond drilling. The best result from difficult drilling was 12 m of sludge samples at 1.2% Pb, but at a level shallower than expected. The equivocal results in the drilling led Trend to suspect either surface enrichment, a fault control or deep weathering. CEC/Samin (1980–84), exploring for McArthur River-type targets, also encountered drilling

Table 20. Stratigraphic subdivision of the Osmond Range succession (after **Grey and Griffin, 1990**)

Unit	*Thickness (m)*	*Rock type*	*Relationships to other units*
Helicopter Siltstone	165	Laminated khaki siltstone and shale; some fine-grained quartz sandstone	Conformable on Wade Creek Sandstone Sandstone
Wade Creek Sandstone	600	Clean, well-sorted quartz sandstone; cross-bedding, ripple marks, slumped bedding common in upper parts	Unconformable on Bungle Bungle Dolomite
Mount John Shale member 1128 ± 110 Ma	200	Khaki and some black shale and siltstone, minor quartz sandstone; some beds highly ferruginous	Sandstone rests unconformably on Bungle Bungle Dolomite; shale member is lens in Wade Creek Sandstone
Bungle Bungle Dolomite	1 000	Dolomite and dolomitic shale, several; quartz sandstone beds up to 30 m thick	Conformable on Mount Parker Sandstone; contains stromatolites, notably *Collenia frequens* and *Conophyton cylindricum*
Mount Parker Sandstone	150–300	Clean quartz, sandstone, commonly with pebbly lenses; commonly ferruginous just below Bungle Bungle Dolomite	Strongly unconformable on Red Rock beds

NOTE: *after* Dow and Gemuts (1969)

problems in broken ground and completed only one diamond and one percussion hole. They obtained a best intersection of 5 m at 0.429% Pb.

At Paradise Creek, CEC/Samin drilled two diamond holes. They recognized good correlation of galena mineralization between the holes, suggesting a stratiform origin despite the lack of finely bedded textures. The best intersection was 1 m at 4.81% Pb.

Reference: GSWA-WAMEX - I 464, I 1977.

King Leopold Orogen

Chianti

Prospect: Zn; Cu; Pb; Ag
Location: 16°34'20"S, 124°03'E; 23 km north-northeast of Oobagooma Homestead

Massive stratiform and breccia base-metal mineralization is present in a 3 by 150 m gossanous zone in north-northwesterly striking Marboo Formation slate and quartz–sericite schist (turbiditic metasandstone and phyllite) north of the Lennard Granite. The sedimentary rocks are intruded and broken up by the Ruins Dolerite and are also faulted subparallel to bedding. The mineralization occurs as disseminated pyrrhotite with minor pyrite, chalcopyrite, sphalerite and galena in graphitic slate; as massive, fine-grained pyrrhotite with chalcopyrite, sphalerite and galena; and as breccia mineralization containing about 60% rock fragments. Disseminated sulfides are also present in meta-dolerite. Post-mineralization faulting and dolerite intrusion seems to have caused some remobilization of sulfides.

ACM (1971–72) mapped the prospect, carried out magnetic and Turam surveys, and followed up with RAB, percussion and diamond drilling. The company considered the sequence to contain andesite and rhyolite, but this seems unlikely in the light of recent GSWA mapping (Tyler and Griffin, 1992). One diamond hole intersected the structurally complex massive ore and breccia zone. A best intersection of 6.55 m at 1.06% Cu, 0.93% Pb, 2.85% Zn and 29 g/t Ag was obtained. Follow-up drilling failed to extend the mineralized zone beyond the previously known 150 to 180 m strike extent. Turam anomalies beyond this zone were due to unmineralized graphitic phyllite.

References: Marston (1979), Tyler and Griffin (1992), GSWA-WAMEX - I 530.

Albany–Fraser Orogen

Trilogy

Prospect: Au; Pb; Zn; Cu; Ag
Location: 33°45'21"S, 120°12'25"E; 7.5 km south-southeast of Kundip

Gold, silver and base-metal mineralization was discovered during exploration drilling in 1997 by Homestake and Tectonic Resources NL, located in shallow-marine metasedimentary rocks of the Mesoproterozoic Mount Barren Group (1550–1300 Ma) (**Chapter 8**).

The host rocks lie on the southern flank of an overturned, refolded syncline, dipping southeast at between 40° and 60°. The host Kybulup Schist in this area consists of quartz–sericite–chlorite schist and phyllite, with local dolomite and muddy dolomite. Evidence from recent mapping by the GSWA in the Ravensthorpe area suggests that the Mount Barren Group metasedimentary rocks formed in a separate terrane and have been thrust over the Archaean basement from the southeast (Witt, 1998).

The Trilogy mineralization lies within an area outlined by a mobile metal ion (MMI) anomaly measuring about 3 km by 500 m. Preliminary information from Tectonic Resources describes the mineralization as being in a sheet or tabular lode, up to about 50 m thick, dipping south-easterly at about 30°, from a depth of 30 m to at least 200 m. Both the bedding and regional structures dip to the southeast in this area. The strike length is in excess of 400 m. Mineralization lies within a halo of silica alteration. Near the surface the mineralization occurs as massive-sulfide bands up to 1.5 m thick, with minor sulfide stringers and disseminations.

Tectonic Resources have suggested that there are two constrasting and partly overlapping zones within the mineralization, one copper–gold and one polymetallic. One intercept from the polymetallic zone gave 16 m at 0.25 g/t Au, 1.76% Cu, 12.13% Pb, 9.45% Zn and 122 g/t Ag from 100 m downhole. The gold zone includes intersections such as 16 m at 5.97 g/t Au (including 4 m at 19.72 g/t Au), and is said to contain 631 000 t grading 7.2 g/t Au and 3% Cu (Minerals Investor, October 1997). One-metre intercepts as high as 30.3 g/t Au, 5.20% Cu, 32% Pb and 19.5% Zn have been recorded in various areas of the mineralized zone (Tectonic Resources Quarterly Report, September 1997) and Australian Stock Exchange report March 1998).

At this stage it is not clear if the mineralization is syngenetic or epigenetic, stratabound or shear controlled. This uncertainty inhibits evaluation of the significance of this discovery.

References: Witt (1998), Tectonic Resources Quarterly Report, September 1997 and Australian Stock Exchange Report March 1998, Louthean (1997), Wilkinson (1997).

Carbonate-hosted type — summary of geology and mineralization

Most of the carbonate-hosted massive-sulfide deposits and prospects recognized in Western Australia are of the Mississippi Valley type; i.e. predominantly epigenetic mineralization in limestone and dolomite formed at basin margins or on intra-basin arches.

Distribution

Deposits of this type in Western Australia are predominantly of Devonian and Carboniferous age and are located

in the Canning and Bonaparte Basins. In the Canning Basin most deposits are on the Lennard Shelf and show a variety of forms associated variously with fractures, breccias or favourable stratigraphic horizons. Similar styles are found in the Bonaparte Basin.

However, in the central Canning Basin significant base-metal mineralization has been discovered, over a 19 km strike length, in Ordovician to Silurian dolomite overlying the southern margin of the Broome Platform and adjacent to the Admiral Bay Fault. Minor carbonate-hosted mineralization is also recognized in Meso-proterozoic sedimentary rocks of the Bangemall Basin and in Devonian sedimentary rocks of the Carnarvon Basin.

Canning and Bonaparte Basins

Geological framework

The Canning and Bonaparte Basins, which were probably connected until the Middle Ordovician, originated as part of a larger basin caused by intracratonic downwarping. In the Silurian, both basins developed as separate intracratonic rifts but with a similar evolutionary history.

Figure 83 summarizes the stratigraphy of both basins and relates it to tectonic developments and timing of mineralization. There were four main phases of evolution in both basins. The first, from the Cambrian to the Ordovician, reflects the development of an intracratonic sag which may have been caused by the removal of enormous volumes of mafic magma from the mantle to produce the Lower Cambrian Antrim Plateau Volcanics. The second, from the Silurian to the Late Carboniferous, reflects intracratonic rifting and the separation of the basins. The third phase saw a reactivation of rifting and sag, and the fourth phase was marked by northeasterly trending rifting and continental breakup. Phases one and two have relevance to the development of epigenetic massive sulfide deposits in the Ordovician and Middle to Late Devonian–Early Carboniferous.

During the latter part of the first phase, extensive Ordovician carbonate and siliciclastic rocks were deposited in the Canning Basin. Between 1000 and 3000 m were laid down with thickening south of the northwesterly trending Admiral Bay Fault, suggesting that this feature was active during the Ordovician. Details of the resulting stratigraphy in the vicinity of this fault during

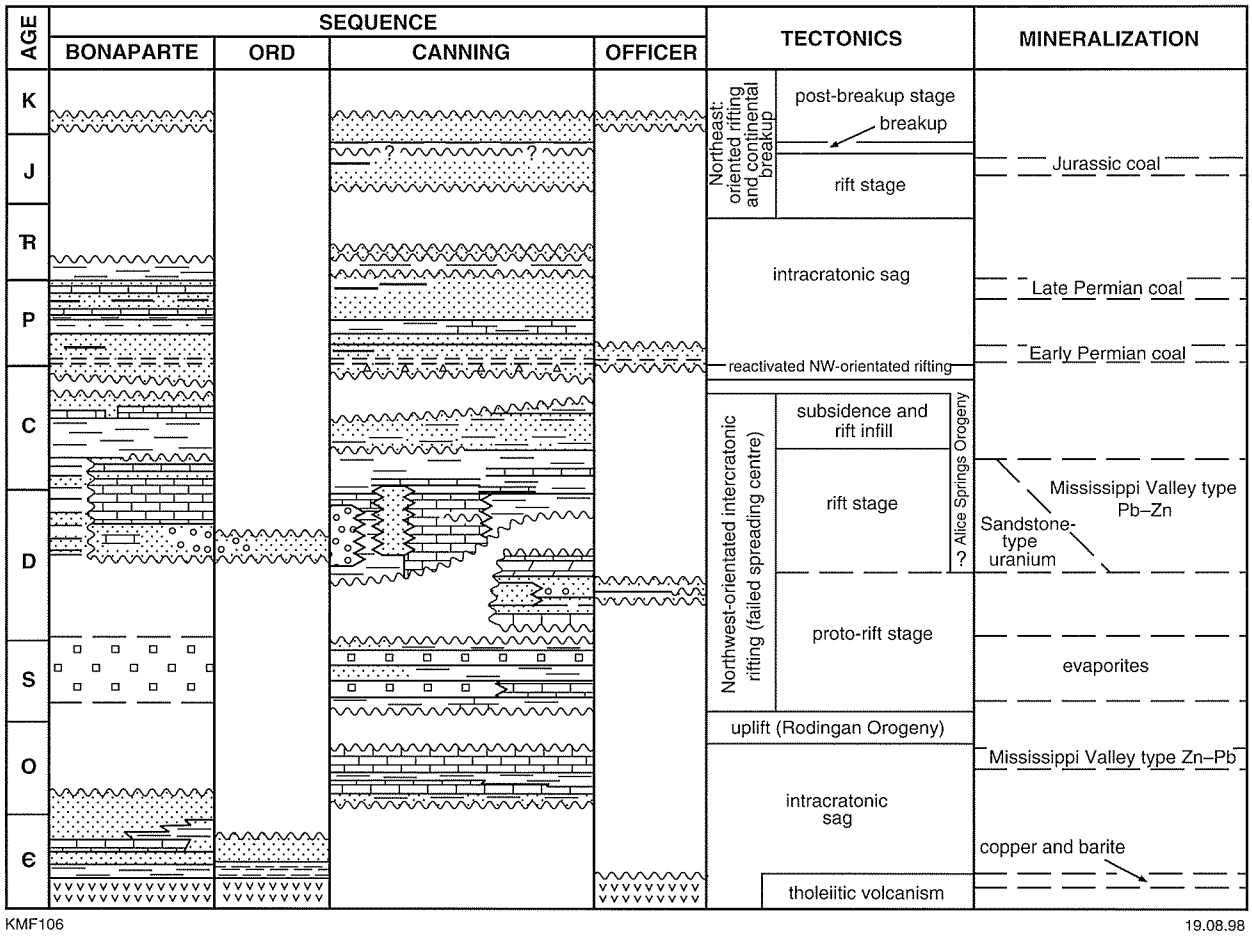


Figure 83. Bonaparte and Canning Basins: sequence summary, tectonic history and mineralization (*after* Mory and Dunn, 1990)

the Ordovician and Silurian are described by Williams (this volume).

The early part of the second phase was 'pre-rift' in character (Brown et al., 1984), with the broad elongate arch of the Broome platform separating a penecontemporaneous downwarp to the south, in the Kitson Sub-basin, from a graben system to the north, in the Fitzroy Trough. During this phase, up to 1350 m of carbonates, siliciclastics and evaporites of the Carribuddy Group were followed by as much as 1000 m of shallow-marine siliciclastics of the Tandulla Group. Evaporites equivalent to the Carribuddy Group are also believed to have been deposited in the deeper part of the Bonaparte Basin (Petrel Sub-basin) at this time.

The second-phase sedimentation, during the Middle Devonian to Early Carboniferous, was controlled by northwest-oriented rifting in the Fitzroy Trough and in the Petrel Sub-basin. In both the Canning and Bonaparte Basins this led to the development of Devonian carbonate-reef complexes marginal to the rifts, on the Lennard Shelf and on the Carlton and Burt Range Shelves. The Lennard Shelf reef complex is about 50 km wide and 350 km long and has been divided (Playford, 1984) into two depositional cycles; the Givetian–Frasnian Pillara cycle and the Famennian Nullara cycle, with a total thickness of up to 2000 m. The Pillara cycle rocks are exposed only in the southeast of the shelf, in the Pillara and Emanuel Ranges, while the Nullara cycle rocks are preserved to the northwest in the Horseshoe and Napier Ranges.

This period was followed by a 'subsidence and rift infill' phase in both basins during the latter part of the Carboniferous, characterized by rapid deposition of deltaic basin-fill sequences; the Weaber Group in the Bonaparte Basin and the Anderson Formation in the Canning Basin.

Mineralization

Zinc–lead–silver mineralization in the Lennard Shelf of the Canning Basin, is located both in the Pillara cycle rocks (Cadjebut, Kapok, Blendevale, Twelve Mile Bore and Geikie Gorge), and in the Nullara cycle rocks (Narlarla, Wagon Pass) (Fig. 84). The mineralization in the Pillara cycle is hosted primarily in platform and platform-margin facies limestones that show local, intense dolomitization. These are flanked, and in some cases overlain, by reefal and marginal slope-facies carbonates and by basinal-facies shales. Murphy (1990) describes the mineralization in all known occurrences as showing the characteristics of Mississippi Valley-type deposits, ' . . . being stratabound, epigenetic, replacement or open space filling styles of sulfide mineralization.' Galena and sphalerite predominate with an associated gangue of marcasite, pyrite and calcite.

The major Pinnacle Fault is adjacent to the eastern part of the Lennard Shelf, where the major resources are located, and presumably was a significant factor in focusing mineralizing basinal fluids into this area. The major deposits are all associated with faults. Muhling (1994) has subdivided these thus:

Hosted in fault zones: Blendevale and Kapok where mineralization fills cavities in tectonic breccias.

Cavities alongside faults: These host clusters of high-grade lenses as at Twelve Mile Bore and Narlarla (possibly related to hydrothermal karst processes)

Replaced evaporites: Cadjebut in the footwall of the Cadjebut Fault.

Neither Wagon Pass nor Chedda Cliffs are directly fault related, being updip wedge-outs characterized by disseminated mineralization.

Tompkins et al. (1994b) have described textural and lead isotopic evidence for a generally weak, early mineralization event of finely disseminated sphalerite and marcasite in primary porosity cements at Cadjebut, and have documented and summarized evidence from Ringrose (1989) and McManus and Wallace (1992) for a similar early mineralization event seen to variable degrees at Geikie Gorge, Blendevale, Wagon Pass and Narlarla. On similar evidence they described a major, later mineralizing event associated with cements in large secondary vugs and cavities at Cadjebut and suggested that a similar second-stage event might be responsible for the main fault-related mineralization at Blendevale, Twelve Mile Bore, and possibly Narlarla. The first event is considered to have occurred early in the diagenetic history, prior to significant burial (late Givetian–early Frasnian) while the later event followed chemical compaction and burial (mid-Carboniferous). This view is in contrast with that of McManus and Wallace (1992), based on cathodoluminescence cement stratigraphy in the Geikie Gorge mineralization, that mineralization in both primary and secondary porosity took place in a single phase during early burial diagenesis in the late Fammenian–early Tournaisian, immediately following dolomitization.

The indications of the relationship between basin evolution and the fluid flow that led to mineralization are the subject of ongoing research. Tompkins et al. (1994b) suggested a connection between the waning stages of the Alice Springs Orogeny, uplift in the Lennard Shelf, sea-level regression in the Canning Basin, and migration of large volumes of basinal brines from the Fitzroy Trough to the Lennard Shelf. Eisenlohr et al. (1994) suggested that such a sea-level fall could raise basin temperatures, inducing hydrocarbon gas maturation to be capable of expelling large volumes of brine. Such a process would explain the association of the Lennard Shelf and other deposits, with regional unconformities.

The main stratabound zinc–lead–silver mineralization discovered to date in the Bonaparte Basin occurs at Sorby Hills in the eastern part of the basin. Mineralization has developed in alternating dolomitic and clastic units of the Lower Carboniferous Burt Range Formation on the east flank of the Proterozoic Pincombe Inlier in the Burt Range Sub-basin. Most mineralization is hosted by a breccia zone that occurs at the base of the middle member of the Burt Range Formation. In the western Bonaparte Basin, minor mineralization is associated with the platform facies of the Fammenian Ningbing reef complex in the Carlton Sub-basin.

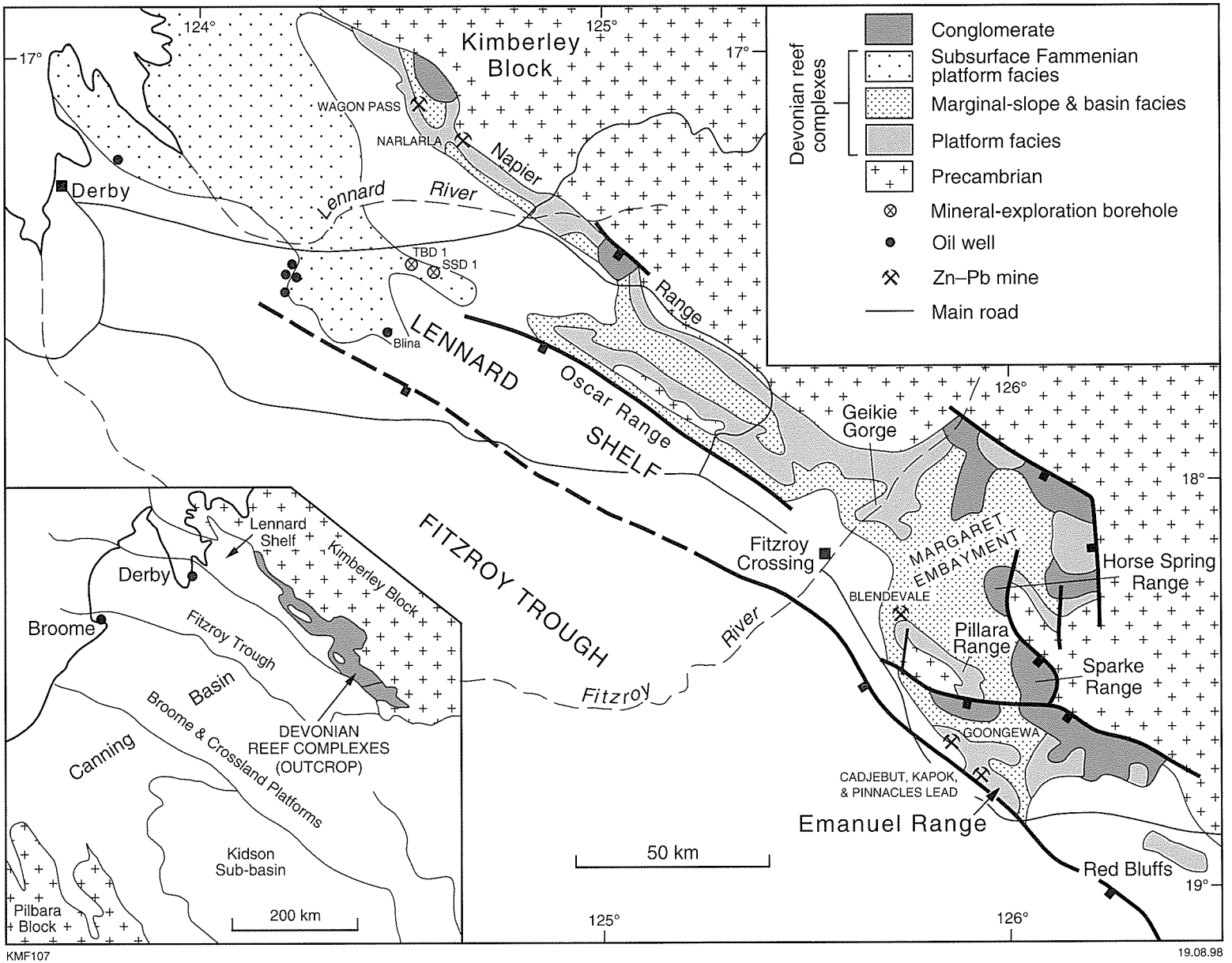


Figure 84. Generalized map of the Devonian reef belt of the Lennard Shelf (*after* Playford, 1984)

Zinc–lead–silver mineralization at Admiral Bay is located within Ordovician strata of the Upper Nita Formation, following the intersection with one of the major faults of the Admiral Bay Fault zone. It appears to form a ribbon-like, stratabound body, which extends over 16 km along strike, is between 200 and 400 m wide, and lies between 1280 and 1600 m below the surface.

Exploration

Exploration in relation to carbonate-hosted deposits within the Canning and Bonaparte Basins was carried out mainly between 1970 and 1990. During this time a significant new province for Mississippi Valley-type lead–zinc–silver deposits has been defined, with important discoveries at Sorby Hills, Blendevale, Cadjebut and Admiral Bay.

The first discovery of base metals, however, was in 1901 when the Narlarla lead–zinc deposit was first pegged. Owing to its remote location, Narlarla was not worked until 1948, when Devonian Pty Ltd began mining. Between then and 1966, when mining ceased, about 11 000 t of ore was extracted from two orebodies. Meanwhile, in 1949, regional mapping by the BMR (Matheson and Guppy, 1949) located surface mineralization near Pillara Spring. Concerted exploration for this target type did not start until the late 1960s, however, with follow-up at Pillara Spring.

In August 1971, Aquitaine located the Sorby Hills 'Discovery Gossan' in the Burt Range Sub-basin of the Bonaparte Basin after the company had followed up reports of minor indications of lead and zinc both at the surface and in the Spirit Hill No. 1 well drilled by Oil Development NL/Westralian Oil Ltd. Between 1974 and 1977 a combination of detailed IP and aeromagnetic surveys and intensive RC and diamond drilling led to the delineation of thirteen pods of mineralization over an 8 km strike length.

In the Lennard Shelf in the early 1970s a number of companies recognized the potential of the reef complexes for MVT mineralization and began to use regional, helicopter-supported exploration to cover large areas. Trend and Amax took up extensive areas, defined by stream-sediment geochemistry and gossan search, including the Napier Range, the Oscar Range and the Pillara Range. Intensive exploration to percussion-drilling level in the Pillara, East Pillara and Pinnacles–Emanuel Range areas met with limited success. In the mid-1970s, Shell and then BHP became involved with both the Trend and Amax joint ventures. BHP, the principal operator, favoured the North American exploration approach of systematic grid drilling, which led to the location of high-grade mineralization in the Pillara area in 1978 and, following this, the delineation of the Blendevale deposit. Further grid drilling in the 1980s led to the discoveries of Cadjebut (BHP–Shell) in 1984 and Twelve Mile Bore (BHP–Cyprus) in 1985.

In the central Canning Basin lead sulfide mineralization was discovered in 1981, in the vicinity of the Admiral Bay Fault, during oil exploration by Meridian Oil. CRA took up large areas of mining tenements over the fault zone area and began deep drilling of selected targets in 1986 (Williams, this volume).

Deposits, prospects and occurrences

Lennard Shelf

Cadjebut

Operating mine: Zn; Pb
Location: 18°42'46"S, 125°57'49"E; 71 km southeast of Fitzroy Crossing

The Cadjebut deposit, situated at the southern end of the Emanuel Range (Figs 84 and 85), lies within the lower dolomite sequence of the Givetian part of the Pillara Limestone. It is just north of the west-northwesterly trending Cadjebut Fault, a splay of the regional Pinnacle fault, which has a 400 m downthrow to the south. The main ore-grade mineralization occurs in two stratiform lenses that extend 3 km along strike subparallel to the Cadjebut Fault, within the stratigraphically uniform, gently dipping sequence summarized in Figure 86. The stacked lenses are from 25 to 150 m wide and up to 6 m thick, separated by 6 m of low-grade mineralization. They dip at 5 to 10° to the south-southwest and contain 3.5 Mt of ore grading 17% Zn + Pb with a cutoff at 7% Zn + Pb.

The high-grade mineralization is contained in dolomitic siltstone units. There are two defined styles; in part rhythmically banded and colloform, but also occuring in breccia zones and cross-cutting veins (Murphy, 1990). Tompkins et al. (1994c) considered the rhythmically banded, zinc-rich ore (Fig. 87) to predate the cross-cutting, lead-rich, stratabound breccia ore, although both are considered to be part of a single mineralizing event. The banded ore occupies two horizons throughout the lower lens (lens 2) and in the northern portion of the upper lens (lens 1). The later lead-rich ore, and collapse breccias, associated with minor sinistral shearing along the Cadjebut Fault and other small-displacement reverse faults in the mine, is confined to the southern portion of lens 1.

Tompkins et al. (1994c) summarized the mineralogy of the banded ore as comprising: ' . . . 0.1 to 1 m-thick layers of repetitive 5 to 15 mm-thick bands of sphalerite, galena, Fe sulfide, and calcite. Three generations of sphalerite are developed symmetrically about a dark brown, hydrocarbon-bearing lamination of sucrose dolomite, detrital quartz, and feldspar. Galena is associated with the second generation colloform sphalerite, and marcasite occurs as a post-main ore mineral phase. Late stage blocky calcite fills open cavities.' The banded ore has a laterally equivalent halo of banded marcasite and barite with or without calcite (Fig. 87). Tompkins et al. (1994c) considered the rhythmically banded ore to be hosted by precursor evaporitic laminates with the banding reflecting original sedimentary textures. They suggested the conversion of gypsum to anhydrite, during platform burial in the late Devonian to mid-Carboniferous, resulted in volume loss and the creation of cavities which provided the passageway for zinc-rich, hydrocarbon-bearing

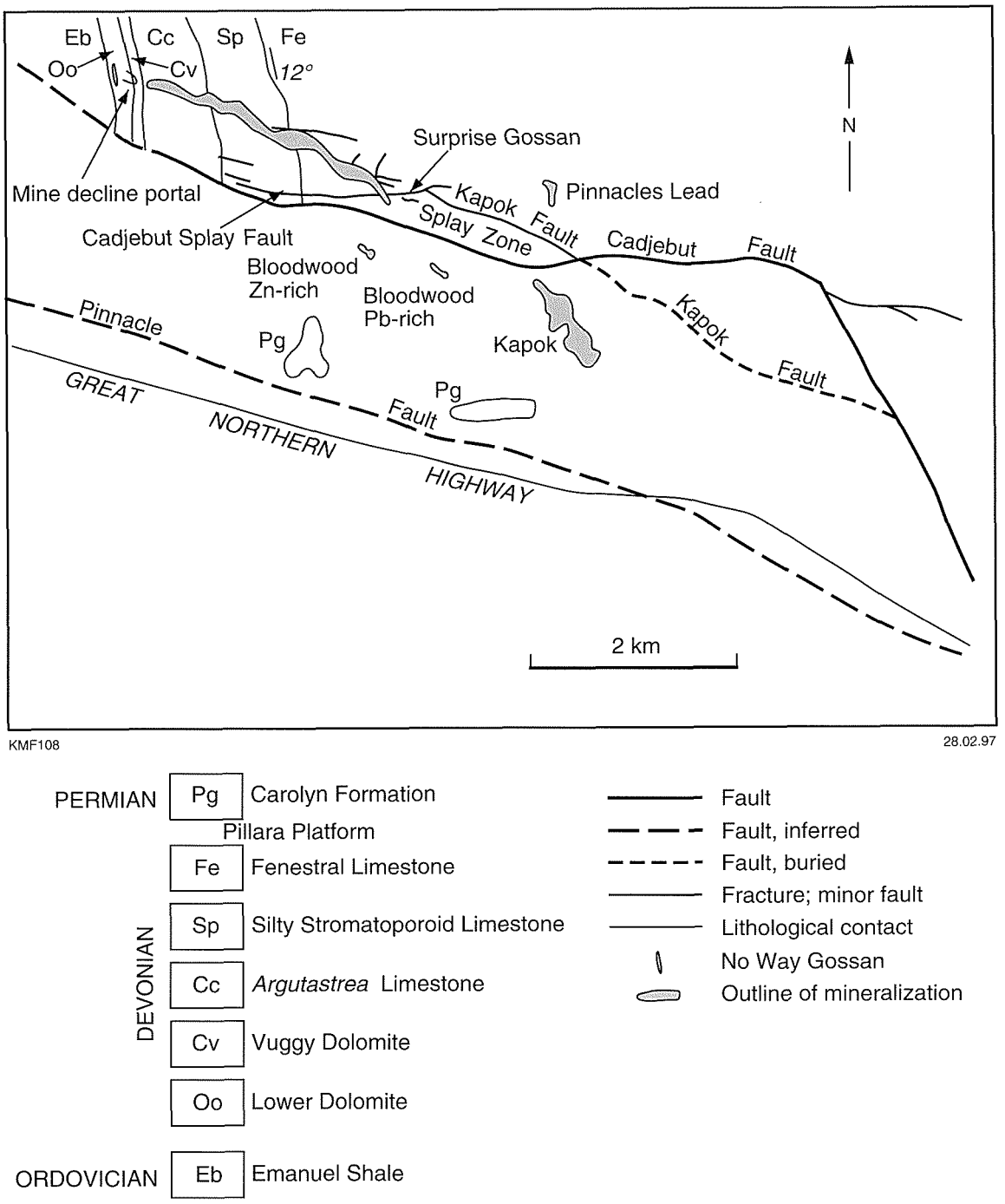


Figure 85. Principal geological features of the Cadjebut fault zone (*after* Tompkins et al., 1994b)

solutions. They further considered that the hydrocarbons, introduced with the ore fluids, acted as a catalyst for sulfate reduction and dissolution of the evaporites, leading to precipitation of base-metal sulfides and enlargement of cavities.

Wallace (1994) reported that cathodoluminescence cement stratigraphy indicates that burial dolomitization immediately preceded the main mineralization event and suggests that the increase in the volume of burial dolomite in the Cadjebut fault indicates that the fault acted as a conduit for basinal brines and that burial and mineralizing fluids moved north from the fault; this conclusion is also supported by the assymetric mineral zonation around the lenses. He also suggests that the geometry of the ore lenses and textural evidence indicate an association with a gas or liquid hydrocarbon phase during mineralization, and that the deposit was formed by metal-sulfide precipitation occurring within and around a series of hydrocarbon reservoirs trapped within an anticlinal structure. Kempton et al. (1994) also stressed the importance of hydrocarbon occurrence in localizing

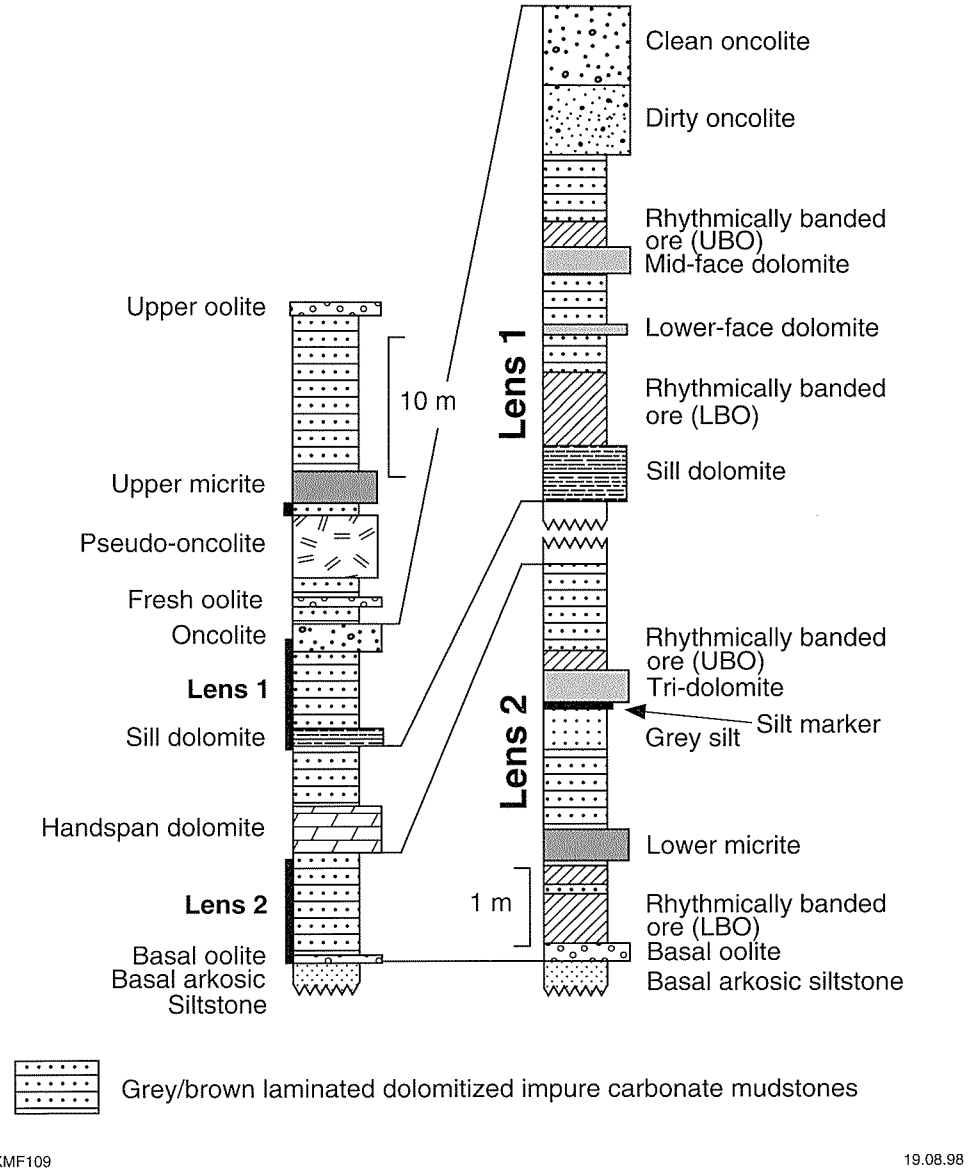


Figure 86. Stratigraphic column of the lower dolomite at Cadjebut (*after* Tompkins et al., 1994b)

mineralization, suggesting that banded ore textures may reflect the positions of hyrocarbon–brine contacts.

From carbonate and sulfide petrographic and geochemical evidence, Tompkins et al. (1994b) also recognized an earlier (Middle Devonian), weakly developed mineralizing event at Cadjebut. Finely crystalline sphalerite and marcasite laths are found in dolomite cements within the primary porosity of the evaporitic sequences. Detailed diagenetic studies (Pedone, 1990) indicate that this event preceded significant burial.

Cadjebut was discovered by BHP–Shell in 1984 and developed in 1987 as an underground mine. Production began in 1989 and was completed in 1997. Production in 1996–97 was 107 209 t of Zn concentrate at 61.9% Zn, and 25 615 t Pb concentrate at 76.83% Pb. In 1994, BHP sold its 58% stake in Cadjebut and its other Lennard Shelf exploration properties to Western Metals NL, now Western Metals Ltd.

References: Murphy (1990), Pedone (1990), Louthean (1992), Kempton et al. (1994), Tompkins et al. (1994b), Tompkins et al. (1994c), Wallace (1994), Minerals Gazette (March, 1995), Bester (1998).

Kapok

Deposit: Zn; Pb
Location: 18°44'03"S, 126°00'19"E; 75 km southeast of Fitzroy Crossing

This deep, 'blind' deposit, 4.5 km east of the Cadjebut mine, also within the Cadjebut Fault splay zone within the Pillara Limestone, was discovered in 1989 by BHP as a result of aeromagnetic interpretation. Diamond drilling has

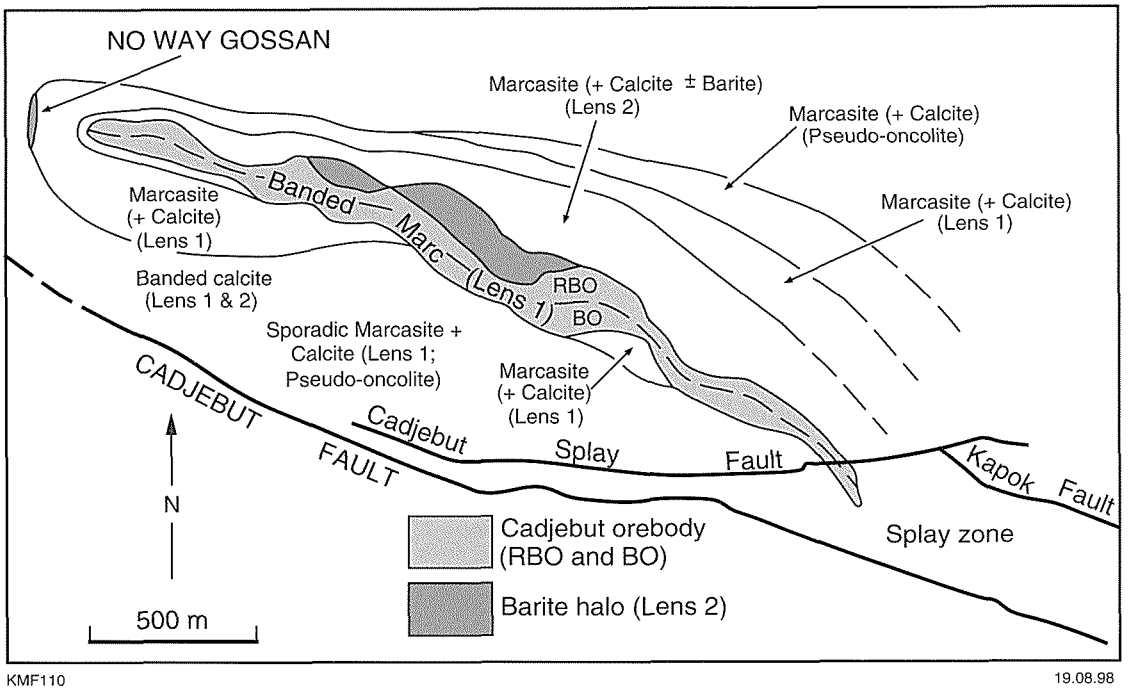


Figure 87. Detailed plan view of the Cadjebut area (*after* Tompkins et al., 1994b)

defined zinc and lead mineralization 350 m below the surface, dipping at 70° and related to a splay fault. Two smaller bodies lie within this splay zone; the Bloodwood zinc-rich and lead-rich bodies (Fig. 87).

Western Metals Ltd commenced mining the Kapok deposit in 1997.

References: Tompkins et al. (1994c), Minerals Gazette (Sept., 1994), Bester (1998).

Twelve Mile Bore–Goongewa (Prices Creek)

Deposit: Zn; Pb
Location: 18°37'50"S, 125°51'24"E; 65 km southeast of Fitzroy Crossing

This 'blind' deposit occurs from about 50 m below surface within Frasnian dolomitic platform and reef facies carbonates of the Pillara Limestone and lies against the southeast-striking Cadjebut Fault on its west side. On the east side of the fault lies the Ordovician Emmanuel Shale. The mineralization is made up of sphalerite, marcasite, galena and calcite within solution cavities in the dolomitic platform carbonates and forms subhorizontal, stratabound lenses or pods. Dolomitization, as ground preparation, predates the mineralization. Significant intersections include 17 m at 15.3% Zn, 1.4% Pb and 58 g/t Ag and 15 m at 11.1% Zn, 4.1% Pb and 61 g/t Ag.

The deposit was discovered by BHP–Cyprus in 1985 during wide-spaced grid drilling south of the Cadjebut Fault. By 1994, drilling had established an inferred resource of 3.5 Mt at 10% Zn and 2% Pb, and a demonstrated resource of 2.4 Mt at 10.1% Zn, 2.7% Pb and 38 g/t Ag. Mining of the Coongewa deposit, owned by Western Metals Ltd, began in 1995.

References: Murphy (1990), Minerals Gazette (Sept., 1994), Bester (1998).

Blendevale

Deposit: Zn; Pb
Location: 18°19'27"S, 125°46'20"E; 25 km southeast of Fitzroy Crossing

The Blendevale deposit is at the northern end of Limestone Billy Hills, within the Pillara Limestone of the Givetian–Frasnian platform facies, which dips to the north at between 5 and 8°. In this area the Pillara Limestone has been divided into a lower platform-bank facies and an upper reef-atoll facies, and has been affected by a series of northerly to north-northeasterly trending normal faults, being displaced by between 10 and 200 m and forming a series of horst–graben structures. The 'Blendevale graben' (Fig. 88) hosts the mineralization within the two defining faults, the Eastern and Western faults, which have breccia zones up to 30 m wide. The Western fault (100 m displacement) hosts the bulk of the mineralization over a strike length of 2 km and between 80 and 500 m below surface. A major splay off the northern end of the Western fault, the F10 fault, also hosts mineralization of up to 10 m width over 150 m of the fault, 350 m below the surface.

The mineralization is mainly sphalerite, galena and marcasite–pyrite rimming limestone clasts within solution-modified fault breccias (Bailey and Murphy, 1988). The various types of breccia are considered by Ringrose (1989) to have formed by a combination of tectonic, hydraulic

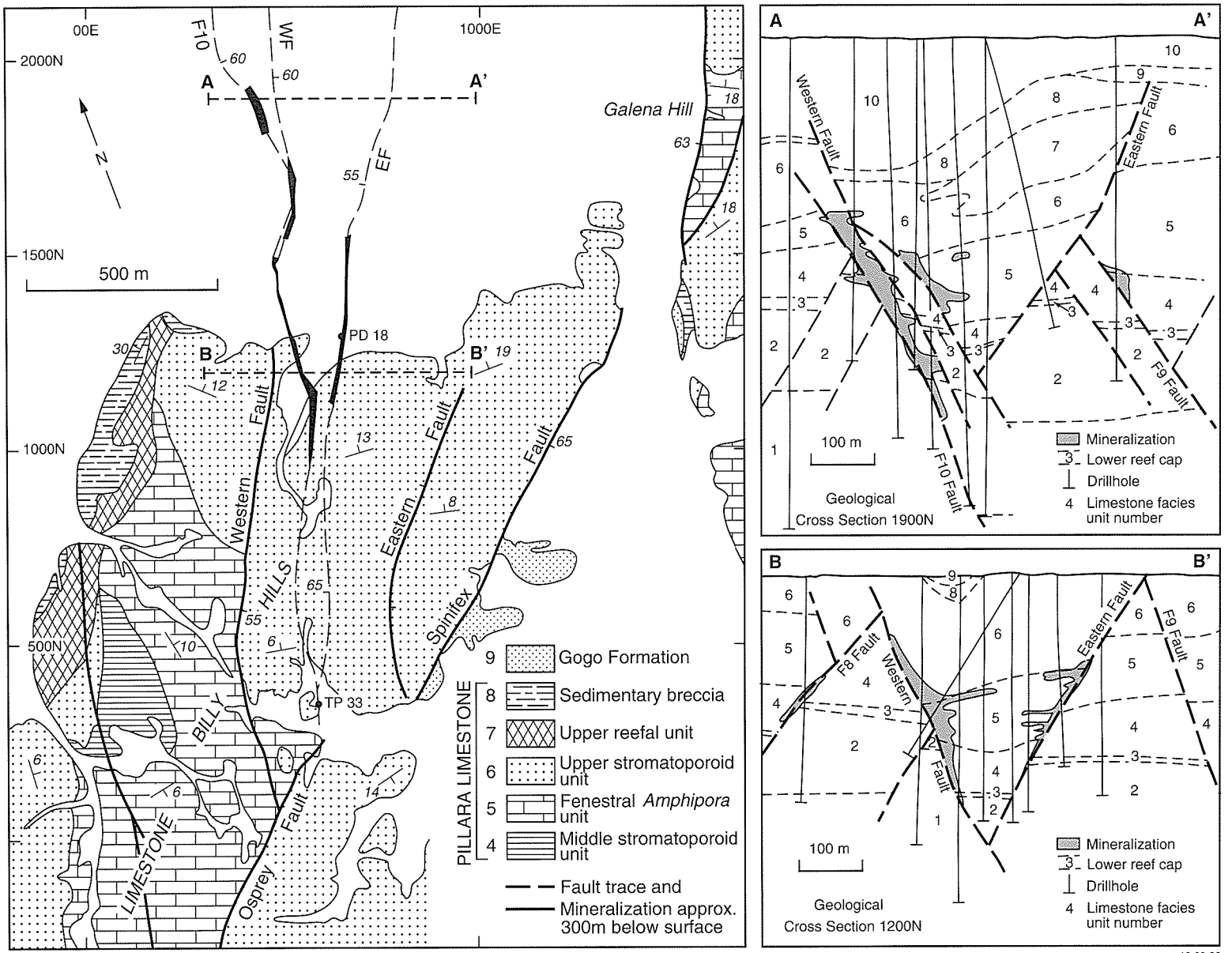


Figure 88. Blendevale: geological plan and cross sections (*after* Murphy, 1990)

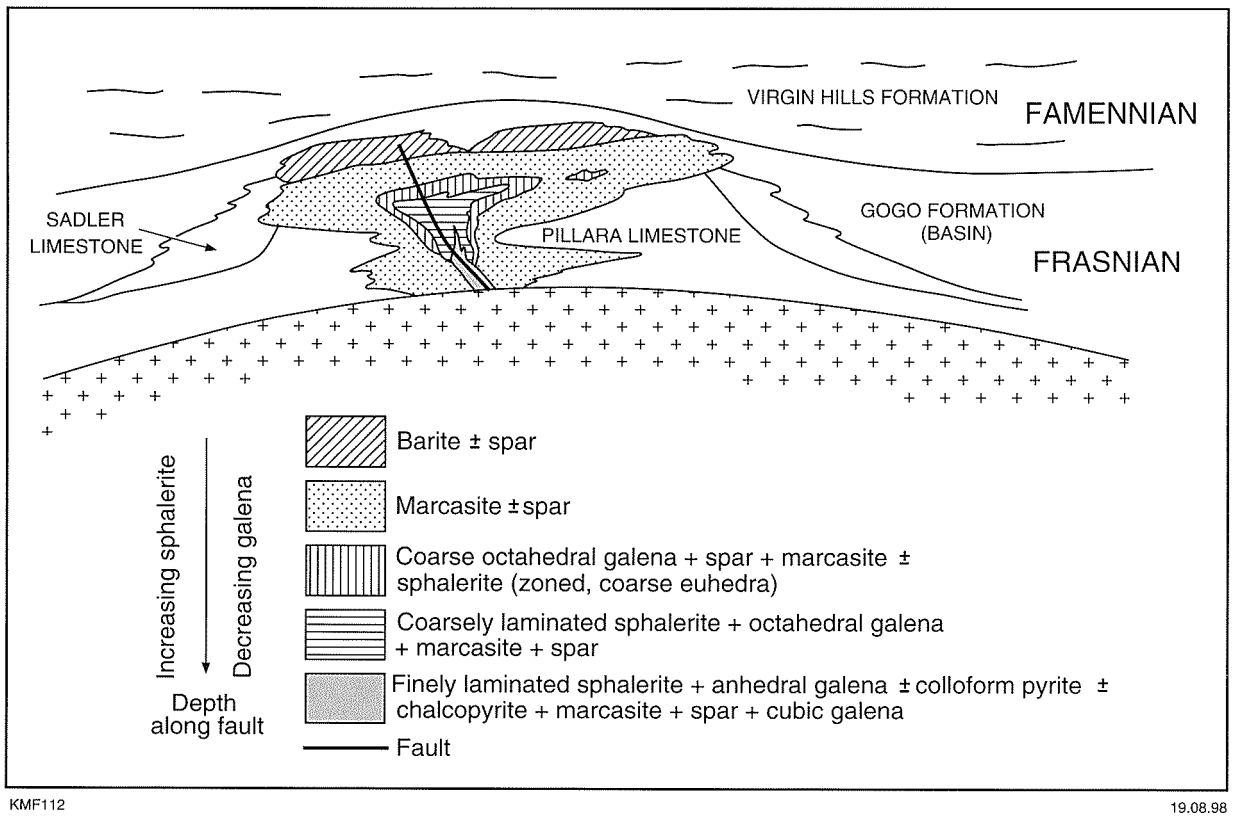


Figure 89. Sulfide-gangue mineral zonation in the Blendevale graben — schematic (*after* Ringrose, 1989)

and solution-collapse effects, related to the activity of mineralizing fluids ascending along the fault zones. Brecciated mineralized clasts within a later sphalerite–galena–calcite matrix cement indicate more than one pulse of mineralization. Ringrose (1989) recognizes a weak disseminated sphalerite mineralization, within the fenestrae of fenestral limestones, that appears to predate the fault breccia mineralization. This may equate with the pre-burial mineralizing event recognized by Tompkins et al. (1994a) at Cadjebut. A broad zoning of sulfide mineralization at Blendevale is indicated on Figure 89 (*after* Ringrose, 1989). The Zn:Pb ratio is approximately 3:1 throughout the mineralization with grades averaging 7% Zn and 2.2% Pb; however, along the F10 fault grades of 13.3% Zn and 4.3% Pb have been recorded.

The mineralization was discovered by BHP in 1978 by diamond drilling on 800 m grid spacing. Feasibility studies were nearing completion in 1997. The deposit contains a resource in situ of 19.5 Mt at 7.9% Zn and 2.4% Pb.

References: Louthean (1992), Murphy et al. (1986), Ringrose (1989), Bailey and Murphy (1988), Murphy (1990), Tompkins et al. (1994a).

Brooking Gorge (Discovery Gossan, Screaming Gossan, Black Gossan)

Prospect: Zn; Pb
Location: 18°02'10"S, 129°26'15"E; 20 km north-northwest of Fitzroy Crossing

This prospect lies at the southeastern end of the Oscar Range, where the platform facies of the Pillara Formation is flanked to the south by marginal-slope facies of the Sadler Limestone. Sphalerite and minor galena are hosted by breccia-bearing, northwesterly trending, solution-enlarged joints or faults within skeletal and oolitic grainstone of the Sadler Limestone and close to a contact with a platform-margin subfacies. These structures dip steeply to the northeast, extend to at least 170 m depth, and contain pyritic mosaic breccia as well as mineralization. Dolomitization is generally absent in this area. Surface samples have given up to 39.4% Zn and 0.7% Pb.

A number of companies have looked at this area since 1969. These include Serem (1969–70), Shell (1970–75), Trend (1971), Amax (1972), Trend (1973), Shell/BHP (1976) and BHP (1977–83). Early work was restricted mainly to geochemical sampling with limited percussion drilling. However, BHP carried out increased surface work including gravity profiling and resistivity depth sounding prior to percussion and diamond drilling. Best drill intersections include 3 m at 5.46% Zn and 0.55% Pb, and 5 m at 1.78% Zn and 0.88% Pb. The area was explored by Billiton (1987–1995) but was relinquished despite geological success with intersections up to 4 m at 4.3% Pb + Zn in four diamond holes at Screaming Gossan.

Reference: GSWA-WAMEX - I 2654, I 8151.

NARLARLA (Devonian, Barker Gorge)

Abandoned mine: Pb; Zn; Ag; Cu
Location: 17°15'40"S, 124°43'45"E; 125 km east of Derby

This deposit consists of two, rich, outcropping orebodies within marginal slope-facies sedimentary rocks of the Upper Devonian Napier Formation on the south side of Barker Gorge. These bodies are now mined out, but previously were expressed as low outcrops of gossan 490 m apart. Because of the early discovery of these deposits there have been numerous studies of their geology, mineralogy and petrology, including those of Woodward (1907), Finucane and Jones (1939), Prider (1941), Hutton (1965), Halligan (1965) and Gellatly (1970). Their work was summarized by Blockley (1971).

In 1983, GSWA dewatered the Narlarla No. 2 pit to allow detailed mapping and sampling. The results of this work are reported by Ringrose (1989) and the summary below is compiled largely from that work.

The dip of the Napier Formation in this area is 20–30° to the southwest and is largely depositional. The Barker River Gorge, to the north, coincides with the axis of an embayment in the marginal slope. Both deposits are made up of galena and sphalerite with minor iron sulfides and important secondary ore zones of cerussite, smithsonite and hydrozincite with lesser azurite, chamosite and malachite. The mineralization also contains silver and minor cadmium, antimony and copper.

The No. 1 deposit is within chloritic rock and feldspathic and siliceous dolomite with fissile features related to a 105°-trending fault which partially controls the mineralization. The main trench workings and a pit are coincident with the fault and measure 30 by 11 by 2.1 m.

The No. 2 deposit is enclosed in typical Napier Formation reddish dolomitic packstone and grainstone, with intercalated argillaceous to rudaceous siliciclastic and carbonate breccia. Immediately surrounding the ore these rocks are highly chloritized. The breccia appears to represent a prominent debris flow, on the marginal slope, which has been colonized by stromatolites. Bedding in the pit strikes at 310° and dips between 15 and 40° to the west, most steeply in the ore zone. The mineralization now forms pods and irregular masses in the lensoid breccia. It is partly discordant and fault controlled and forms replacement, disseminated, vein and open-space fill. The main fault in the pit, with associated ore pods, strikes at 110°. The lens-shaped ore remnants within the pit are part of an original secondary ore cap over the primary body. The surviving primary ore contains up to 90% of ore minerals The skeletal–botryoidal, 'colloform' ore textures are typical of low-temperature formation, with rapid precipitation in regions of high porosity.

The sequence of post-depositional events relating to mineralization have been outlined by Ringrose (1989). They are:

(a) Early diagenetic lithification of marginal slope detritus by calcium carbonate precipitation,
(b) Compaction, stylolitization and dolomitization related to regional migration of compaction fluids,
(c) Chloritization, following dolomitization, with some overlap; fault controlled,
(d) Mineralization; ore-bearing solutions localized by east-southeasterly trending faults and zones of high porosity. Some mixing of fluids to give rapid and repeated sulfide precipitation and chloritization, wall-rock dissolution and collapse. Further chloritization in the waning phase, and
(e) Oxidation of the primary ore by meteoric fluids.

The deposit was found in 1901 and worked between 1948 and 1966, during which period 2115.37 t of lead, 2866.87 t of zinc and 1162.4 kg of silver were produced from shafts and opencuts. Prior to mining, Finucane and Jones (1939) estimated the reserves to be 1148 t at 38.67% Pb, 177.6 g/t Ag and 0.58% Cu in the No. 1 body, and 11580 t at 35.5% Pb, 21.1% Zn, 0.65% Cu and 174 g/t Ag. They estimated grades of 31% Pb, 17% Zn, 0.6% Cu and 124 g/t Ag in the oxidized zone. A representative sample of primary ore taken from the stockpile in 1964 gave 23.2% Pb, 30.9% Zn, 0.48% Cd, 0.1% Sb and 162 g/t Ag. Shell (1972–83) tested possible stratabound extensions downdip and along strike through mapping and drilling but without success. Great Australian Resources (1981–85) considered the data on Narlarla and agreed with Gellatly (1970) that Narlarla was syngenetic, presumably having some similarity with Irish-type deposits. Fire Hills Gold (1985 on) presently hold the ground and have conducted grab sampling. They planned, in 1989, to process stockpiled Zn ore.

References: Woodward (1907), Finucane and Jones (1939), Prider (1941), Hutton (1965), Halligan (1965), Gellatly (1970), Blockley (1971), Marston (1979), Louthean (1992), Ringrose (1989), Playford (1980), Murphy (1990), GSWA-WAMEX - I 2653, I 2776.

CHEDDA CLIFFS

Prospect: Pb; Zn; Cu; Ag
Location: 17°13'S, 124°37'E; 12 km west-northwest of Narlarla

At this prospect a 20 by 30 m gossan, the surface expression of a small, steeply dipping tabular orebody, lies near a contact of massive forereef limestone and calcarenites of the upper part of the Famennian Napier Range Formation. The gossan, which features limonite, cerussite, hydrozincite and malachite, contains up to 31% Pb, 11% Zn, 1% Cu and 100 g/t Ag and anomalous iron, cobalt and cadmium in outcrop, and extends to a depth of 15 m. In the primary mineralization galena, marcasite, pyrite, sphalerite and chalcopyrite are present as irregular masses and disseminations in a matrix of black organic mud filling caves and caverns in a palaeokarst horizon. These extend to at least 30 m below the outcrop. Fletcher (1980) describes the mineralization as being at the intersection of weakly mineralized faults.

CEC/Mimets/Placer (1972–78) carried out surface geochemistry at the prospect (obtaining the above results)

and found an association with silver, cobalt, cadmium and mercury. Soil and stream-sediment sampling indicated a broad halo of mineralization. A total of 13 percussion holes was drilled to test the gossan. High-grade mineralization was encountered in three holes with best intersections of 10 m at 8.6% Pb and 1.2% Zn, and 10 m of 4.6% Pb and 4.0% Zn in calcarenite within an envelope of clayey, blue-black mudstone. These results have been followed up by the Billiton/BHP Napier Range Joint Venture (1978 on).

References: Fletcher (1980), GSWA-WAMEX - I 786.

Wagon Pass

Deposit: Pb; Zn
Location: 17°11'S, 124°37'59"E; 88 km east of Derby

The Wagon Pass deposit, some 12 km northwest of and along strike from Narlarla, is hosted by the forereef limestone of the Famennian Napier Formation which conformably overlies the cobbly, dolomitic Van Emmerick Conglomerate. The host unit consists of red algal wackestones and terrigenous stylobedded, fossiliferous, silty, commonly dolomitized packstones conformably overlain by the Nullara Limestone, an undolomitized reefal assemblage. The mineralization (>1% Pb + Zn) forms a simple tabular, stratabound lens in lower Napier Formation vuggy dolomite, extends 300 m north-northwest along strike, is 30–80 m wide and between 3 and 36 m thick. Wagon Pass is a blind deposit that lies at a depth of about 250 m and consists of complex granular and colloform intergrowths and semi-massive assemblages of sphalerite and galena with lesser pyrite, marcasite, chalcopyrite, bornite, digenite, covellite and bravoite. The mineralization is associated, in the hangingwall, with fine, green chloritic clay, and chlorite alteration is commonly characterized by Pb + Zn exceeding 0.1%.

Dolomitization and chloritization predated the mineralization and were controlled by host-rock permeability during relatively deep burial. Mineralization was the result of the influx of basin-derived compaction fluids with sulfides precipitating where fluids, flowing through open spaces, intersected a source of reduced sulfur, possibly related to sulfate in dolomitizing fluids or the activity of bacteria in meteoric water. The competency of the host is therefore an important factor with brittle fracturing allowing fluid ingress.

The deposit was discovered in 1980 by the Shell (Billiton)/BHP joint venture, which has been exploring the Napier Range since 1978 seeking possible extensions of the Narlarla mineralization. Initial geological mapping, rock-chip sampling and limited drilling outlined target areas. Airborne magnetics and further drilling led to the discovery intersection in NRD 23 which gave 29.8 m at 16.8% Pb + Zn. Copper and silver are also associated, and cadmium, arsenic, antimony and mercury have been established as pathfinder elements. An inferred resource of 500 000 t at 6.3% Zn and 7.7% Pb has been established.

References: Louthean (1992), Murphy (1990), Buchhorn (1986), Ringrose (1989), Playford (1980).

Canning Basin (Central)

Admiral Bay lead–zinc–silver deposit

Contribution by V. A. Williams[1]

Admiral Bay, a deeply concealed carbonate-hosted zinc–lead–silver deposit some 140 km south of Broome in the Canning Basin, bears some similarities to the Lennard Shelf deposits but is hosted in Ordovician strata on a separate structure, the Admiral Bay Fault Zone. A significant feature of the deposit is its considerable depth of 1280 to 1600 m below surface.

The deposit is located at latitude 19°14'S and longitude 122°17'E and is approached via the McLarty Track and other access roads constructed for petroleum exploration since the 1960s.

Exploration history

Lead sulfide mineralization was first identified on the Admiral Bay Fault Zone in 1981 when Meridian Oil NL drilled petroleum well Great Sandy No. 1 (Norlin, 1984). Subsequent petroleum wells also intersected lead and zinc sulfides leading CRAE to apply for exploration licences over the area in 1986. Twenty-four deep drillholes totalling 37 472 m have been completed together with regional and local geophysical surveys along the Admiral Bay Fault Zone. The deposit remains under CRAE titles.

Admiral Bay

The main zinc-dominated part of the Admiral Bay deposit is stratabound and appears from available evidence to have a ribbon-like geometry, following the intersection between the upper Nita Formation and one of the major branches of the Admiral Bay Fault. The better mineralization is known over 16 km of strike, appears to be some 200 to 400 m wide, and is set within a halo of thinner and/or less mineralized lenses that extend hundreds of metres laterally and vertically from it. A second mineralized zone in a small area at the base of the Nita Formation is dominated by lead.

Drill testing of the deposit is far from complete and drill density is low. However it has been possible to estimate an initial inferred resource as follows (CRA report to shareholders, 1990):

	Upper Zone	*Lower Zone*
Intersections	10	3
Tonnes (million)	120	20
Lead (%)	2.3	16.9
Zinc (%)	6.4	0.4
Silver (g/t)	32	57

[1] Principal Geologist CRA Exploration Pty Limited

Previous descriptions

A description of the Admiral Bay Deposit is given by Connor (1990). Geology of the deposit area is described from the petroleum exploration perspective by Conolly et al. (1984) and Norlin (1984).

The Admiral Bay Fault Zone

The Admiral Bay Fault Zone is one of several northwesterly-striking faults that divide the Canning Basin into a series of uplifted areas and intervening sub-basins. The zone separates the Broome Arch (north) from the Willara Sub-Basin (south). The fault zone is known over two hundred kilometres of onshore extent from petroleum and CRAE seismic data. Two broad structural domains are recognized (Fig. 90).

- A western zone comprising multiple subparallel faults.
- An eastern zone dominated by a single large fault.

The boundary between these domains is marked by a poorly defined jog or transfer structure oblique to the main fault trend in the Great Sandy No. 1 area. The Admiral Bay deposit coincides with a major west-northwesterly striking fault on the western flank of that structure.

Local geology

The major fault that coincides with the Admiral Bay mineralization appears from seismic interpretation to be an upward-branching flower structure (Fig. 91). Uplifted fault blocks within the structure give rise to an antiformal feature that at the broad level of the Nita Formation hosts the best-known mineralized zones. Knowledge of geology around the deposit is based on deep drillholes comprising rotary non-cored intervals from surface to the lower Carribuddy Group and diamond drillcore below that to the upper Goldwyer Formation. Units in the core-drilled interval are described below.

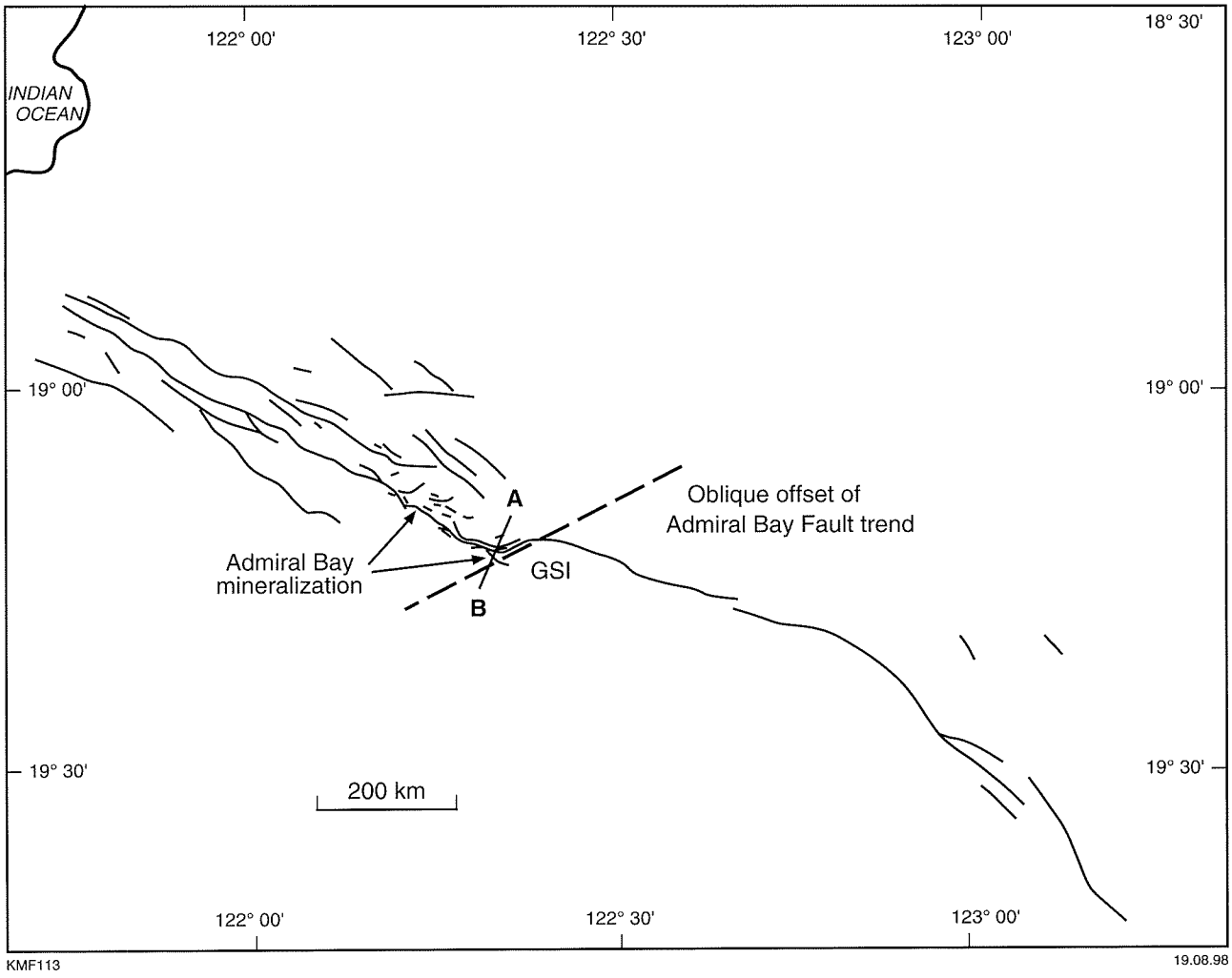


Figure 90. Admiral Bay Fault Zone traces at top of the Nita Formation (*modified from* a compilation of CRAE and petroleum seismic data *by* R. H. Castleden. GS1 = Petroleum Well Great Sandy 1)

Goldwyer Formation

The Middle Ordovician Goldwyer Formation overlies limestones and shales of the Willara Formation, which in turn overlies a fining-upward conglomerate–sandstone–shale sequence of the Nambeet Formation. As seen in seismic sections (Fig. 91) the Goldwyer Formation and earlier Canning Basin units appear to thicken abruptly across the mineralized fault. Where preserved, bedding dips between subhorizontal and 45° in the reef facies, whereas subhorizontal bedding alone typifies the rest of the Admiral Bay sequence.

In the wider deposit area, the Goldwyer Formation typically comprises highly fissile grey to dark-green shale with bioclastic interbeds; however, a substantially different facies exists in the mineralized fault zone and shows a close spatial coincidence with the best mineralization in the Nita Formation. This variation of the Goldwyer Formation is heavily overprinted by various alteration assemblages, but stromatolites, oncolites and spar-balls are preserved in places. These, together with paucity of shale, suggest that this facies variant originated as an algal bioherm or reef. A similar conclusion was reached by the petroleum explorers (Connolly et al., 1984).

Alteration assemblages in the Goldwyer Formation reef facies include barite–carbonate as massive veins and as pervasive replacements of the host rocks, siderite, iron oxides including magnetite, silica, and bituminous material. Massive galena and/or chalcopyrite aggregates up to one metre across have been intersected in the barite–carbonate veins.

The dominant shaly facies of the Goldwyer Formation is far less altered. It comprises finely fissile soft shale beds ranging from 5cm to several metres thick with minor bioclastic beds a few centimetres to a few metres thick. The shales contain abundant fossils in places. These include graptolites, trilobite fragments, nautiloid cephalopods, and rare conularid tests. The bioclastic beds are dominated by hydraulically sorted smooth or crenulate brachiopod shells and bryozoan fragments. A biozonation pattern has been identified whereby bryozoans dominate the bioclastic beds on the northern flank of the reef facies but are virtually absent on the southern side where brachiopod fossils dominate the assemblage. This relationship has potential to provide a guide to ore as the reef facies appears to be parallel to the best grades in the overlying Nita Formation.

Nita Formation

The Middle Ordovician Nita Formation overlies the Goldwyer Formation, with which it shows a gradational conformable contact. Known thicknesses of the Nita Formation range from 46 to 120 m but do not change abruptly across the Admiral Bay Fault Zone. A sag phase of basin deposition is inferred for this formation as opposed to the active-fault phase evident in underlying units.

Upper and lower members of the Nita Formation are recognized in drillcore. The lower Nita Formation is dominated by impure limestone to dolomite with worm burrows and irregular sparry carbonate-filled vugs. Minor shale laminae occur in sets throughout the lower Nita Formation. They are regarded as depositional cycles and number up to thirty in places, although as few as ten cycles are present over the Goldwyer Formation reef facies. Thicknesses of the lower Nita Formation also vary over the Goldwyer Formation reef position from 27 m above the contact to 81 m in flanking positions. These variations suggest that the reef formed a mound during early Nita Formation deposition. Post-depositional features include stylolites of varying intensity, coarsely recrystallized dolomite with induced porosity, partial replacement by barite, and locally abundant barite–carbonate veins.

The upper Nita Formation is more heterogeneous than the lower member and contains a range of facies including massive competent carbonate mudstone, shell-hash packstone–wackestone, shaly mudstone, laminated carbonate siltstone, minor shale, and oolitic grainstone lenses. Stylolites and varying amounts of dolomite characterize the upper Nita Formation and the largely replacive lead–zinc mineralization is best developed here. Shale-rich units of the upper Nita Formation commonly contain coarse barite with a bladed habit, possibly indicating pseudomorphous replacement of gypsum.

The upper Nita Formation is typically 20 m thick but ranges from 10 to 25 m without showing systematic thickness variation over the Goldwyer Formation reef-facies position. The lower boundary of the upper Nita Formation is marked by the base of a distinctive, laminated carbonate siltstone one metre or so thick that is recorded in all drillholes and forms the best stratigraphic marker identified to date. In the prospect area the upper boundary of the Nita Formation is gradational with shales of the overlying Carribuddy Group, although local silicification typical of weathering has been noted at the top of the unit in two holes.

Lower Carribuddy Group

Apart from limestone lenses resembling those in the Nita Formation at its base, the lower Carribuddy Group consists of irregularly interbedded red to green mudstone and soft calcareous to dolomitic siltstone. Where thinly interbanded, these rocks show disturbed features such as breccia texture or discontinuous lenticular outlines typical of carbonate–mud sequences. Minor anhydrite lenses have been identified in this assemblage (McCracken, S., 1994, pers. comm.) and minor thin lenses of coal occur in places a short distance above the Nita Formation. Minor siliciclastic sandstone layers are present 100 to 200 m above the Nita Formation. A common mineral in the lower Carribuddy Group is pink barite, which occurs either as disseminated 1 mm spots or as narrow veins.

This part of the Carribuddy Group passes upward into a thick, reactive red shale interval. The major evaporites of the Carribuddy Group are largely absent over the Admiral Bay Fault Zone but appear, from seismic sections, to exist a few kilometres north and south of the fault (Fig. 91). The Carribuddy Group is overlain unconformably by the Permian Grant Group, which in turn is unconformably overlain by Mesozoic sedimentary rocks.

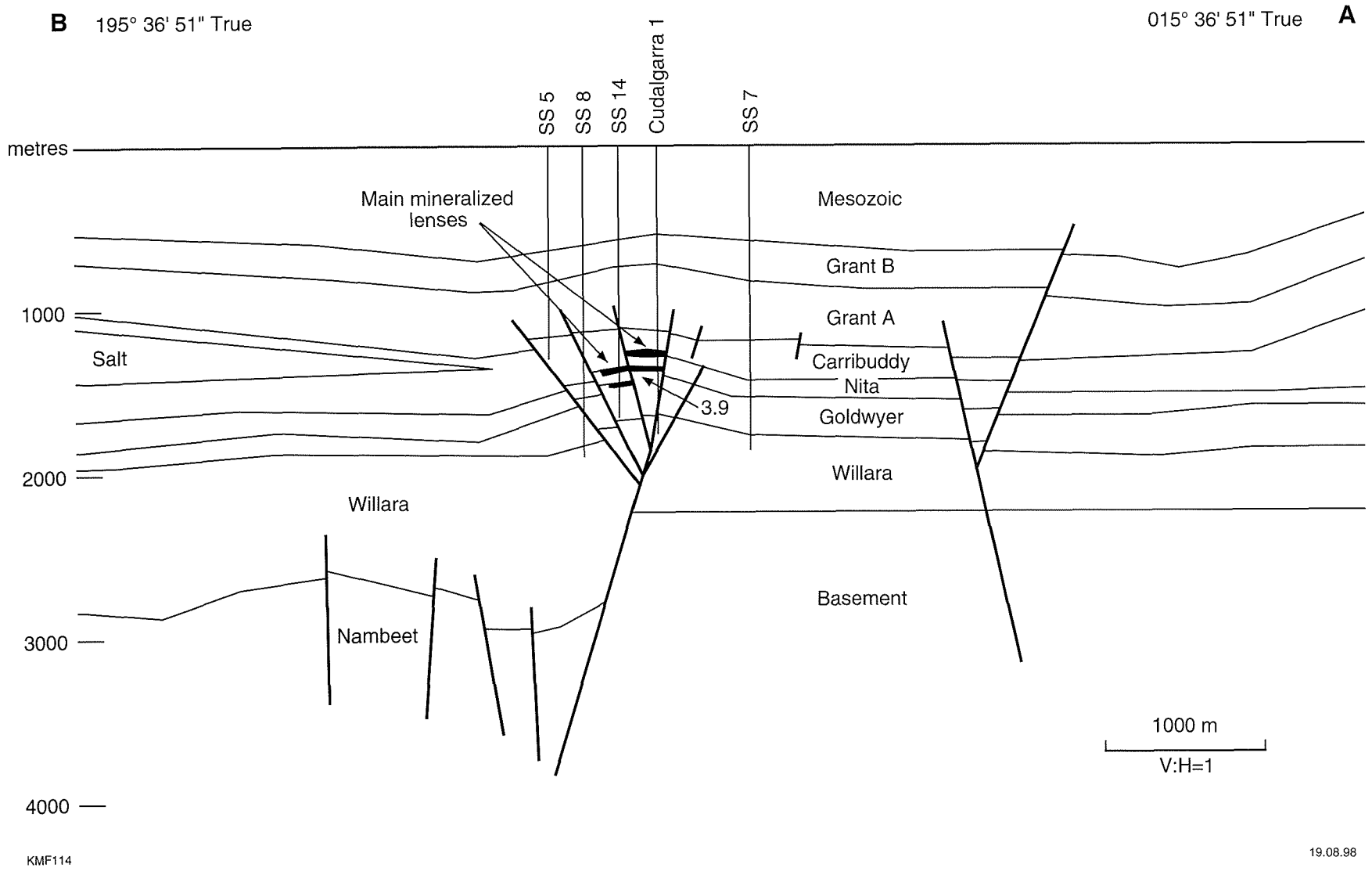


Figure 91. Admiral Bay deposit, geological section AB from Figure 90 (*based on* interpretation of CRAE seismic line Q88-109 *by* R. H. Castleden)

Mineralization

A large-scale vertical metal zonation affects both the low-grade mineralized envelope and the main mineralized lenses. A lower copper-dominated zone in the Goldwyer Formation passes upward into a lead-dominated zone that broadly corresponds to the upper Goldwyer–lower Nita interval. Zinc dominates the interval between the upper Nita Formation and the Carribuddy Group. Lateral metal-zonation patterns have not been identified to date.

The lower copper zone, which does not appear to be economically significant, is marked by isolated chalcopyrite aggregates in barite–carbonate veins. Massive chalcopyrite aggregates up to one metre across have been intersected in places. Less-common galena and pyrite 'blows' are also found but they are separate from the chalcopyrite occurrences and from each other.

The lead-dominated zone is best represented in massive layer-parallel bands of galena–barite at the contact between the Goldwyer reef facies and the Nita Formation in a small area around petroleum well Cudalgarra No. 1 (Fig. 92). Drill intercepts up to 15 m at 17% Pb and 63 g/t Ag have been achieved. This style of mineralization is associated with leached porous ground in the overlying Nita Formation, and in one case a barite-filled cavity exists above the leached ground. This is reminiscent of the widely documented Viburnum Trend solution-collapse breccia structures (e.g. Mouat and Clendenin, 1977). Outside the high-grade lead occurrences, the zone is represented by widely disseminated fine galena grains that give rise to weakly elevated lead contents typically in the range 100 to 5000 ppm.

The upper zinc-dominated zone is more widespread than the copper and lead zones. This zone is concentrated in the top few metres of the upper Nita Formation and all holes drilled in the region have at least a few grains of disseminated sphalerite in this interval, even in otherwise barren localities. Within a few hundred metres of the Admiral Bay Fault, multiple lenses of low-grade zinc mineralization in the upper Nita Formation and lower Carribuddy Group are spread over vertical thicknesses of up to 150 m where the Goldwyer Formation reef facies is present some distance below. The best grades in the top few metres of the upper Nita Formation are also recorded in this position.

Pale-yellow sphalerite dominates the assemblage and forms fine disseminated grains and aggregates that replace the host limestone and dolomite, showing no particular association with either. At hand-specimen scale, two sites of sphalerite concentration predominate:

- replacement of very fine carbonate mudstone in rims around former voids, which are commonly infilled by barite–saddle dolomite–galena assemblages or fluorite–galena assemblages. The voids are typically irregular in shape, a few centimetres across, and have a crude alignment with bedding. They are interpreted to represent some form of solution-induced porosity.
- replacement of matrix in organic–inorganic packstone to wackestone; and worm-burrow fills.

Although barite–carbonate veins with minor galena and rare sphalerite do occur in this zone, they are far less abundant than in the lower lead and copper zones.

Liquid hydrocarbons or bituminous residue occur in isolated places in the Nita Formation and Carribuddy Group. They are a very minor constituent of the rock volume and are held in isolated voids with very low porosity and permeability. The hydrocarbons tend to be associated with the sphalerite mineralization but only a few sphalerite concentrations contain them. In one case, a sandstone of the Carribuddy Group preserves a relict oil–water interface with sphalerite and minor galena concentrated immediately below the oil zone.

Age constraints on the mineralizing event (or events) are poor. Apparent absence of mineralization in the Grant Group is taken to indicate pre-Permian emplacement.

Ore genesis

Present thinking on genesis of carbonate-hosted lead–zinc deposits revolves around:

- a conduit for metalliferous brines such as a fault or a regional aquifer (Eisenlohr et al., 1994; Muhling, 1994);
- a restricting structure to concentrate fluid movement into a confined volume of host rock (Anderson, 1991; Clendenin, 1993);
- some models attach importance to the presence of sulfate-bearing evaporites or sulfate-bearing fluids as a sulfur source (Kaiser et al., 1987);
- some models invoke the presence of hydrocarbons as a reductant (Leventhal, 1990; Anderson, 1991; Henry et al., 1992);
- some workers note the common presence of a shale cap to the mineralized system.

All these features have counterparts in the Admiral Bay setting. At a regional scale, the Admiral Bay Fault provides a conduit and focusing site for fluid movement. This was possibly enhanced by dilational movement around the oblique offset of the main fault trend in the Great Sandy No. 1 area. Sulfate-bearing evaporites are still present in the sequence and the former presence of gypsum is inferred from the bladed habit of some barite grains. Hydrocarbons and their bituminous residues are also present. The shale-dominated lower Carribuddy Group provides a possible cap sequence.

The role of the reef facies some distance below the main Admiral Bay mineralization appears to have greater importance than for other examples of carbonate-hosted deposits. Although reef-facies associations are common they apply at a much broader scale than those seen at Admiral Bay. In the case of the Viburnum Trend (Larsen, 1977), a digitate stromatolite reef facies underlies the ore zones but covers a much larger area than do the orebodies. The Lennard Shelf deposits (Murphy, 1990) lie in a Devonian reef-dominated sequence but, again, the reef structures are regional in extent and the ore deposits are not confined to them.

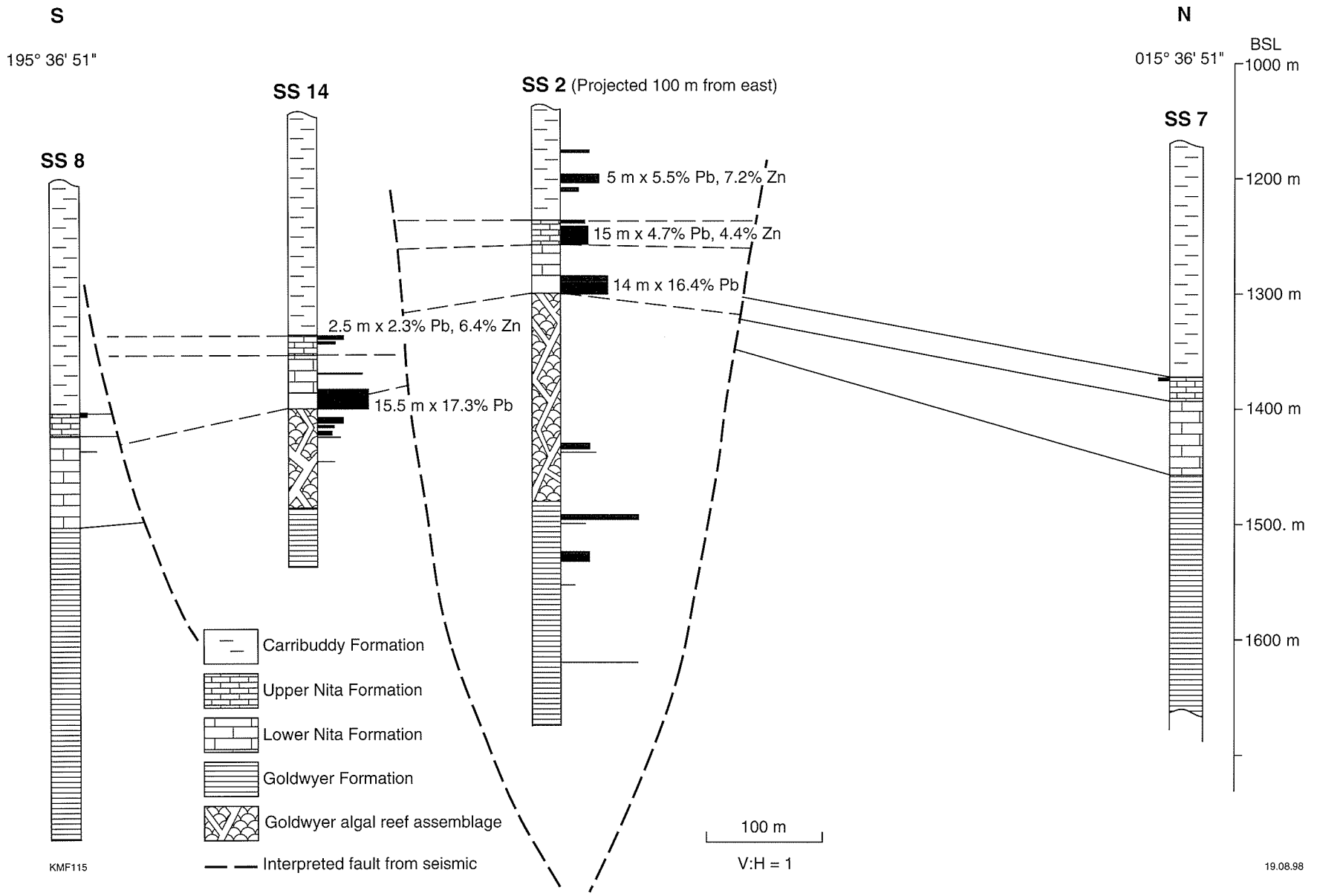


Figure 92. Drill profile along section AB, Admiral Bay, showing mineralized intercepts and rock-facies distribution (*based on* a compilation of CRAE)

By contrast, the Goldwyer Formation reef facies is small, with horizontal dimensions that closely match those of the best mineralized zones and lying a short distance below them. The reef facies does not persist along the full length of the fault, and drillholes that intersect the fault in the absence of the reef facies have only modest grade mineralization in the Nita Formation. The reef can therefore be viewed as a subset of the fault zone that shows the closest spatial coincidence with the best mineralization.

A possible explanation for the importance of the reef position lies in the competence of the reef rocks relative to that of the Goldwyer Formation shale facies. A common experience during drilling operations is that the shale facies collapses within a few days of drilling. If this condition also existed during fault movement then these rocks would not sustain any fault-induced opening for long. Fluid movement through this sequence would therefore be retarded. The Goldwyer Formation reef facies, on the other hand, is composed of more-competent lithologies and may have had a greater propensity to sustain dilational fault openings over much longer periods. Presence of the reef facies may therefore have provided a focusing mechanism that preferentially introduced metalliferous fluids into the sequence around it.

Acknowledgements

Knowledge of Admiral Bay geology is the product of study by a number of geologists involved with the project. A. G. Connor, C. M. Lennox, R. H. Ingebritsen, R. H. Castleden and S. McCracken in particular contributed observations and ideas which influenced this paper. CRA Exploration Pty Ltd approved publication of this contribution.

Barbwire

Prospect: Pb; Zn
Location: 19°30'S, 125°E; 150 km south-southwest of Fitzroy Crossing

The Barbwire Terrace lies on the northeastern side of the Broome Arch about 250 km east of the Admiral Bay prospect and about 150 km southwest of the Lennard Shelf. The terrace occupies a structural high bounded by the major Dummer Range and Fenton Fault systems. The position of the terrace creates potential for carbonate-hosted mineralization in shelf-facies Devonian carbonates between 100 and 500 m below the surface. Southwest of the Dummer Range Fault, on the Crossland Platform, Middle to Upper Devonian strata are absent owing to Middle Carboniferous erosion, but the carbonate-bearing Ordovician Nita and Goldwyer Formations have been intersected in stratigraphic wells.

Shell (1981–83) sampled old petroleum exploration wells drilled by Wapet and obtained significant zinc but lesser lead values. Anomalous lead, zinc and copper in cuttings from Crossland No. 1 gave non-coincident highs of 2.4% Pb, 1.78% Zn and 0.2% Cu (sample intervals are not given). Based on this result more-prospective ground was considered to lie outside the tenement. Follow-up work by BHP from 1985 to 1986 and between 1988 and 1991 included gravity surveys and the drilling of seven holes. Old WMC holes were also fillet sampled to give a best intersection of 1 m at 0.25% Zn in Pillara Limestone. The sampling also suggested that some of Shell's anomalous assays were the result of contamination. CRA (1987–90) covered tenements complementary to those of BHP and concentrated on the potential of the Devonian sedimentary rocks. Aeromagnetic, gravity and seismic surveys were undertaken to further elucidate the geology, and two unsuccessful holes were drilled. This led to the recognition of intermittent fault activity in the Devonian that provided access to mineralizing fluids, and of one prospective structure (associated with anomalous lead and zinc in the WMC hole Abutilon 1, at depths between 625 and 748 m). Owing to depth considerations, the area was given low priority and relinquished.

Exploration was carried out by Pasminco in the early 1990s, targeting both Ordovician and Devonian carbonates. The company considered the Barbwire and Jurgurra Terraces to be southern counterparts of the Lennard Shelf. Only weak zinc and lead mineralization was located (≤4 m at 0.12% Zn).

References: GSWA-WAMEX - I 2079, I 2723, I 4654, I 4739, I 6869, I 7627, I 9423.

Bonaparte Basin

The 5 km-thick Cambrian to Permian sequence in the Bonaparte Basin is dominated by Late Devonian to Early Carboniferous marine sedimentary rocks laid down in an extensional environment which reflects the latter part of the development of a rift basin bounded by Precambrian basement to the east and west. Figure 93 shows the distribution of the broad stratigraphic elements. In the south and east, faulting extending from the Halls Creek Orogen controlled the detailed development of the basin. The Precambrian Pincombe Inlier was an emergent palaeohigh during Late Devonian to Early Carboniferous sedimentation and separates the Burt Range Sub-basin in the east from the Carlton Sub-basin in the west. Figure 94 summarizes the stratigraphy in the Burt Range Sub-basin within which the Burt Range Formation, made up of dolomitized limestone and clastic units, represents a continuation of marine deposition which began in the Late Devonian. The succession was divided by Rowley and Lee (1986) into five lithological units, with a total thickness of 300 m.

Sorby Hills

Deposit: Pb; Zn; Ag; Ba
Location: 15°26'15"S, 128°58'30"E; 55 km northeast of Kununurra

The stratabound lead–zinc sulfide mineralization at Sorby Hills occurs in the eastern Bonaparte Basin in alternating dolomitic and clastic units of the Early Carboniferous Burt Range Formation, developed on the east flank of the Proterozoic Pincombe Inlier. Most mineralization is hosted

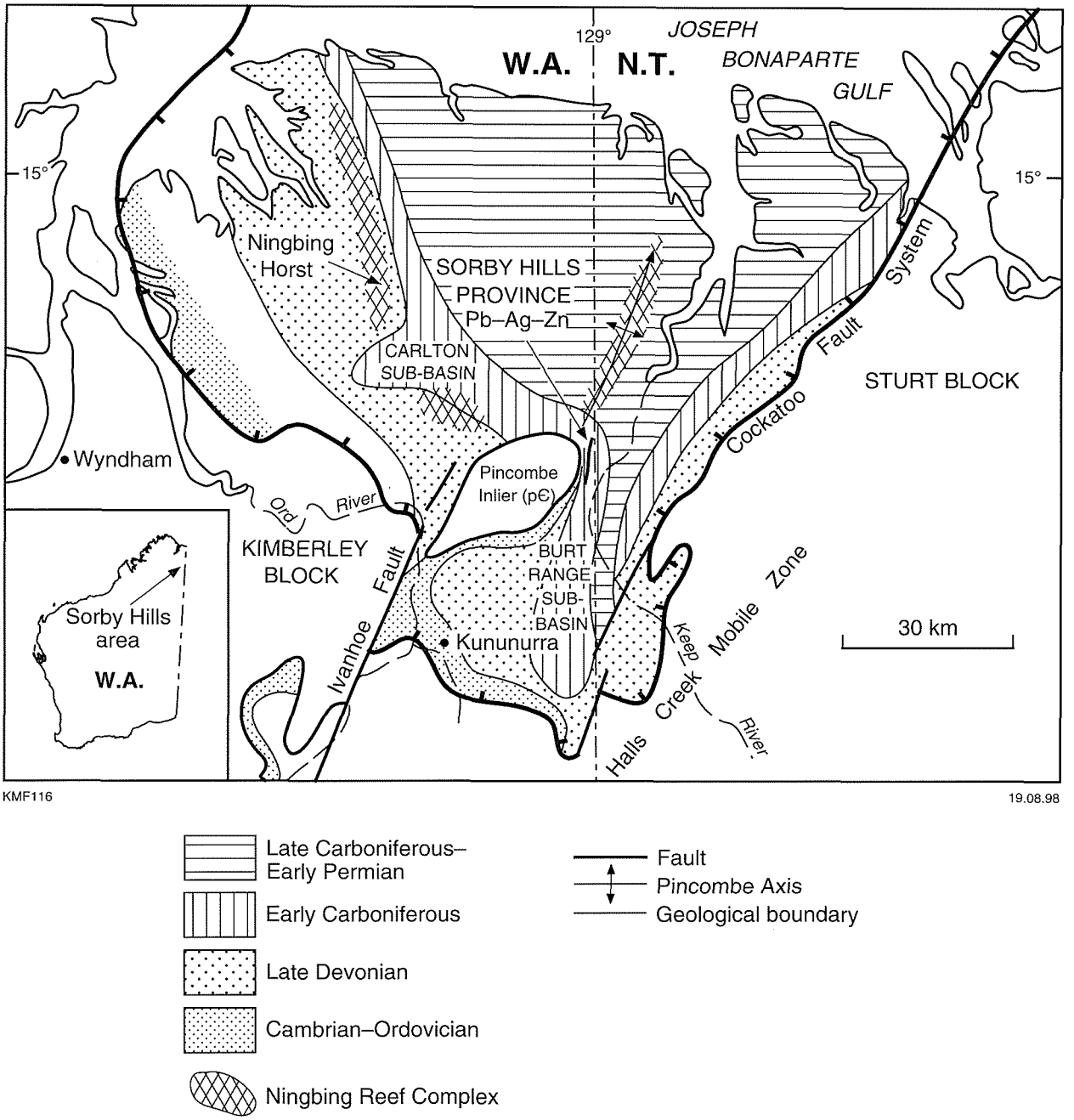


Figure 93. Bonaparte Basin: regional setting of the Sorby Hills deposit (*after* Jorgensen et al., 1990)

by a 15 to 20 m-thick breccia zone (Dolomite II, or DII). This zone lies at the base of the middle member of the Burt Range Formation, the Knox Siltstone, and is made up of reworked clasts of Sorby Dolomite and Knox Siltstone. The extensive dolomitization is genetically related to the mineralization and has completely recrystallized the primary calcite-rich rocks, creating porosity estimated to be up to 15% in part of the Sorby Dolomite. A secondary dolomitization event is indicated by coarse dolomite in fracture linings and vugs.

The epigenetic mineralization is developed over a broad area with thirteen irregular bodies along 8 km of strike, named pods A to J plus the Alpha and Beta trends (Fig. 95). The dolomite breccias are at minor unconformities in the sequence, and are associated with synsedimentary slumps, faults and palaeochannels, or with low-lying areas related to synsedimentary anticlines reflecting basement highs. The mineralization is associated with post-dolomitization intergranular porosity. Within the breccias three textural types of mineralization are present. The first type represents an early phase and is characterized by the development of galena in the silty matrix of the breccia. In the second or intermediate type, coarse-grained octahedral galena occurs in fractures and pores and in the matrix. Some colloform sphalerite is also

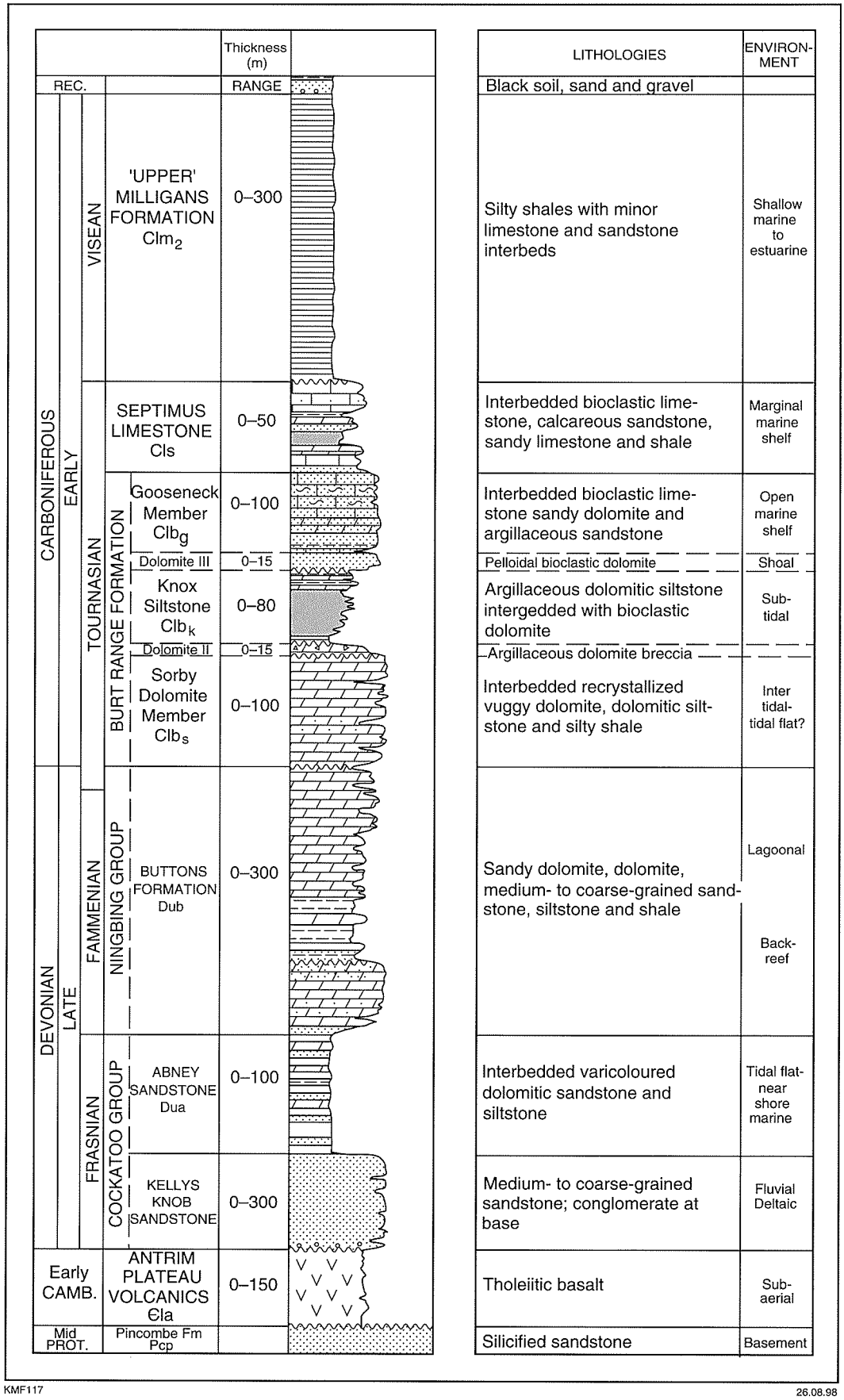


Figure 94. Sorby Hills: stratigraphy (*after* Lee and Rowley, 1990)

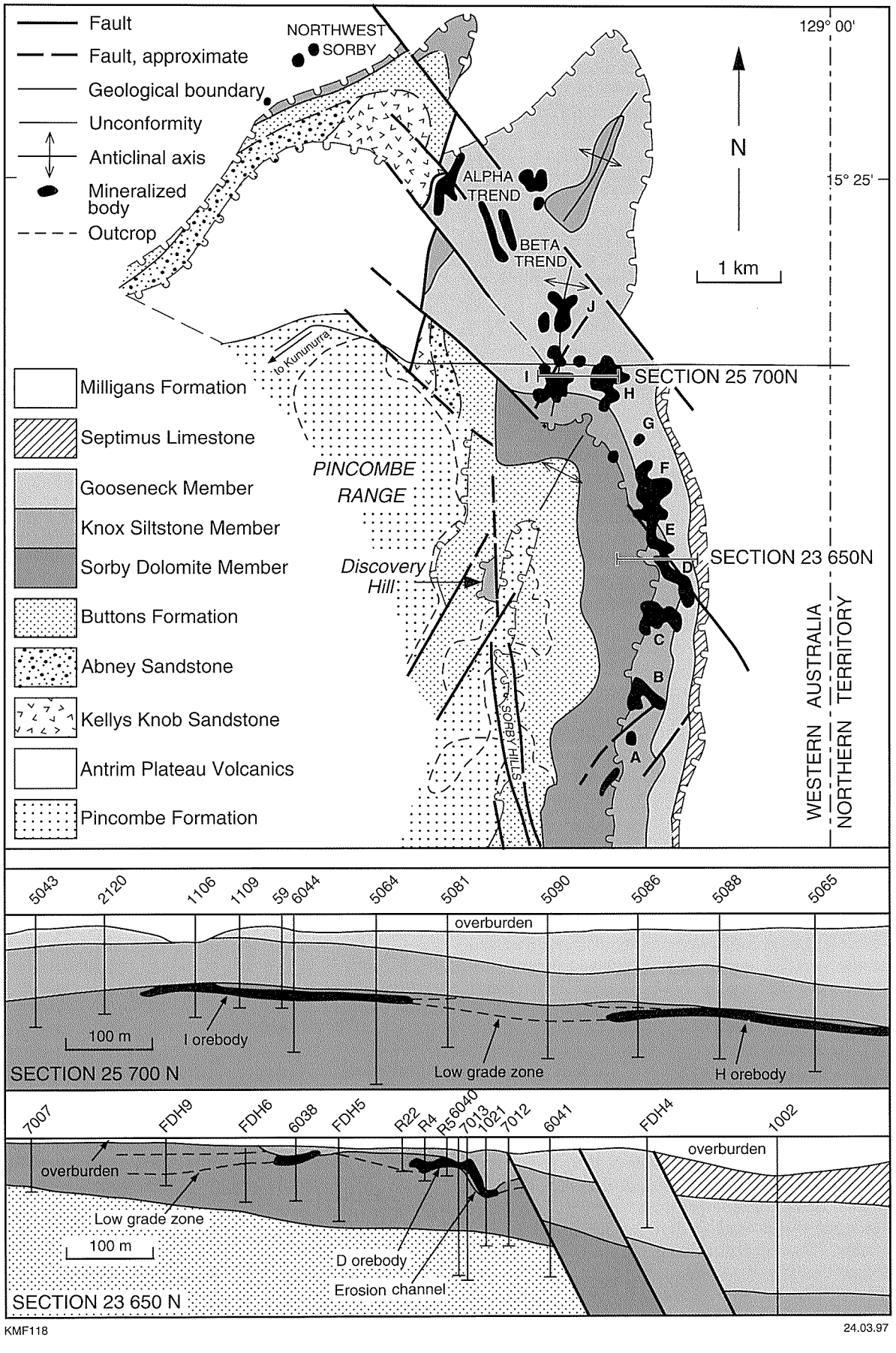


Figure 95. Sorby Hills: geology, mineralization and cross sections (*after* Jorgensen et al., 1990)

present in fractures. This mineralization type is the most common and can occur in massive bodies up to 1.5 m thick. The third, late type is sphalerite dominant with some galena and is found in late fractures and solution cavities. In general the ratio of galena to sphalerite is about 10:1. Tetrahedrite, tennantite, bournonite, marcasite, pyrite and pyrargyrite are also present in minor amounts in the mineralized zones. Details of sulfide mineralogy, paragenesis and textures are provided by Ringrose (1989).

Rowley and Lee (1986) divided the ore pods into four types. Pods A to G (Fig. 95) occur in palaeochannels within the DII breccias. Pods H to J are also in DII but are controlled by northeasterly trending palaeohighs expressed as relatively flat-lying anticlines. These have acted as structural traps for the mineralization. The two subparallel Beta pods are in tensional collapse breccias within the DIII unit. Other minor zones of this type are found elsewhere in the Burt Formation. The fourth mineralization type is represented by the Alpha pod in which tectonic and sedimentary breccias along the faulted margin of the Pincombe Inlier are mineralized. Individual pods measure up to 700 by 500 m in area and are, on average, about 5 m thick.

Jorgensen et al. (1990) consider that basinal brines have leached base metals from Proterozoic debris within the sedimentary rocks of the basin and have then transported the metals and concentrated them in favourable sites. Hydrogen sulfide, derived from the numerous oil and natural gas occurrences in the basin, is considered to have contributed to the fixing of the metals. The north-northeasterly trending tensional fault system marginal to the Pincombe Inlier is considered to have channelled the metalliferous brines into an area favourably predisposed to host the metal accumulations in diagenetically produced zones of high permeability where the original limestone has been extensively dolomitized. The linear trends in the ore development reflect the fault system. Earlier movements in the tensional fault regime may also have controlled the synsedimentary slumping and brecciation.

Interest in the area followed reports of minor lead and zinc at the surface, and in the Oil Development NL/ Westralian Oil Ltd Spirit Hill No. 1 well in 1960. Aquitaine found the Sorby Hills 'Discovery Gossan' in 1971 and, as a result of grid geochemical drilling, located the main D–E mineralized trend in 1973. Between 1974 and 1977 a combination of detailed IP, EM and aeromagnetic surveys helped to define some of the mineralized trends. In general, however, due to its inhomogeneity, the mineralization is poorly conductive. Intensive RC and diamond drilling was the main tool that led to the delineation of the variety of mineralized pods. The Alpha and Beta trends were outlined in 1976–77. Gamma logging was vital in defining the lithology and stratigraphy. Closer drill spacing in the early 1980s, along with the preliminary work on a decline, revealed greater complexity in the ore zones at the expense of continuity. Increasingly high-grade material was recognized as occurring in discrete pods. The abandoned decline also highlighted a potential problem of high water flows into any mine workings.

To the south of Sorby Hills, the favourable host dolomitic facies was seen to give way to a less prospective limestone facies.

An indicated resource of 16.24 Mt at 0.6% Zn, 5.25% Pb and 56 g/t Ag has been reported for the mineralized bodies.

References: Ringrose (1989), Jorgensen et al. (1990), Lee and Rowley (1990), Rowley and Lee (1986), Louthean (1992, 1994), GSWA-WAMEX - I 6182.

Ningbing

Prospect/occurrence: Zn; Pb; Ag
Location: 15°14'30"S, 128°40'E; 4 km north of the abandoned Ningbing Homestead

At Ningbing, within the Carlton Sub-basin of the Bonaparte Basin, the Famennian barrier-reef complex consists of forereef, reef and backreef-facies carbonate rocks and extends for 60 km along a northwest strike. Zinc and lead mineralization, in the form of secondary carbonate, silicate and oxide cavity filling and stringers, outcrops within flat-dipping (0–15°) forereef, dolomitic, clastic (talus breccia) carbonate sedimentary material over an area of 1100 by 200 m. Mineralization consists of disseminated and patchy galena and sphalerite in dissolution cavities with marcasite–pyrite, calcite and minor secondary silica. Cerussite and zincite are noted in outcrop.

The area was examined by a joint venture that included Seltrust, Amax and CRA (1972–85). The best drillhole intersections at the prospect, all in primary ore, were 2 m at 4.8% Zn and 0.27% Pb, 2 m at 1.9% Zn and 1.1% Pb, within 13 m of 1.54% Zn and 0.18% Pb, and 12 m of 1.9% Zn and 1.1% Pb. Further drilling severely limited strike and dip extensions. Exploration by Aquitaine/St Joe Bonaparte (1972–83), also in the Ningbing Complex, achieved poor results but suggested that if potential existed it was on the west side of the range where surface mineralization, dolomitization and structure are most prominent.

References: GSWA-WAMEX - I 2872, I 3167.

Carlton Hill

Occurrence: Zn; Pb
Location: 15°19'S, 128°46'E; 31 km east-northeast of Carlton Hill

Disseminated zinc sulfides are present on a southern projection of reef limestone from Ningbing. The prospective horizon appears to have formed on a fairly open marine platform with carbonate sands gradually giving way to algal and coralline patch-reefs and reefs. Mineralization occurs in dolomitized calcarenite and consists of disseminated sphalerite and marcasite with very minor galena. There is no accompanying copper or silver. Cadmium levels vary with those of zinc to a maximum of 164 ppm.

The area was explored by Alcoa (1972–81) who considered that it covered a basement hinge line with

potential for Ningbing reef facies. Mapping and a vacuum-drill geochemical survey delineated an area of anomalous bedrock. False-colour infrared photography successfully identified areas of structural complexity reflecting strong reverse faulting. An IP survey identified two anomalous areas, one of which is roughly coincident with the mineralization located. Percussion drilling identified mineralization in only 2 holes out of 32. The best intersections were 2 m at 2.61% Zn and 2 m at 2.26% Zn within 10 m of 1.00% Zn in dolomitized calc-arenite. Lead grades up to 0.27% were recorded. However, the favourable horizon seems to be of limited extent.

Reference: GSWA-WAMEX - I 2389.

Knob Peak (Arch, Placer)

Occurrence: Zn; Pb
Location: 14°57'35"S, 128°34'40"E; 58 km north-northeast of Carlton Hill

Zinc–lead mineralization is indicated by a zinc-rich gossan forming outcrops 2 km south-southeast of Knob Peak within the Famennian Ningbing reef complex. The gossan is within a massive dolomitized breccia horizon, which contains a few algal horizons and discontinuous bands of dolomitic shale. Mory and Beere (1988) suggested that this unit is within the backreef facies of the Djilirri Limestone, which in this area is highly dolomitized. The unit lies near the top of the Djilirri Limestone and dips to the east beneath the unconformably overlying forereef and reef marginal Garimala Limestone. There may be some karst on this unconformity surface.

The gossan contains variable amounts of hydrozincite and hemimorphite with lesser cerussite and massicot. Separate gossan samples gave up to 43% Zn, 3.7% Pb and 44 g/t Ag (Aquitaine). The mineralization seems stratabound, though outcrop evidence suggests some fault control or even karst/unconformity control.

Mimets (1972–73) carried out geological mapping and grab sampling. Some zinc anomalism was located but not followed up. From 1972 Placer used reconnaissance geochemistry and, subsequently, more detailed geochemistry and IP surveys to locate the 'Arch' gossan. Diamond drilling follow-up to the south recorded a maximum intersection of only 2 m at 0.2% Zn and 0.04% Pb. A joint venture of Mimets/CEC/St Joe Bonaparte/Aquitaine (1972–83) followed up Placer's work with geological mapping, ground magnetics and IP surveys. Three percussion holes were drilled at the Arch gossan giving a best intersection of 2 m at 1.3% Zn and 0.14% Pb and, near surface, 8 m at 2.02% Zn and 0.2% Pb. Follow-up deeper diamond drilling by Aquitaine gave only 1.15 m at 0.32% Zn. It was noted that minor zinc mineralization was widespread in the Jeremiah Member (Djilirri Limestone). CEC considered that mineralization appeared to be present at or near the top of the pre-Ningbing (Garimala) sequence. They suggested that this surface might be partly karstic and that greater mineralization occurs where faults meet the surface. Some follow-up was carried out by D. F. Ward (1986–1994), a former CEC geologist, but without significant results.

References: Mory and Beere (1988), GSWA-WAMEX - I 507, 2872, I 3325.

Point Springs

Prospect/occurrence: Zn; Pb; Ag
Location: 15°23'S, 128°54'E; 41 km north-northeast of Ivanhoe Homestead

The Point Springs prospect lies in the transitional zone between the platform-carbonate and conglomeratic facies of the Carlton and Burt Range Sub-basins respectively, and a deep-water basinal shale environment to the north. In the prospect area, Upper Devonian carbonate, overlain by Milligan Shale, contains disseminated lead–zinc mineralization at two levels. The upper-zone mineralization is developed just beneath the Milligan Shale contact and consists of weakly disseminated galena and trace sphalerite in granular, commonly friable dolomite with minor pelitic bands. There is little development of fracture-related mineralization in this situation. The lower zone forms a stratabound blanket of galena disseminations in stylolitic dolomite with associated vuggy dolomite and arenaceous dolomite. Highly mineralized zones coincide with beds with high fossil crinoid content. Minor sphalerite and pyrite accompany the mineralization.

Exploration by Seltrust and Tenneco (1978–82) established a mineralized trend over 1.4 km and up to 300 m wide. A gravity survey was carried out to locate possible faults. Diamond-drill intersections gave up to 7.38 m at 1.08% Pb and 10.58 g/t Ag, also 16.89 m at 0.53% Pb and 5.16 g/t Ag, including 0.45 m of 3.2% Pb and 37 g/t Ag (the latter in a carbonate pinch-out trap). These zones were judged to be of limited extent and possibly containing between 5 and 10 Mt of ore.

Reference: GSWA-WAMEX - I 3167.

Potential

It is difficult to gauge the potential for further major discoveries of carbonate-hosted mineralization in Western Australia. Since the discovery of Cadjebut in 1984, no new discoveries that are not satellites of known deposits have been made on the Lennard Shelf. In the eastern Lennard Shelf, the combination of proximity to a major fault separating trough and shelf, and stratigraphic wedge-outs against basement highs, explains the success rate in this area. In the western shelf, a number of widely spaced faults separate the limited areas of shallow-platform lithologies from the trough.

It may be, however, that the continuing research into the processes involved in the formation of the deposits will allow more targeted and successful exploration. In particular, detailed elucidation of structure is important. Kempton et al. (1994) suggest that the recognition at Cadjebut of a porosity/hydrocarbon control in association with oil-filled structures should promote the use of petroleum exploration models in further exploration. Thus, structures which might provide hydrocarbon reservoirs would be likely targets. These comments would also be applicable to the Bonaparte and Carnarvon Basins.

Windrim (1994) considers the Ordovician Admiral Bay deposit, in the central Canning Basin, to have more in common with 'Irish-style' carbonate-hosted/sedex-type mineralization, suggesting a partial syngenetic origin. He also suggests that there is scope in several basins for more deposits of this type, presumably principally in the Bonaparte and Carnarvon Basins and elsewhere in the Canning Basin.

Gascoyne Complex

Deposits, prospects and occurrences

Jubricoo Creek

Prospect: Pb; Zn; Ag
Location: 22°32'S, 115°19'E; 17 km west of Nanutarra Homestead

Vertical lead and zinc veins occur in dolomitic marble and amphibolite of the Morrissey Metamorphics, which are surrounded by granite. Individual veins are about 20 m long, 0.5 m wide, and contain galena. Minor chalcopyrite was seen in one sample. Surface sampling gave a maximum of 19.5% Pb, 11.0% Zn and 340 g/t Ag in separate samples. Drilling results were poor with less than 0.1% Pb or Zn, but penetration was limited.

The veins are exposed in two old pits. CEC (1973) took up the prospect on the basis that the presence of zinc and silver in the veins within dolomites could suggest MVT potential. The company drilled IP/VLF-EM anomalies with 15 percussion holes.

Reference: GSWA-WAMEX - I 2814.

Bangemall Basin

Deposits, prospects and occurrences

Joy Helen

Prospect: Pb; Cu; Zn; Ag
Location: 23°15'15", 115°46'20"; 33.7 km northeast of Maroonah Homestead

In the old workings at Joy Helen, carbonate-hosted base-metal sulfides form irregular flat-dipping segregations in silicified dolomite breccia (which may be part of an algal reef complex) of the Irregully Formation. Minerals recognized in the workings are cerussite, galena, sphalerite, malachite, azurite, cuprite and chrysocolla. The form of the mineralization is poorly defined. Separate surface samples at the workings gave up to 35% Pb, 5% Cu and 19g/t Ag. Chuck (1984) considers that the weathered and bleached host rocks constitute an ancient weathering profile. He suggests that the mineralization was introduced into the sequence along a fault or shear zone, and subsequently oxidized and remobilized by Tertiary groundwater. However, lead isotope determinations on the Joy Helen, and a similar deposit nearby, indicate that mineralization is of Middle Proterozoic age (Richards, J. R., and Fletcher, I. R., 1985, pers. comm.).

Several shallow shafts and numerous costeans have tested the mineralization over about 46 m. Air-blast drilling by Westfield (1961–67) located only a few patches of mineralization in the surrounding area. Drill intersections were up to 1.5 m at 13.7% Pb and 1.5 m at 11.5% Pb and 1.6% Cu. Herald Resources (1990–91) carried out reconnaissance geochemistry nearby but with no significant results.

References: Blockley (1971), Marston (1979), Chuck (1984), GSWA-WAMEX - I 3227, I 4879.

Carnarvon Basin

Geological framework

The Carnarvon Basin extends 1000 km along the west and northwest coastline of Western Australia, is up to 300 km wide and contains sedimentary rocks ranging in age from Silurian to Quaternary. Onshore, the succession is up to 7 km thick and offshore, 15 km of section is known.

The Merlinleigh Sub-basin is one of several sub-basins in the Carnarvon Basin that were active depocentres, primarily in the Palaeozoic between 250 and 450 Ma. The sub-basin is a west-dipping half-graben onlapping Precambrian rocks to the east and bounded on the west by a major fault system (Fig. 96). The sub-basin contains up to 3000 m of Permian succession, with Devonian and Carboniferous in the north, and a thin cover of Cretaceous and/or Tertiary.

Devonian and Lower Carboniferous sedimentary rocks are exposed along the eastern margin of the Merlinleigh Sub-Basin. The sequence is about 2000 m thick and consists of basal sandstone overlain by alternating calcareous and sandy units, each 300–500 m thick. The calcareous units (Gneudna Formation and Moogooree Limestone) have potential both as hydrocarbon source rocks and for hosting base-metals mineralization.

The Gneudna Formation is a mixed-carbonate and siltstone sequence with some interbedded sandstone near the base and top (Hocking et al., 1987). This unit was deposited on a wide shallow-marine shelf in a sediment-depleted regime. A reef-like accumulation is suggested in the Point Maud Member but Hocking et al. (1987) consider that the deposition may have been too far south for the extensive reef development seen in sedimentary rocks of the same age on the Lennard Shelf and in the Bonaparte Basin.

The Moogooree Limestone is a shallow-marine deposit. Limestone dominates but dolomite makes up more than half of the section in some areas. Carbonate lithotypes range from mudstone to coarse grainstone.

The Upper Carboniferous and Permian sedimentary rocks in the Merlinleigh Sub-Basin rest unconformably on either Devonian–Lower Carboniferous rocks northeast of the Kennedy Range, or on Precambrian basement east of, and probably below, the range.

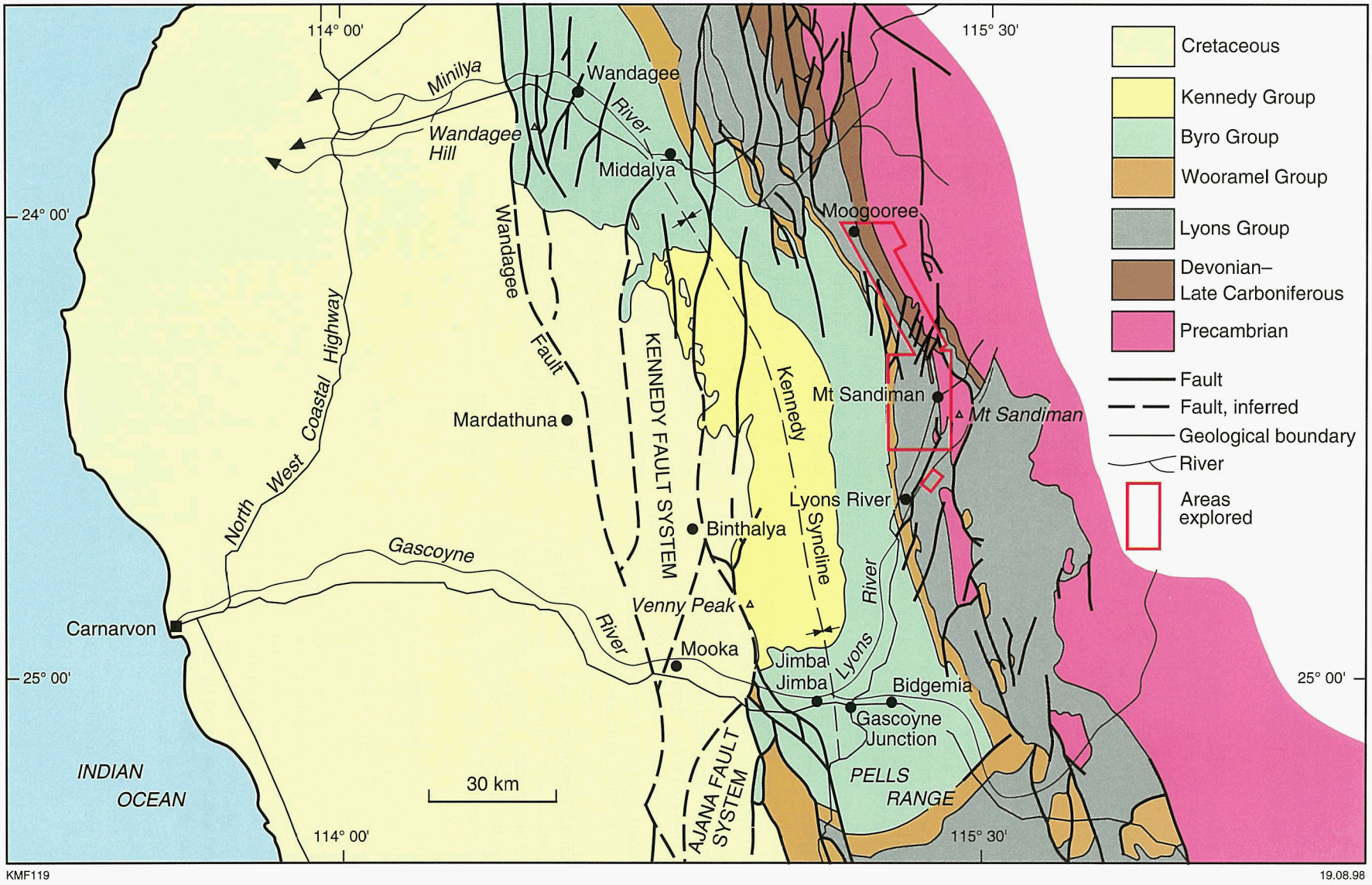


Figure 96. Carnarvon Basin (Kennedy Range area): geology and base-metal exploration since 1970

Mineralization

Exploration for base metals in the vicinity of the Kennedy Range has been in progress since the early 1970s and has concentrated on two main target types: the Mississippi Valley Type, and the clastic-hosted type in carbonaceous shales.

Prospective units for the former are the Devonian Gneudna Formation, the Carboniferous Moogooree Limestone and the Upper Carboniferous Callytharra Formation. Outcrops of these units lie in a north-northwesterly trending zone to the east of the Kennedy Range where exploration has been carried out by a number of companies.

Both the Gneudna Formation and the Moogooree Limestone are unconformably overlain in this area by the Carboniferous Lyons Formation, a suitable trap rock. Veins carrying barite, galena and sphalerite cut both Precambrian basement and overlying Lyons Group sedimentary rocks south of Mount Sandiman Homestead, suggesting that metalliferous brines were circulating in the sedimentary rocks from Late Carboniferous times.

Exploration

Aquitaine (1972–1974) (I 556B), concentrated on the Moogooree Limestone in the immediate area of Moogooree Homestead, where this unit is dolomitized and shows favourable reefs and breccias. Helicopter-assisted rock sampling followed by two diamond drillholes gave assays up to 2.2% Zn and 1400 ppm Pb. Geological mapping and auger drilling were undertaken but not followed up. Inco (I 2064) continued in this same area in 1980, with geological mapping confirming a palaeokarst overlain by Permian sedimentary rocks. Induced polarization surveys indicated potential sulfide conductors. Attempts to drill prospective zones were frustrated by problems with cavities in the rock. Up to 1% Pb was found in the Gneudna Formation but this mineralization was of limited extent.

Considering the potential of the Moogooree Limestone and the Gneudna Formation to be still untested, EZ (I 4106) and Aberfoyle Resources (I 4140) again took up this area, with wider coverage in 1988. Extensive soil and rock-chip sampling failed to extend the known mineralization, and reinterpretation of Inco's IP results suggested that anomalism did not relate to sulfides. This whole zone, where the Devonian–Carboniferous sedimentary rocks are exposed along the margin of the Precambrian basement, was tested by Dominion Mining between 1990 and 1993 (I 7158) with limited success.

Reconnaissance exploration by Inco over the Callytharra Formation, east of the Kennedy Range, indicated low potential. This may be due to the relatively poor trap rock characteristics of the overlying Moogooloo Sandstone or to the main mineralizing event preceding the deposition of the Callytharra Formation.

It would seem that if there is base-metal potential in the Devonian to Permian part of the sequence in this area, then it would be highest in the basal Devonian–Carboniferous carbonate units.

Deposits, prospects and occurrences

Moogooree

Occurrence/prospect: Pb; Zn
Location: 24°10'S, 115°16'E; 15 km south-southeast of Moogooree Homestead

Gossans with up to 2.2% Zn and 1.3% Pb occur in oolitic, dolomitic limestone of the Devonian Moogooree Limestone. This unit seems to be most prospective where it is overlain by efficient trap rocks of the Lyons Group, along 11 km of strike.

Aquitaine (1972–74) and Inco (1980) both carried out rock-chip sampling and drilling. The best drill results were 1.1% Zn (Aquitaine) and 1 m at 1.3% Zn (INCO). Chip samples gave up to 2.2% Zn and 1.3% Pb. Drilling was also carried out by CEC (1980–84). Electrolytic Zinc (1988–89) conducted stream and soil sampling with negative results. Aberfoyle (1988–89) re-evaluated and downgraded IP anomalies from previous exploration. Dominion (1990–93) carried out RC drilling to follow up anomalous soil and gossan sampling (2300 ppm Pb and 2400 ppm Zn). Samples with disseminated galena gave a maximum of 12 m at 0.27% Pb and 0.5% Zn + Pb.

References: Harrison (1985), GSWA-WAMEX - I 556B, I 2064, I 4106, I 4140 I 7158.

Chapter 8

Hydrothermal vein-type deposits

Summary of geology and mineralization

An outline of genetic concepts and some difficulties associated with classifications of vein-type deposits are included in **Chapter 4**. Vein-type deposits containing significant lead, zinc and silver in Western Australia are typically high grade but of limited dimension. This, and their generally complex, structurally controlled form, make them unattractive for mining in contrast to the lower grade but high tonnage large disseminated deposits of volcanic and sedimentary association. Many of the known vein deposits were mined in the late nineteenth century and the first half of this century but are now mainly of historical interest. No vein-type deposits are being mined at present.

Details of past production and the history of exploration are given by Blockley (1971).

Distribution

Plate 1 shows the broad distribution of vein-type deposits in Western Australia. Most examples occur in cratons and orogens, suggesting a close association of the deposits with deeper crustal igneous and metamorphic processes. The highest deposit densities are in the Proterozoic basins of the Capricorn Orogen and in the Proterozoic gneisses of the Northampton Complex.

North Pilbara granite–greenstone terrane

Geological framework

The geological framework of the northern Pilbara has been outlined in **Chapter 6**, and the summary below highlights features which may relate to the distribution and associations of vein-type deposits.

This terrane is made up of granite–gneiss complexes (or granitoid domes) with intervening belts of variably folded volcanic and sedimentary sequences that were deposited between about 3.56 and 2.77 Ga (Krapez, 1993). In a recent summary of the terrane Hickman (1990) asserted that the pattern of granitoid domes and flanking belts was produced by solid-state diapirism of a pre-existing granitoid complex coupled with syntectonic granitoid intrusion. Granitoid ages cluster within four groups: 3.5–3.43 Ga, 3.34–3.265 Ga, about 3.00 Ga, and about 2.85 Ga (Krapez, 1993). Deposition of the earlier sedimentary/volcanic sequences is considered to have predated the diapirism, whereas deposition in the later basins is considered to have been generally limited to areas of present outcrop (Hickman, 1990).

Deformation within the greenstones, including major upright folding, has been interpreted as related to diapirism, and as mentioned above, diapirism occurred between 3.34 and 2.95 Ga in at least four phases, and at various times in different areas. A later phase of horizontal, or subhorizontal deformation is indicated by major strike-slip faults and related folding between 2.99 and 2.8 Ga.

Mineralization

The earliest vein-type mineralization, containing lead and zinc, seems to be that associated with stratiform and vein-type barite at North Pole. This occurs at about the same stratigraphic level as the syngenetic felsic volcanic-associated copper–lead–zinc in the Duffer Formation (3.465–3.470 Ga). On the basis of relatively high source U values in the lead at North Pole, Thorpe et al. (1992a) have suggested that the mineralizing fluids reflect a mixing of material from the Warrawoona Group and appreciably older recycled felsic basement rocks.

At Miralga Creek, the gold–zinc–lead–copper mineralization is both epithermal and transitional to porphyry copper in origin, associated with a quartz-porphyry stock in basalts of the Warrawoona Group. The lead age of 3.449 Ga is approximately equivalent to the age of the host rocks. At Coongan River and Coppin Gap, lead and lead–zinc in quartz veins in Salgash felsic volcanic rocks (~3.45 Ga) are related to a later felsic volcanic and intrusive episode at about 3.33 Ga. At Soansville, lead in a quartz vein in Gorge Creek mafic rocks (~3.32 Ga) gives an age of 3.132 Ga. Hickman (1990) has suggested that epigenetic gold mineralization between 3.34 and 3.00 Ga was produced by the entry of hydrothermal fluids derived by metamorphic devolatilization of the lower crust.

Collins and Marshall (a, this volume) describe a second phase of volcanogenic mineralization in the Whim Creek Belt, associated with the waning phase of a resurgence of caldera development, at the conclusion of

Whim Creek Group volcanism. Hot-spring activity in a subaerial environment resulted in widespread epithermal quartz veining with some silver–lead and possible gold mineralization within the Negri Volcanics. Zinc:lead ratios are all considerably less than one (e.g. Comstock Lode).

Other lead–zinc–silver vein type occurrences, such as those at Cookes Creek, Lynas Find and Hillside, seem to be associated with post-tectonic granitoids in the range 2.5–2.74 Ga. Other granite-associated occurrences for which ages are not available are Nunyerry, Wodgina, Tabba Tabba and Abydos.

Exploration

The high grade of vein-type lead–zinc mineralization has meant that deposits have generally been discovered and developed at an early stage in the history of mining and exploration throughout Western Australia. The small size and the economies of scale also dictate that in other than exceptional circumstances vein deposits are not viable for modern large-scale mining and have therefore not been a focus of active exploration in the modern era. This is particularly true in remote areas such as the Pilbara.

In most cases the vein-type mineralization that has been recognized in recent exploration has been in association with stratabound/stratiform volcanogenic copper–lead–zinc mineralization, representing either a stringer zone below the mineralization or a late-stage remobilization. Occurrences and related exploration at Quartz Circle, Murphy Well, North Pole and Evelyn are of this type. Some exploration has also targeted mineralization transitional between epithermal and porphyry-copper types, for example at Miralga Creek and Yarrie South, where associated gold would provide the main incentive for exploration.

Deposits, prospects and occurrences

Cookes Creek

Occurrence: Pb; F; Ag
Location: 21°38'30"S, 120°27'E; 6 km south of Sunday Hill

Galena is reported in late-stage quartz–fluorite veins associated with the post-tectonic Cookes Creek granite (2.60 Ga). Samples give up to 21.8% Pb and 11.5 g/t Ag. The occurrences are reported to be too small to warrant mining.

References: Blockley (1971), Hickman (1983).

Quartz Circle

Prospect: Zn; Ag
Location: 21°40'15"S, 120°11'45"E; 35 km north-northeast of Nullagine

Exploration for copper–zinc in calc-alkaline, intermediate to felsic volcanic and volcaniclastic rocks of the Duffer Creek Formation in the McPhee Dome, has located lead–zinc mineralization at Quartz Circle. Both massive and vein-type base mineralization are present.

Percussion and diamond drilling by Alcoa (1976–80) intersected 15% pyrite with traces of galena and sphalerite. Particular intersections of 7.2 m at 22.5% Zn and 14.14 m of massive sphalerite with 28.5% Zn, 0.33% Cu, 0.51% Pb, 0.145% Cd, 68 g/t Ag and 0.5 g/t Au were located in coarse agglomerate and breccia. Sphalerite occurs in cerussite and gypsum-lined veins with traces of pyrite and galena. The mineralization is in the Quartz Circle Member (Upper Duffer Creek Formation) dacitic pyroclastic rocks (coarse to fine subaerial tuff), which are subhorizontal with gentle south dips. Follow-up work in the vicinity by BHP (1977–84) tested quartz–sulfide stockwork veins for gold content within the same unit. Clackline (*now* Herald Resources) acquired the prospect in 1983 and has been exploring it since 1984 in joint venture with Pancontinental.

References: GSWA-WAMEX - I 1947, I 3193.

Warrawagine

Occurrence: Pb; Ag
Location: 20°50'S, 120°45'E; 6 km west of Warrawagine

A sample of galena from 'West of Warrawagine' on the Oakover River, examined in 1927, contained 80.8% Pb, 498.58g/t Ag and a trace of gold.

Reference: Blockley (1971).

Coongan Siding (Dooleena Gap)

Abandoned mine: Pb
Location: 20°55'S, 119°43'E; 8 km southwest of Eginbah Homestead

Stratabound massive galena has been mined from a silicified shear zone between serpentinite to the east and felsic volcanogenic metasedimentary and intrusive ultrabasic rocks of the Salgash Subgroup. The zone strikes at 038°, dips 55° east, is up to 9 m wide at the workings and contains sheared country rock, quartz veins and stockwork. A vein on the hangingwall side has been worked out over 60 m along strike. Ore material contains up to 40.1% Pb. Richards et al. (1981) obtained a lead date of 3.339 Ga from galena. This has been recalculated by Thorpe et al. (1992a) as 3.329 Ga. This date is consistent with an association between this epigenetic mineralization and a felsic volcanic intrusive episode between 3.30 and 3.33 Ga (Thorpe et al., 1992a).

Production in 1955 was 5.1 t of lead and 1399.6 g of silver.

References: Blockley (1971), Hickman (1983), Richards et al. (1981), Thorpe et al. (1992a).

Coppin Gap

Occurrence: Pb
Location: 20°54'30"S, 120°06'E; 2–3 km south of the Coppin Gap Cu–Mo deposit

A quartz vein containing galena and sphalerite with lesser copper and traces of silver cuts basalt, dolerite, shale and quartz–carbonate (?metasedimentary) of the Salgash Subgroup. A lead-model age of 3.326 Ga has been calculated by Thorpe et al. (1992a) and is consistent with the same felsic volcanic episode as Coongan Siding; between 3.30 and 3.33 Ga. The Coppin Gap granodiorite has been given an ion microprobe age of 3314 ± 26 Ma (Williams and Collins, 1990), supporting a genetic relationship with the vein mineralization.

References: Richards et al. (1981), Thorpe et al. (1992a), Williams and Collins (1990).

Murphy Well

Occurrence: Zn; Cu; Pb; Ag
Location: 20°57'30"S, 119°55'E; 150 km southeast of Port Hedland

Base-metal mineralization is associated with narrow quartz veins in granite related to acid stocks intruding the Duffer Formation. The veins are locally anomalous in base metals near Jenkins Well, 7 km east-southeast of Murphy Well, and at Murphy Well. Surface samples give up to 3.4% Zn, 2.7% Cu and 0.149% Pb (Duval 1981–82). The veins are narrow, steeply dipping on an easterly strike, and show traces of pyrite and chalcopyrite. They show little potential for large-tonnage mineralization.

Esso (1972–75) initially explored in this area for VMS targets in andesitic and dacitic volcanic rocks with graphitic and pyritic horizons. Two gossans gave high silver (210 g/t), but copper and lead gave a maximum of only 1750 ppm and 3756 ppm respectively. Drilling results were negative in pyritic and graphitic horizons. Duval (1981–82) was primarily exploring porphyry-style copper–molybdenum targets in the Cundaline Gap and Talga Peak areas and found little evidence of hydrothermal systems.

References: GSWA-WAMEX - I 906, I 2457, I 3317.

Yarrie South

Occurrence: Au; Zn; Ag; Cu
Location: 20°44'S, 120°11'30"E; 90 km southeast of Goldsworthy

Quartz veins cut foliated ultramafic rocks of the Gorge Creek Group in the Shay Gap Syncline on the east side of the Muccan Batholith. The southernmost of two limonitic veins assayed 2.56% Zn, 0.14% Cu, 2.4 g/t Au and 83 g/t Ag.

Australian Anglo (1969–73) explored to drilling level for porphyry-style copper–molybdenum in the general Coppin Gap area. Quartz vein systems related to granodiorite intrusives contained pyrite, molybdenite, chalcopyrite and pyrrhotite. Results for zinc were negative. Pennzoil (1981) explored similar targets in the same general area with discouraging results from grab sampling.

References: Marston (1979), GSWA-WAMEX - I 942, I 1328.

North Pole (Stubbs)

Prospect/occurrence: Pb; Ba
Location: 21°06'S, 119°22'E; 38 km west-northwest of Marble Bar

The North Pole Dome is a 35 km diameter structure with a granite core surrounded by mafic to felsic volcanic and metasedimentary rocks, and cherts of the Warrawoona Group. Barite mineralization occurs within fracture-controlled chert boxworks and in tabular, stratigraphically controlled chert bodies. The deposits follow an 8 km-long stratigraphic zone immediately beneath the lowest major chert of the succession. Hickman (1972) considered these deposits to be of sedimentary origin, invoking invasion of the fracture system by diapiric folds of the bedded barite. However, Hickman (1990) and Newmont (1980, I 2760) considered the barite to be of exhalative origin with associated vein stockwork. Finely disseminated galena and sphalerite are associated with the barite. Newmont reported zinc sulfide in shallow drilling by Dresser and Getty with up to 8 m at 2.8% Zn and 0.78 m at 3.67% Zn. A chip sample also gave 4.0% Pb and 310 g/t Ag in a narrow chert–barite horizon at Stubbs Prospect (21°06'20"S, 119°27'E). Newmont tested stratiform VMS potential downdip from the barite without success.

Richards et al. (1981) and Thorpe et al. (1992a) report lead ages of >3.4 Ga and 3.49 Ga respectively for the North Pole mineralization. A few gneissic rocks in the area have given similar ages.

Blockley (1971) has also reported in this general area a vein containing galena associated with quartz, cerussite, malachite and barite worked in 1949 for about 0.6 t lead. Concentrates assayed 50–80% Pb and 180–500 g/t Ag. In tenements surrounding the Breens Copper Mine (*see* Marston, 1979), CEC (1973–85) tested a stratiform zinc anomaly in felsic and intermediate volcanic rocks (1700 ppm Zn and 980 ppm Pb in rock-chips). Drilling intersected up to 2 m at 0.12% Cu, 0.51% Zn and 10.5 g/t Ag. A barite outcrop was also mapped and evaluated. Esso (1973–75) conducted VMS exploration to diamond-drilling level, with no tangible results.

References: Blockley (1971), Hickman (1972, 1983, 1990), Richards et al. (1981), Thorpe et al. (1992a), GSWA-WAMEX - I 910, I 2760, I 5792.

Miralga Creek

Prospect: Au; Zn; Pb; Cu
Location: 21°09'S, 119°32'40"E; 19 km east-southeast of North Pole

Base-metal mineralization at Miralga Creek has been interpreted as transitional between epithermal and porphyry-copper styles associated with a felsic porphyry stock in subaqueous to subaerial basalt of the Warrawoona Group (Goellnicht et al., 1988). Disseminated, stringer, vein and hydrothermal breccia-hosted mineralization occurs around the marginal intrusive breccia of the stock and in association with porphyry dykes. An early phase of pyrite–chalcopyrite mineralization is followed by a later sphalerite–galena–tetrahedrite–silver–gold assemblage

characterized by vertical zoning. Associated alteration reflects potassium metasomatism.

Fluid-inclusion studies (Goellnicht et al., 1988) indicate the main alteration and mineralization to be partially due to dominantly magmatic, high-temperature, high-salinity fluid. A later, lower temperature and salinity fluid dominated by seawater was also involved and the complex zoning and alteration are interpreted as being related to the mixing of these fluids. Metals are considered to have been transported as chloride complexes. The porphyritic host rocks have been established by zircon U–Pb dating at 3.449 Ga (Thorpe et al., 1992a). A lead-model age obtained from galena at Miralga Creek gives 3.447 to 3.451 Ga (Groves, 1987).

The prospect is being explored by the Sipa/Ashling JV following earlier work by Miralga Mining (1984 on). Exploration by Noranda (1984–88) in an area 2 to 5 km west of the main prospect located minor quartz–barite–galena–cinnabar veining, with up to 6.6% Pb and 0.2% Zn, in felsic dykes and pyroclastic rocks.

References: Goellnicht et al. (1988), Groves (1987), Thorpe et al. (1992a), GSWA-WAMEX - I 3541.

Hillside (Hillside Station, Cooglegong)

Occurrence: Pb
Location: 21°37'S, 119°26'E; 61 km southwest of Marble Bar

Two pods of coarse galena are located alongside a quartz vein in granite gneiss. Some tantalite, tin and beryllium are present along strike in the same vein and are related to the nearby Cooglegong Adamellite. Richards et al. (1981) report a lead age of 2.4 to 2.5 Ga for the mineralization and an Rb–Sr date of 2.55 ± 0.13 Ga for the adamellite.

Reference: Blockley (1971).

Sandy Creek

Occurrences: Pb; Ag; Zn; F
Location: 21°50'S, 119°50'E; 30 km east of Nullagine

Galena and sphalerite are reported in a gangue of fluorite and quartz in basalt within the Coongan Syncline. Anglesite and cerussite are also present. A sample contained 53.9% Pb, 32.34 g/t Ag and 6.02% Zn.

In this general area Alcoa (1968–73) conducted regional exploration for VMS targets. WMC (1973) also tested the Spinaway/Sandy Creek area for VMS, with negative results.

Reference: Blockley (1971).

Abydos 2

Prospect: Zn; Cu; Pb; Ag; Ba
Location: 21°36'S, 118°55'E; 4.3 km northwest of Woodstock outstation.

A narrow quartz vein, trending 150° and dipping vertically in granite gneiss of the Yule Batholith, containing galena, cerussite and anglesite disseminated in small bunches, has been worked over 30 m in a trench of to 2.4 m maximum depth.

References: Blockley (1971).

Soanesville

Occurrence: Pb
Location: 21°31'S, 119°10'E; 8 km south of Pyramid Hill

Galena occurs in a quartz vein within mafic volcanics of the Gorge Creek Group on the western margin of the Tamborah greenstone belt extension. Thorpe et al. (1992a) have calculated a lead age of 3.132 Ga for the mineralization.

References: Richards (1986), Thorpe et al. (1992a).

Lynas Find

Occurrence: Pb
Location: 20°58'S, 118°56'E; 75 km south-southeast of Port Hedland

A quartz vein, striking at 150° and dipping 80° east, in granite gneiss of the Carlindi Batholith, contains galena and cerussite over 15 m. The granite intrudes sedimentary rocks of the Warrawoona Group and the vein is younger than the deformation of the Gorge Creek Group. Minor workings, 7.6 m long by 1.5 m deep, yielded a small amount of hand-picked ore. Only low-grade material remains. A lead-model age of 2.742 Ga has been calculated for this occurrence (Thorpe et al., 1992a). Richards et al. (1981) have suggested that the mineralization may be related to a 2.7 to 2.9 Ga pervasive event affecting the granitic domes of the region.

References: Blockley (1971), Richards et al. (1981), Thorpe et al.(1992a).

Tabba Tabba

Occurrence: Pb; Ag
Location: 20°40'S, 118°52'E; 50 km southeast of Port Hedland

A galena sample taken in 1927 from a vein within the Carlindi Batholith gave 80.3% Pb, 144.01 g/t Ag and some gold.

References: Simpson (1951), Blockley (1971).

Wodgina

Occurrence: Pb; Zn
Location: 21°25'S, 118°30'E; 130 km south of Port Hedland

Finely granular galena with associated sphalerite is present in a 1.5 m-wide quartz vein in granite of the Yule Batholith. Anglesite, cerussite, smithsonite and hemimorphite are present at the surface.

In a separate occurrence, a few kilometres southeast of Wodgina, a sample of coarsely crystalline galena

yielded 74.6% Pb, 65.94 g/t Ag and 0.82 g/t Au. Exploration in the 1970s and 1980s in the pegmatites has been principally for tin and tantalum.

Reference: Blockley (1971).

Evelyn (Croydon, Lady Evelyn, Quarmby)

Abandoned mine: Cu; Zn
Location: 21°05'50"S, 117°50'40"E; 42 km east of Pyramid Homestead

Copper mineralization at the Evelyn Mine occupies a line of shears trending at 055° and dipping 70–80° northwest. The ore has been worked over 240 m in actinolite and tremolite–chlorite–quartz schists, which represent a gabbroic to pyroxenitic sill, and in metasedimentary rocks of the upper Gorge Creek Group. Limonitic boxwork gossans exist as lenses up to 40 m long by 5 m wide. Ore minerals present in the surface material include malachite, chrysocolla, azurite and limonite. Chalcopyrite, marcasite and sphalerite are representative of primary ore. Primary ore, encountered below 26 m, is relatively zinc rich and mining was abandoned due to this factor. One sample of mined ore gave 15.2% Cu and 1.7% Zn. No assays from the zinc-rich zone are recorded. Gossans range up to 0.25% Cu, 2.25% Pb, 0.21% Zn, 375 g/t Ag. Dump samples gave up to 40.5% Cu, 7.6% Pb, 6% Zn, 490 g/t Ag, 0.24% As, 1.65 g/t Au and 600 ppm Ba (Aquitaine 1976–78).

The mineralized zone is in the west limb of a major northeast-plunging, tightly folded anticline, and is considered to have a combined stratigraphic/structural control. Probable rod-like shoots of ore within the strike-shear zone plunge north at 35–55° and probably represent structural concentration of lower grade stratabound mineralization, of probable exhalative origin, originally sited on the mafic–ultramafic/sedimentary rock contact.

The main period of mining, from 1899 to 1907, produced 59 845 t of copper ore at 17.89% Cu. Bell Bros (1969–72) carried out stream-sediment and rock-chip sampling over the mine area as part of a more regional program. Mapping at the same time noted the importance of shear intersections in localizing the relatively small individual ore shoots within the generally stratabound zone. High cobalt (≤1150 ppm) in rock-chip sampling suggested an association with the amphibolite. Aquitaine (1976–78) drilled two diamond holes into the shear/contact zone. Mineralization was encountered in only one of the holes, with an intersection of 2.25 m at 0.4% Cu, 0.02% Pb, 0.38% Zn and 2 g/t Ag; however, this was considered to have missed the main mineralized body. It was concluded that although it was possible to interpret the surface and drillhole data in terms of a large faulted sulfide body at depth, it was more likely to reflect narrow pipe-like bodies with very limited tonnage potential.

Reference: Blockley (1971), Marston (1979), GSWA-WAMEX - I 2366, I 3231.

Comstock Lode (Colorado)

Abandoned mine: Pb; Ag
Location: 20°53'S, 117°48'E; 6 km south-southwest of Whim Creek

A west-northwesterly trending zone of coalescing quartz veins hosts lead and silver over a surface area of 50 by 10 m in the Comstock Member andesite of the Rushall Slate in the Whim Creek Group. The mine consists of several costeans over the top of a prominent ridge just south of the Mons Cupri copper deposit. Small cross faults cut the 107 m-thick andesite flow. Galena, anglesite, cerussite, pyromorphite, malachite and azurite have been recorded from the lode.

Production between 1915 and 1917, and again from 1950 to 1953, totalled 78.2 t lead and 28.8 g silver. A total of 66.7 t of copper ore at 18.67% Cu yielded 12.44 t copper. A number of small costeans have worked the main ladder-vein zone. The largest is 12 by 9 m across and 4.5 m deep. Picked ore graded between 40 and 67% Pb, and 300 and 1800 g/t Ag.

References: Blockley (1971), Marston (1979), Hickman (1983), Woodward (1911), Simpson (1951).

Nunyerry (Flat Rock)

Prospect: Pb; Ag; Zn
Location: 21°41'S, 117°53'E; 115 km southeast of Roebourne

Lead and silver are present in quartz veins in granite of the Nunyerry Inlier; two intersecting veins have been worked. Workings are scattered over 180 m on the richer, 105° trending vein. The second, lower grade vein trends at 195° over 107 m. A rich ore zone is located at the intersection of the main vein with a minor branch vein. A dump sample gave 62.5% Pb, 0.48% Zn and 223.94 g/t Ag.

The prospect was discovered in 1957 by D. Watkins, who produced 1.16t of lead and 381.32 g of silver. Lead-isotope data suggest an Early Proterozoic age for the mineralization (Richards et al., 1981).

References: Blockley (1971), Richards et al. (1981).

Andover (Brothers United, Woolcock)

Abandoned mine: Pb; Ag; Zn; Au
Location: 20°53'S, 117°06'E; 12 km south-southwest of Roebourne

A fissure vein up to 1.8 m wide in granite and gabbro in the Roebourne Syncline, trending at 355° and dipping at 50–85° east, hosts mineralization in a pegmatite vein within the granite. In the gabbro the vein is almost pure quartz. The ore minerals are galena, sphalerite, smithsonite and malachite and ore samples contain up to 67.17% Pb and 122 g/t Ag. Zinc carbonate ore (≤38.2% Zn) has been recorded and minor gold (1.43 g/t) is present in some samples.

The deposit was probably discovered in 1872 and was worked to a depth of 11 m in two shafts, but minor production from 1872 to 1911 was not recorded. Recorded production comes from the period 1948–52 with 44.19 t of lead and 14 kg of silver. The workings were briefly examined by Garrick Agnew in 1969–70.

References: Blockley (1971), Hickman (1983), GSWA-WAMEX - I 5163.

Orpheus

Prospect: Zn; Cu; Ag; Au
Location: 20°55'S, 116°59'30"E; 30 km south east of Karratha

Mineralized quartz veins host zinc–copper–silver–gold mineralization in an area 200 m wide along a 1 km strike in acid to intermediate volcanic rocks. Rock chips collected by Dragon Mining NL from the veins within a broad area of outcropping gossan are anomalous with up to 7.4% Zn, 14.7% Cu, 2.25 g/t Au and 8800 g/t Ag in one sample. Peak values for gold and zinc are 23 g/t and 15.5% respectively.

In the scheme of Hickman (1990), the volcanic sequence is Duffer Formation of the Warrawoona Group. In the scheme of Krapez (1993), the volcanic rocks belong to the Regal–Sholl Supersequence. The mineralization appears to coincide with a lineament along the axis of a fold in the volcanic sequence, about 1 km south of the Sholl Shear Zone.

Reference: Louthean (1995b)

Elizabeth Hill (Munni Munni)

Prospect: Ag (Pb; Zn)
Location: 21°05'45"S, 116°51'55"E, 67 km south of Karratha

An unusual and potentially rich silver prospect was originally examined by Agip in 1987 (I 5997) near the northern margin of the layered mafic–ultramafic Munni Munni Complex in the west Pilbara. East Coast Minerals NL have conducted further exploration and have located high-grade native silver close to the Munni Munni fault. The mineralized zone has been traced over 600 m at the surface, in a number of bodies. A costean over the mineralization revealed an 8 m section averaging 1000 g/t Ag, 0.2% Zn and 0.6% Pb. A 10 m section over the same gossan averaged 1.42% Cu and 0.18% Ni. The high-grade mineralized zone is between 5 and 20 m thick, steeply dipping and has been traced down to about 120 m to date, in a discordant, en echelon body with a lower grade envelope. The best drillhole intersection to date is 7.5 m at 23 489 g/t Ag at a starting depth of 109 m.

Barnes (1995) describes the mineralization as occurring in a granite or aplite vein beneath the basal contact of the mafic–ultramafic complex with the primary ore comprising mainly fine- to coarse-grained native silver in a coarse-grained calcite stockwork. This ore also contains argentopentlandite, acanthite, argentite and complex silver sulfide minerals. Associated gossans also contain palladium and rhodium with minor copper, nickel, lead and zinc but no platinum or gold. The mineralized stockwork has developed in a shear-link structure.

Barnes (1995) considers the mineralization to have three possible origins: mainly as a supergene enrichment; related to the Munni Munni Fault in association with quartz veining or granite; or as a differentiate associated with the complex. The freshness of the host rock and presence of primary petrological features argue against a supergene origin. Silver veins without lead is unique in the Pilbara. Differentiation from the Munni Munni Complex is suggested by the presence of palladium and rhodium without platinum. However, silver may also represent a differentiation from the intrusion after assimilation of granitoid country rock into the complex.

References: Barnes (1995), Louthean (1995a), Wilkinson (1995), GSWA-WAMEX-I 5997 A 34894.

Yilgarn Craton

Geological framework

The geological framework of the Yilgarn Craton has been outlined in some detail in **Chapter 6**.

Mineralization

Vein-type occurrences and prospects that host significant copper–lead–zinc are much less common in the Yilgarn Craton than in the Pilbara Craton, but with a higher incidence in the western part of the craton.

In the Murchison Province, copper–lead–zinc-bearing veins are commonly associated with gold and hosted by mafic or ultramafic rocks (Watkins and Hickman, 1990). Galena is a common trace sulfide in gold deposits of the region. In some gold occurrences, such as that in a gossanous quartz vein at Poona, levels of between 1 and 5% of both Pb and Zn are noted.

In the Southern Cross Province the low-grade lead–zinc Mukinbudin (Bonnie Rock) deposit (granitoid hosted) and Dicks Reward prospect (granulite hosted) seem to be the result of relatively high-temperature hydrothermal and metasomatic processes in zones of high-porosity fracturing and brecciation within structural trends. The Brookton occurrence in the South West Province may have some similarities with these.

The group of small but high-grade lead–zinc occurrences east and southeast of Perth, along the Darling Fault, seem to lie on the north-northwest trend of the gneissic foliation.

At Black Flag in the east Yilgarn Craton, where base-metal sulfides are closely associated with epigenetic gold, detailed study has suggested an epithermal origin for the base metals, postdating the gold by 100 m.y. An epithermal origin is also suggested for the recently discovered Nimbus silver–gold–zinc deposit at Boorara, 15 km east of Kalgoorlie–Boulder. The sulfide mineralization appears to form a number of zones in a large, strongly silicified alteration system with complex semi-massive sulfide breccias, sulfide-rich vein stockworks, and disseminated sulfides in felsic volcanic rocks. This discovery may open up potential in the Yilgarn for more deposits of this type when its genetic associations are more clearly established.

The main period of tectonism, metamorphism and granitoid intrusion associated with gold and related base-

metal mineralization in the Yilgarn Craton is between about 2.68 and 2.61 Ga. There is some earlier epigenetic mineralization in the Murchison, as far back as the 3.00 Ga date for syngenetic base metals and gold at Golden Grove. The Black Flag evidence, however, suggests some caution is necessary in assuming a single-phase mineralizing process.

Exploration

As in the Pilbara region, exploration specifically for vein-type copper–lead–zinc has been minimal in the modern era in the Yilgarn Craton. Relevant exploration has, in general, been either VMS or gold-related. Only at Mukinbudin, Dicks Reward and Brookton have epigenetic, hydrothermal/metasomatic bodies of relatively low-grade lead and zinc been examined in their own right, owing largely to the establishment of a low-grade resource at Mukinbudin by Otter/Shell in the mid 1970s.

Deposits, prospects and occurrences

Murchison Province

Fields Find

Occurrence: Au; Cu
Location: 29°02'20"S, 117°14'30"E; 12 km northeast of Warriedar Homestead

In the Fields Find group of workings sulfides are associated with gold mineralization in a quartz vein (1.5 m wide) in basalt/dolerite and felsic porphyry, on the east side of the Yalgoo–Singleton Greenstone Belt. The vein extends for 1.2 km at about 075°, dipping at between 55° north and subvertical, approximately following the strike (but not the south-southeasterly dip) of the enclosing volcanic unit. The metallic minerals are pyrite, pyrrhotite, chalcopyrite and arsenopyrite with minor galena and sphalerite.

Most of the gold production has come from two northerly plunging shoots within a 700 m zone of workings (843 kg of gold averaging 21 g/t). Marston (1979) also reports the production of 30.94 t of copper ore averaging 13.39% Cu from these workings in 1945. Esso (1975) explored the area for VMS targets but found only weak pyritic mineralization.

References: Marston (1979), Watkins and Hickman (1990), GSWA-WAMEX - I 347.

Paynes Find

Occurrence: Cu; Pb; Au
Location: 29°13'30"S, 117°39'10"E; 5 km north-northwest of Paynes Find Homestead

Sulfidic quartz veins in shears in amphibolite (gabbro)/schist contain minor galena in association with gold. The sulfide mineralogy is malachite, chalcopyrite, cerussite, galena, acanthite and goethite.

Browning et al. (1987) record a Pb–Pb model age of 2865 ± 19 Ma for this occurrence.

North Flinders (1975–80) and CRA (1984–89) included the area in VMS regional exploration. No significant results were reported. Sovereign/UCABS in (1985–89) carried out extensive rock-chip sampling in the area with results in separate samples up to 2.2% Cu, 10% Pb, 520 g/t Ag and 1.01 g/t Au. Follow-up drilling gave up to only 0.5% Cu, 0.3% Pb and 0.14% Zn.

References: Watkins and Hickman (1990), Browning et al. (1987), GSWA-WAMEX - I 3601, I 4244, I 4907.

Poona

Occurrence: Au; Zn; Pb; Cu; Ag
Location: 27°08'20"S, 117°26'15"E; 24 km northwest of Coodardy Homestead

A large quartz vein in mafic schist contains narrow sulfide zones. Separate samples contain up to 0.4 g/t Au, 4.47% Zn, 1.5% Pb, 1650 ppm Cu and 36 g/t Ag.

References: Watkins and Hickman (1990).

Paynesville

Occurrence: Pb; Ag; Cu; Au
Location: 28°08'S, 118°30'E; 11.2 km southwest of Paynesville

A quartz vein with argentiferous cerussite, anglesite, malachite and calcite was reported by Blockley (1971) following Simpson (1951). Rock-chips gave up to 56.4% Pb, 1% Cu, 2400 g/t Ag and 0.83 g/t Au, within felsic ?volcaniclastic rocks.

Amax (1977–78) carried out VMS exploration but encountered only pyrite mineralization.

References: Simpson (1951), Blockley (1971), Marston (1979), GSWA-WAMEX - I 651.

Southern Cross Province

Dicks Reward

Prospect: Pb; Zn
Location: 31°10'S, 118°31'E; 22 km northwest of Westonia

Sulfide mineralization is associated with a complexly folded and faulted structure in felsic granulites, derived from fine-grained felsic igneous rocks, within the trend of the Westonia Greenstone Belt. Two anomalous zones (each 1500 × 300 m) lie within a magnetically interpreted suite of northeast-trending faults in an area of poor outcrop. ACM/Orion (1986–90) carried out RC drilling for a maximum of 1.14 g/t Au, 1.36% Pb and 0.79% Zn over 2 m intersections. Sphalerite, galena, pyrite and pyrrhotite were recognized in association with potash-metasomatic alteration and silicification and shear zones infilled by sillimanite. Analogies were drawn with the low-grade Bonnie Rock lead–zinc deposit.

References: GSWA-WAMEX - I 4415.

Koolyanobbing

Occurrence: Pb; Zn
Location: 29°53'S, 119°30'E; 150 km north-northeast of Southern Cross

In this locality, a 6 by 150 m body of quartz with galena and sphalerite occurs within greenstone schist.

Nord (1981–84) carried out low-level VMS exploration in the area but encountered no lead or zinc anomalism in rock-chip geochemistry.

References: Blockley (1971), GSWA-WAMEX - I 3192.

Mukinbudin (Bonnie Rock)

Deposit: Pb; Zn; Ag
Location: 30°42'S, 118°19'E; 30 km north of Mukinbudin

Lead, zinc and silver occur in easterly trending, narrow, magnetite–franklinite and biotite–garnet lenses associated with hydrothermally altered monzonite–syenite zones within Archaean granite and granodiorite at Mukinbudin. A 200 by 250 m magnetite gossan, the 'Dam Gossan', contains franklinite, willemite, galena, sphalerite and coronadite and assays up to 6.7% Pb and 6.8% Zn. Prominent east-northeasterly trending subvertical joints in this area reflect a regional structural trend. Two other lesser mineralized occurrences lie to the north and south. The southern one is on a similar trend whereas the northern occurrence, about 1 km north of the Dam Gossan, trends at about 040°. The 'monzonite–syenite' is a metasomatic rock produced by relatively high-temperature hydrothermal alteration of an original sodic plagioclase–microcline–augite–quartz assemblage by Ca, Fe, Mn, Pb and Zn-bearing fluids. This has produced a rock containing 80% of argillitized and sericitized feldspar with magnetite, spessartine and epidote with minor quartz augite, hornblende, hematite and numerous accessory minerals including grossular garnet, cordierite, calcite, sphene, galena, pyrite, willemite, biotite, apatite, zircon and magnetite. The rock is also anomalous with up to 2.4% Pb and 2.6% Zn.

The narrow mineralized lenses seem to represent areas of total replacement of the host monzonite related to zones of high porosity, fracturing and brecciation within the structural trend.

Asarco (1971–72) first examined the prospect with a limited soil and rock-chip geochemical program and ground magnetics. Otter/Shell (1976–79) carried out percussion and diamond drilling for a best intersection of 2 m at 1.4% Pb, 1.35% Zn and 60 g/t Ag. They estimated a resource of 0.45 Mt at up to 1.5% Pb, 1.25% Zn and >100 g/t Ag. West Coast Holdings (1981–83) carried out a further five-hole diamond-drilling program to test possible extensions, and examined the geochemistry of the alteration and mineralizing processes. They concluded that the extent of the mineralization had been adequately tested and that the deposit was subeconomic.

References: GSWA-WAMEX - I 1244, I 2685-2686.

South West Province

Armadale

Prospect: Pb; Zn; Cu
Location: 32°11'S, 116°02'E; 1.6 km southeast of Armadale

Two quartz veins in granodiorite contain a little galena with sphalerite, pyrite and chalcopyrite.

References: Blockley (1971).

Harvey River

Occurrence: Pb; Ag
Location: 33°04'S, 115°55'E; 3 km east of Harvey

A hand-picked sample of galena assayed 65.6% Pb and 61.58 g/t Ag

References: Blockley (1971).

Mundijong

Abandoned mine: Pb; Zn
Location: 32°19'S, 116°00'E; 3.2 km east of Mundijong

Granite gneiss with a north-northwest foliation and containing bands of amphibolite and mica schist is cut by quartz veins striking at 335°, parallel to the gneissic foliation, and dipping steeply northeast. The veins form an en echelon pattern with the axis trending north. The largest vein carries significant lead and zinc mineralization at its northern end, where it splits into two branches, but is virtually barren over the rest of its 490 m length. Sphalerite, galena and some copper carbonates are present with lesser pyrite and fluorite. Lead grades from 4.5 to 78.4%, zinc up to 19.28% and silver up to 211 g/t.

The mine was worked in 1846, 1870, 1907 and 1926 from a single shaft on 3 levels down to 22 m. There is no record of production.

References: Simpson (1951), Blockley (1971).

Serpentine

Occurrence: Pb; Zn; Cu
Location: 32°22'S, 116°00'E; 24 km south of Armadale

A quartz vein containing galena, sphalerite, chalcopyrite and pyrite assays up to 81.7% Pb, 14.2% Zn, 4.6% Cu and 67 g/t Ag.

References: Blockley (1971).

Brookton

Occurrence: Zn
Location: 32°22'30"S, 116°58'E; 100 km southeast of Armadale

Tuff and sulfidic chert in a sequence of mafic to felsic volcanogenic gneiss and schist have been affected over 2.6 by 0.5 km by chloritization reflecting intense

Mg metasomatism. The metasedimentary rocks contain various amounts of mica, quartz, garnet, cordierite and amphibole. The alteration post-dates granulite metamorphism and is defined by cordierite, phlogopite, magnesian amphiboles and relict or retrograde chlorite and talc. Sulfides are indicated by boxworks in the chert and breccia. At the thickest, eastern end of the zone there are signs of disseminated and stringer-type mineralization. Maximum rock-chip assays are 0.195% Cu and 0.8% Zn.

Otter (1976–83) discovered the alteration zone and associated geochemical anomalies but did not carry out drilling.

References: GSWA-WAMEX - I 3219.

Eastern Goldfields Province

Cundeelee (Ponton Creek)

Occurrence: Zn
Location: 30°32'45"S, 113°15'20"E; 60 km northwest of Zanthus

Anomalous zinc was located in the Cundeelee area during carbonatite search. Up to 3.4% Zn was found in a chlorite–carbonate–sulfide(–sphalerite–pyrite) vein in peridotite during drilling of an intense magnetic anomaly by Union Oil (1984–87). A series of apatite-bearing carbonate veins with anomalous lanthanides, uranium and niobium suggests the possible presence of carbonatite somewhere in the intrusive complex.

References: GSWA-WAMEX - I 3286.

Black Flag (Pirates)

Mine (gold): Au; Pb; Zn; Cu; Ag
Location: 30°32'50"S, 121°13'50"E; 24 km southeast of Ora Banda

Epigenetic base-metal mineralization is associated with gold within the Black Flag Fault at the point where the fault changes from a northerly to a north-northeasterly trend. Most mineralization is within complex quartz(–fluorite–sulfide) breccia hosted by ultramafic and mafic rocks of the Mount Pleasant Sill and Victorious Basalt. The fault is a brittle structure and dips between 60° and 70° to the northeast at the mine. Wall rocks are sheared for up to 5 m adjacent to the breccia system. Base-metal sulfides are predominantly galena and occur in irregular masses with rare inclusions of chalcopyrite. Sphalerite is also present and shows a range of iron contents. Chalcopyrite is locally altered to covellite, digenite and a copper–lead sulfide. Base-metal sulfides tend to be concentrated towards the footwall of the fault whereas gold is more concentrated towards the centre zone and hangingwall. A lead-isotope determination by Curtin University yielded an age of about 2.6 Ga for the galena (Blockley, J. G., 1995, pers. comm.)

Bennett (1989) has suggested that the gold was deposited with pyrite prior to the main period of base-metal mineralization. Barren quartz and carbonate veins postdate the base metals. Bennett also suggested that the base metals were deposited at least 100 m.y. after the gold, in meteoric or sea water, in an epithermal convection system driven by an unexposed granite intrusion. Intersections in mine diamond drillholes show, for example, 14 m at 6.2% Pb, 0.13% Zn, 0.12% Cu and 30 g/t Ag, and 14 m at 2.17% Pb, 1.16% Zn and 27.1 g/t Ag.

References: Bennett (1989), Witt (1993).

Nimbus (Boorara)

Deposit: Ag; Au; Zn (Pb)
Location: 30°47'20"S 121°38'34"E; 15 km east southeast of Kalgoorlie

Discovered in early 1995, the Nimbus deposit lies close to the historic gold-mining centre of Boorara, in deeply weathered and poorly exposed sedimentary and felsic volcanic rocks within the Boorara Domain of the Kalgoorlie Terrane (Swager et al., 1990). Rock types include grey cherts (possibly after black shales), metapelites, meta-arenites and porphyritic felsic rocks, all strongly silicified. Surface mineralization was detected, during follow-up of gold-in-soil anomalies, in a dark-grey siliceous rock and breccia which carries up to 400g/t Ag in a suite of silver halides including chloro-bromo-argyite.

Since the discovery, Archaean Gold NL have outlined three zones of mineralization with an extensive RAB/RC program. Thick, high-grade, shallow mineralization occurs in the Discovery and Eastern zones. In the Discovery zone, averages in excess of 1000 g/t Ag and 0.8 g/t Au (or 14 g/t Au equivalent value) have been obtained in the oxidized zone, which extends to a depth of to about 90 m. Limited drilling in fresh rock has identified a sulfide zone giving values of up to 10% Zn, 6.4% Pb and 0.6% Cu, with a best individual intersection of 17 m at 200 g/t Ag, 0.04 g/t Au, 4.8% Zn, and 0.7% Pb (Au equivalent 2.7 g/t).

The suite of elements (which also includes antimony) in the oxide and sulfide zones, and the felsic volcanic association with intense silica flooding, suggests an epithermal style of mineralization.

References: Westaway (1995), Archaean Gold NL, 1995a,b,c.

Widgiemooltha

Occurrence: Zn
Position: 31°45'S, 121°45'E; 3 km east of Higginsville

Diamond drilling by Barrier (1972) of a gossanous zone during nickel–copper search in ultramafic rocks of the Widgiemooltha Greenstone Belt intersected 0.06 m at 3.7% Zn in a talc–chlorite shear zone, trending southeast and dipping 45° southwest. The zone averaged 1.1% Zn over 3.65 m.

References: GSWA-WAMEX - I 102.

Pilbara Craton – Sylvania Inlier

Geological framework and exploration

The geological framework of the Pilbara Craton and Sylvania Inlier has been outlined in **Chapter 6**.

Deposits, prospects and occurrences

Jimblebar

Occurrence: Pb; Ag; Au
Location: 23°24'S, 120°04'E; 35 km east-southeast of Newman

A quartz vein containing fine-grained galena occurs near the old gold-mining centre of Jimblebar. A sample assayed 10.6% Pb, 22.88 g/t Ag and 6.53 g/t Au.

References: Blockley (1971).

Capricorn

Occurrence: Pb; Ag
Location: 23°30'S, 119°47'E; 16 km south-southeast of Newman

Two bodies (each 200 × 300 m) of quartz–clay–sericite, quartz–chlorite and chlorite schist (greenstone) in granite on the northern margin of the Sylvania Inlier contain small veins or pods with high-grade lead and silver. The mineralization is at the margins of the quartz pods in small (30 × 10 m) fractured quartz zones. Visible cerussite is confined largely to the contacts between vein quartz and schist and is locally abundant. Surface samples give up to 15.3% Pb and 75 g/t Ag. The veins, which may be associated with short splits of a 015° trending shear, are too limited in extent to be of economic interest in themselves.

Maritana Gold (1988–91), following up anomalous samples collected by a prospector, defined two lead–zinc–silver soil anomalies, each 200 by 300 m, and examined the very limited outcrop. They considered that the prospect may have some potential if the exposed mineralization reflected a folded zone of stratabound mineralization. This relatively unlikely situation does not seem to have been followed up.

References: GSWA-WAMEX - I 4977.

Murramunda

Occurrence: Pb; Ba
Location: 23°29'40"S, 120°21'10"E; 2.4 km west of Murramunda Homestead

Galena and barite occur in veins within the east-southeasterly trending fault which forms the northern margin of the Coobina ultramafic intrusion. Lead isotopes, analysed by J. R. Richards (1987, pers. comm.) of the ANU, fell well off the standard growth curve and gave no useful geochemical information.

References: Tyler (1991).

Pilbara Craton–Hamersley Basin

Geological framework

The Hamersley Basin is occupied by the volcano-sedimentary Mount Bruce Supergroup, which unconformably overlies the Pilbara Craton granite–greenstones. The three main components of the Supergroup are the basal Fortescue Group, the Hamersley Group and the Turee Creek Group (Fig. 97).

The Fortescue Group is some 6.5 km thick and consists mainly of mafic volcanic and volcaniclastic rocks with subordinate felsic volcanic, siliciclastic sedimentary and carbonate units. The group has been dated at 2765 Ma (Tyler, 1991). Figures 98 and 99 show simplified stratigraphic columns for various parts of the basin. The Hamersley Group is made up of about 2.5 km of banded iron-formation (containing most of the State's iron ore resources), shale, carbonate and tuff, interlayered with mafic and felsic intrusive rocks, conformably overlying the Fortescue Group. Units in the Hamersley Group are dated at about 2.5 Ga. The conformably overlying argillite and sandstone, with minor carbonate and conglomerate, of the Turee Creek Group (≤5 km thick) is restricted to scattered localities in the southern part of the Hamersley Basin.

The Fortescue Group succession shows general thickening from the northeast to the southwest, and deposition probably extended far beyond the present, structurally derived limits of the 'basin' (Blake, 1993). The succession as a whole formed in a number of distinctly different tectonic settings over about 330 m.y. (*see* lithological and stratigraphic variations in Figs 100 and 101). Table 21 shows the stratigraphy (*after* Trendall, 1990b) divided into six stratigraphic units, which cover most of the regional variations. In simplified form, these can be seen as representing an early phase of pre-rifting, west-northwest – east-southeast crustal extension (Mount Roe Basalt and Hardey Sandstone) followed by deposition in response to the subsequent development of a west-northwesterly trending rift which formed in approximately the position of the southern margin of the craton (Kylena Basalt to Maddina Basalt). Both these phases involved the eruption of extensive flood basalt. Subsequent deposition of the Jeerinah Formation and Hamersley Group occurred in a more stable shallow- to deep-water shelf setting bordering an ocean to the south and west of the craton.

The Mount Bruce Supergroup has recently been described and explained in terms of sequence stratigraphy and Phanerozoic-style plate tectonics (Barley et al., 1992b; Blake, 1993). The lithostratigraphy and sequence stratigraphy are compared in Figure 100, and regional

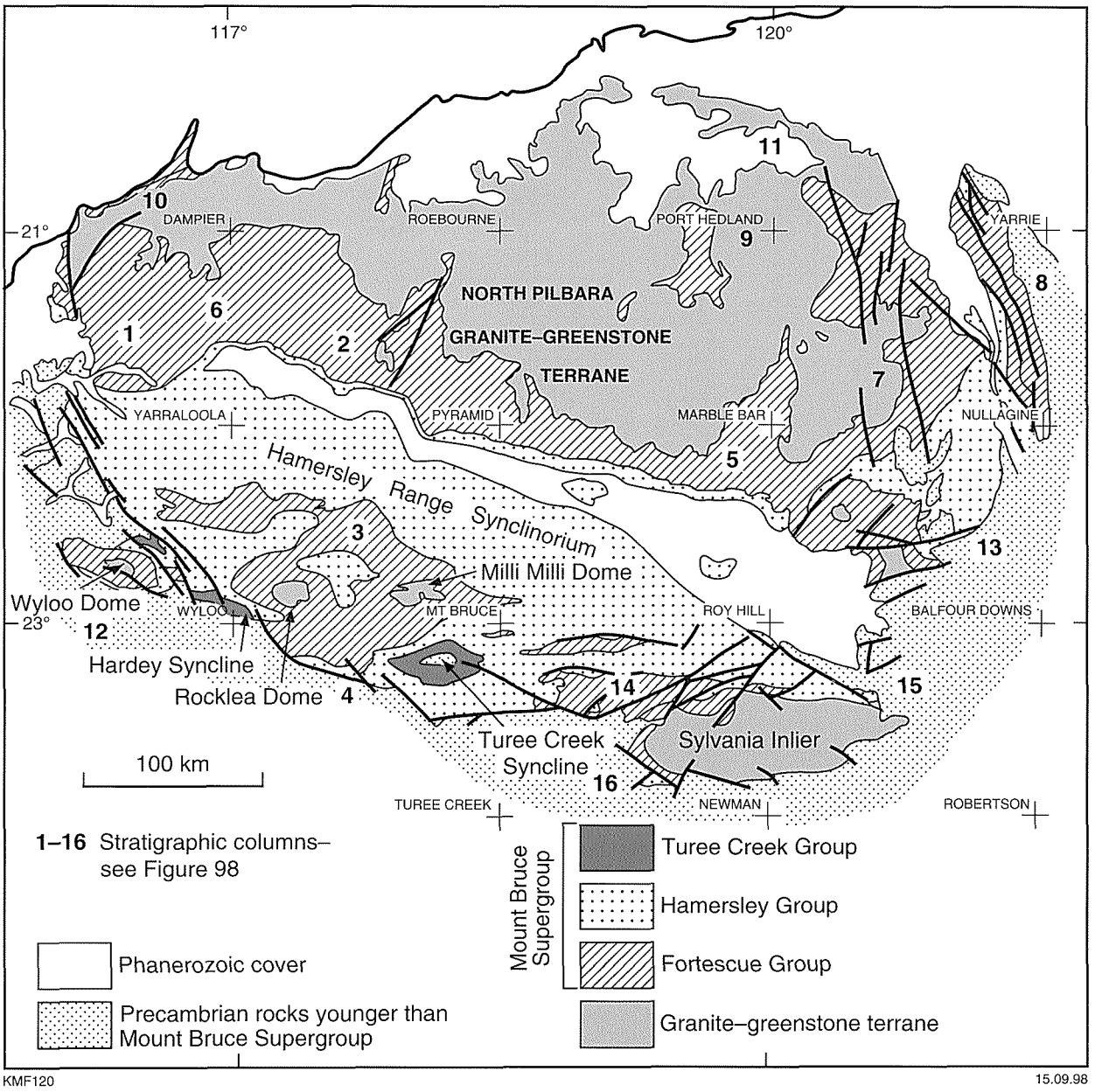


Figure 97. Hamersley Basin: outcrop areas of the Fortescue, Hamersley and Turee Creek Groups showing main structural elements (*after* Trendall, 1990b)

variations in the sequence stratigraphy are shown in Figure 99.

The basin sequence in the isolated Gregory Range outlier (Fig. 101), from the Kylena Basalt upwards, is essentially similar to that in the rest of the basin (Fig. 99). Below this, however, a major felsic volcanic event produced lavas containing stratiform intrusions of the same magma and underlain by the granitic parent of the volcanic rocks, all formed at about 2.7 Ga (Trendall, 1990b).

The basin sequence has been affected by very low-grade burial metamorphism, with grade increasing to the southwest. A north-northeasterly trending set of west-block-down normal faults developed in response to crustal extension and reactivated at later stages. During the Capricorn Orogeny, the Opthalmia Fold Belt developed in the southern part of the exposed Hamersley Basin in response to the collision about 2.0 Ga between the Pilbara and Yilgarn Cratons. In the western part of the fold belt the folds have formed open dome-and-basin structures that trend northwesterly and are interpreted to be pre-orogenic (Tyler, 1991). In the eastern part, tight east–west folds and related thrust faults formed at a later stage, synchronous with the development of the Ashburton Basin.

In the Gregory Range the structure is dominated by faulting and intense local shearing along the length of the range and the Fortescue Group rocks dip gently to the west. Five main faults, which divide the rocks into five

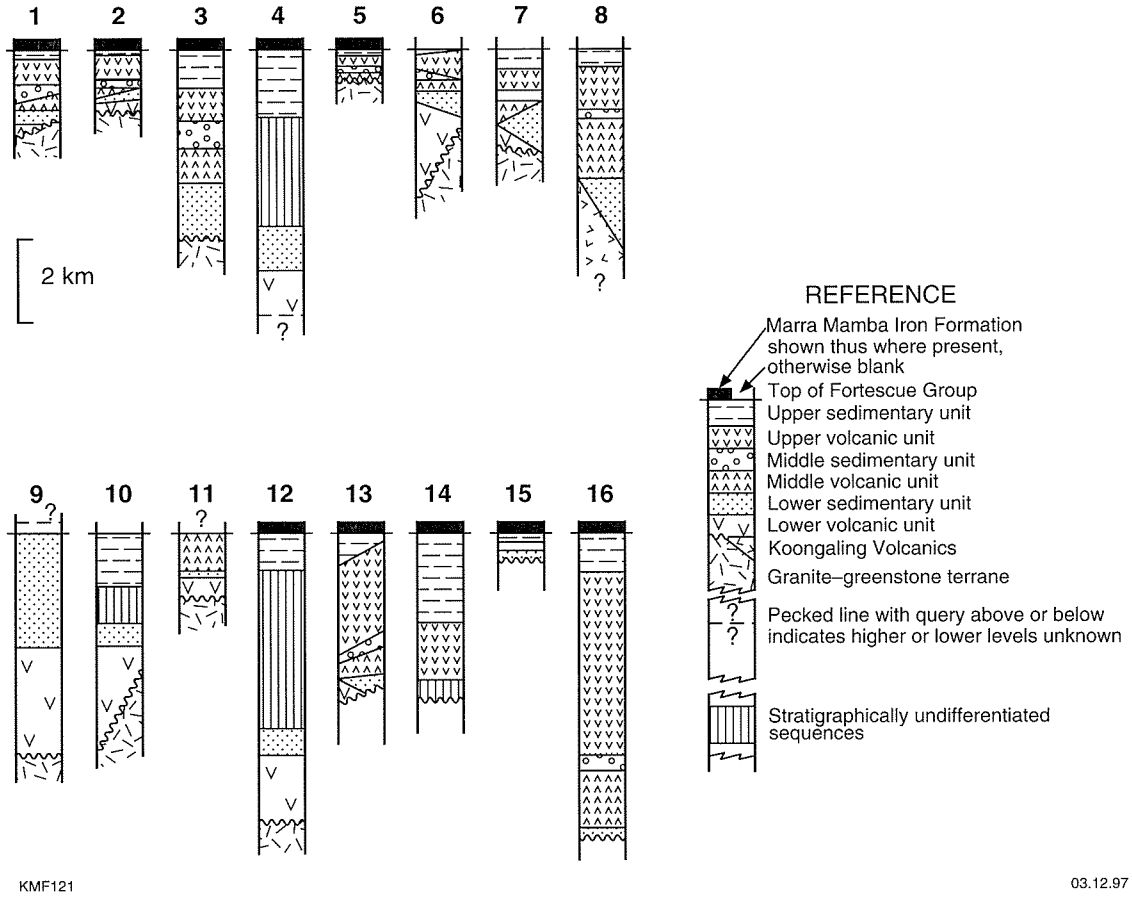


Figure 98. Regional variation in Fortescue Group stratigraphy (*after* Trendall, 1990b)

'slices' (Trendall, 1991), are interpreted as growth faults that may have been reactivated at a later stage.

Mineralization

Most lead–zinc–copper occurrences and prospects in the Hamersley Basin are small vein-type bodies either in the southwestern dome-and-basin structural environment, or in the stratigraphically distinct and structurally complex Gregory Range in the east.

The Braeside lead field occupies an elongate section of the central part of the Gregory Range, within the central part of the Newdegate slice (Fig. 101). The galena mined (about 3000 t between 1925 and 1951) is associated with (intra-slice) faults which cut Tumbiana Formation felsic tuff and rhyolitic lava and underlying ?Kylena Basalt. These faults are subparallel to the main 'slice' faults and the strike of the sedimentary rocks but dip at a steep angle to the east in contrast to those rocks. Ages in the range 2.7 to 2.74 Ga for lead samples from these veins are only marginally younger than the model age of 2.76 ± 0.01 Ga for the Kylena Basalt (Richards et al., 1981). Mineralization is therefore presumably related to the same tectonic events that initiated basin development and early volcanism.

There are small vein-type occurrences of lead, copper, silver and gold around the domes that expose the Fortescue Group and granite–greenstones of the Pilbara Craton in the southwestern part of the Hamersley Basin. These suggest some mobilization of base metals. Lead and copper mineralization associated with easterly trending quartz veins at Coppin Pool (Blight, 1985), on the south side of the Milli Milli Dome, has given a lead age of 2.4 Ga (Richards, J. R., 1982, pers. comm.).

Blight (1985) considered the potential of the Mount Roe Basalt in this area for volcanogenic massive sulfides, but concluded, on the basis of the continental nature of the volcanism, that potential was low.

Exploration

Only minor exploration, largely limited to surface sampling, has been carried out in the modern era in the vicinity of known vein-type lead–zinc occurrences. In the Ragged Hills area some attention was given to the possibility of relatively wide, high-grade mineralized veins or to disseminated targets. Exploration in the Belvedere area of the Wyloo Dome by Placer and Whim Creek principally tested gold potential.

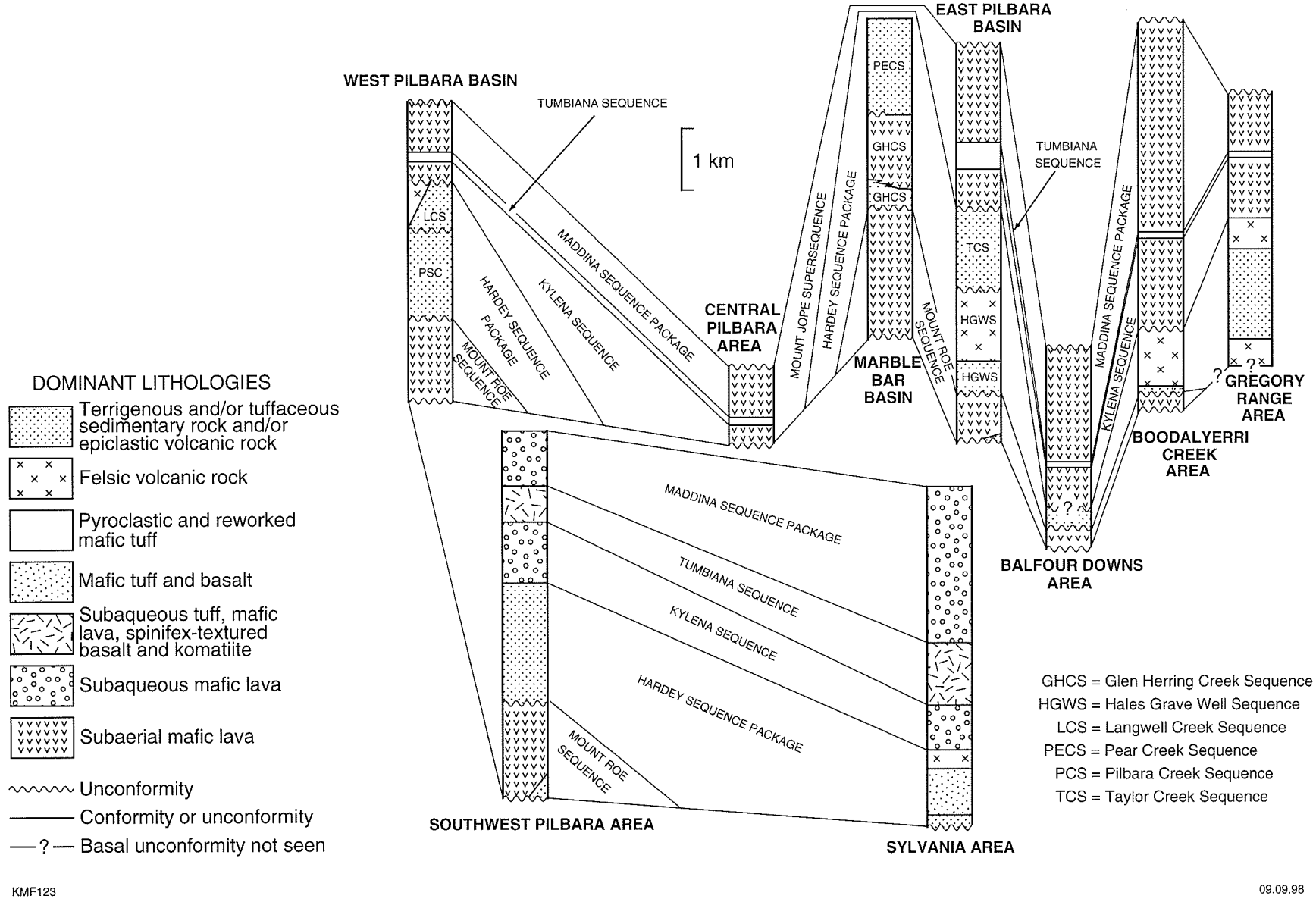


Figure 99. Fortescue Group: regional variation in sequence stratigraphy (*after* Blake, 1993)

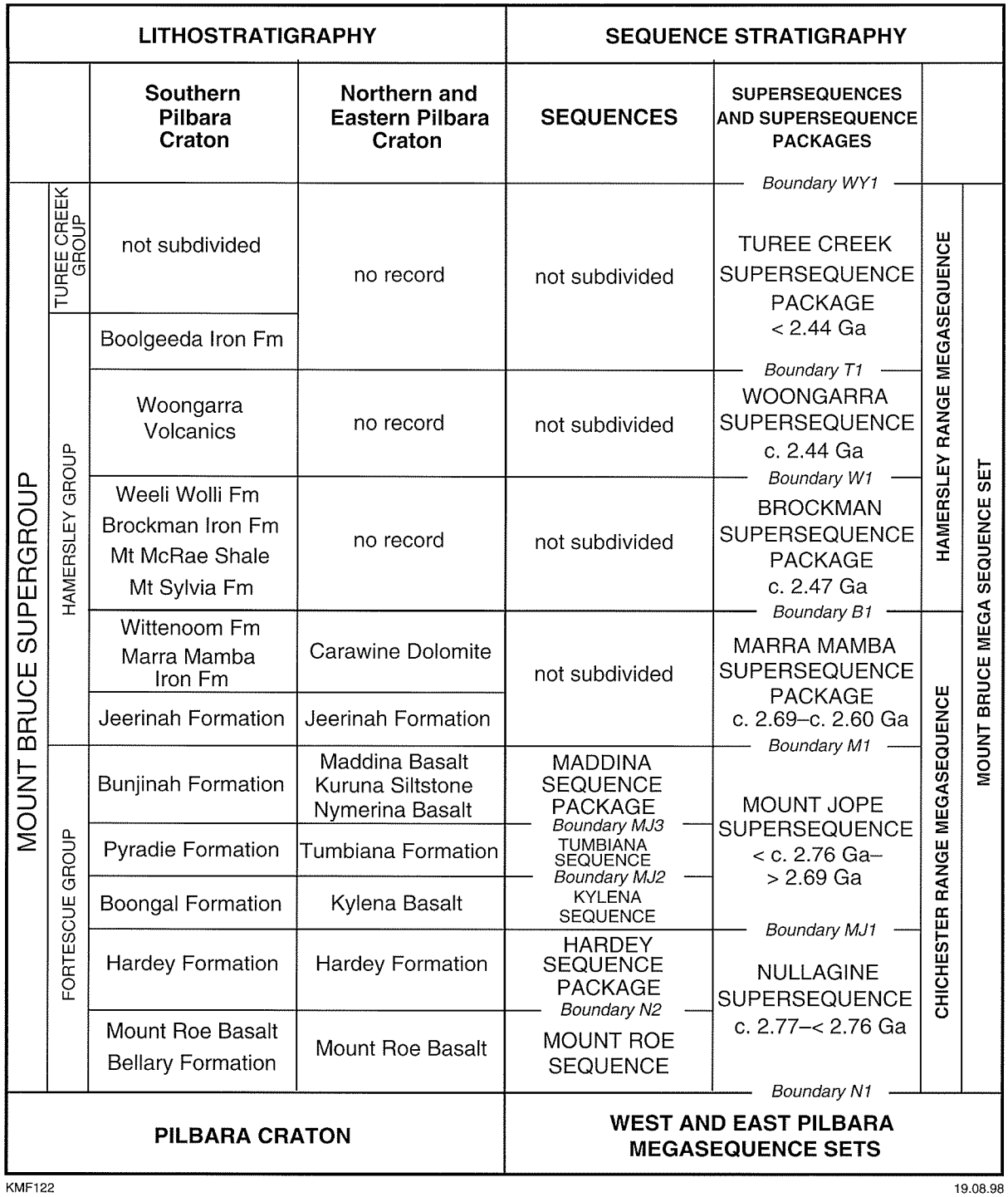


Figure 100. Mount Bruce Supergroup: comparison of lithostratigraphy and sequence stratigraphy (*after* Barley et al., 1992)

Deposits, prospects and occurrences

Barker Well

Abandoned mine: Pb; Ag; Zn
Location: 21°01'S, 121°05'20"E; 50 km south-east of Warrawagine

At the northern end of the Braeside lead field a group of quartz veins trending between 320° and 340° in basalt of the Fortescue Group contains argentiferous galena and sphalerite in five worked bodies. The lodes are up to 64 m long and 1 m wide and samples contain up to 43.7% Pb, 0.9% Zn and 47.4 g/t Ag. Government-sponsored drilling in 1928 gave a best intersection of 2.25 m at 48.6% Pb, 5.5% Zn and 40.43 g/t Ag.

Table 21. Stratigraphy of the Fortescue Group in the northern and southern Hamersley Basin

Northern Hamersley Basin[a]	*Southern Hamersley Basin* [b]
Jeerinah Formation Siltstone; shale and chert; sandstone; local felsic lava, tuff and agglomerate; basalt; mafic sills locally abundant	**Jeerinah Formation** Mudstone and siltstone; chert; sandstone; basalt, pillow basalt and agglomerate; dolerite
Maddina Basalt Vesicular and amygdaloidal basalt and andesite	**Bunjinah Formation** Pillow basalt, vesicular basalt and volcanic breccia
Kuruna Siltstone Sandstone and siltstone; shale; ooidal sediments; pisolitic tuff and banded siliceous limestone	**Pyradie Formation** Ultramafic flows and pillow lavas, tuff, chert
	Boongal Formation Basalt; pillow basalt; volcanic breccia; mafic tuff
Nymerina Basalt Basalt	
Tumbiana Formation (Pillingini Tuff) Siliceous limestone (stromatolitic) and pisolitic tuff; subordinate tuff, basalt and sediments	
Kylena Basalt Massive amygdaloidal and vesicular basalt and andesite; subordinate but widespread interbedded sediments	
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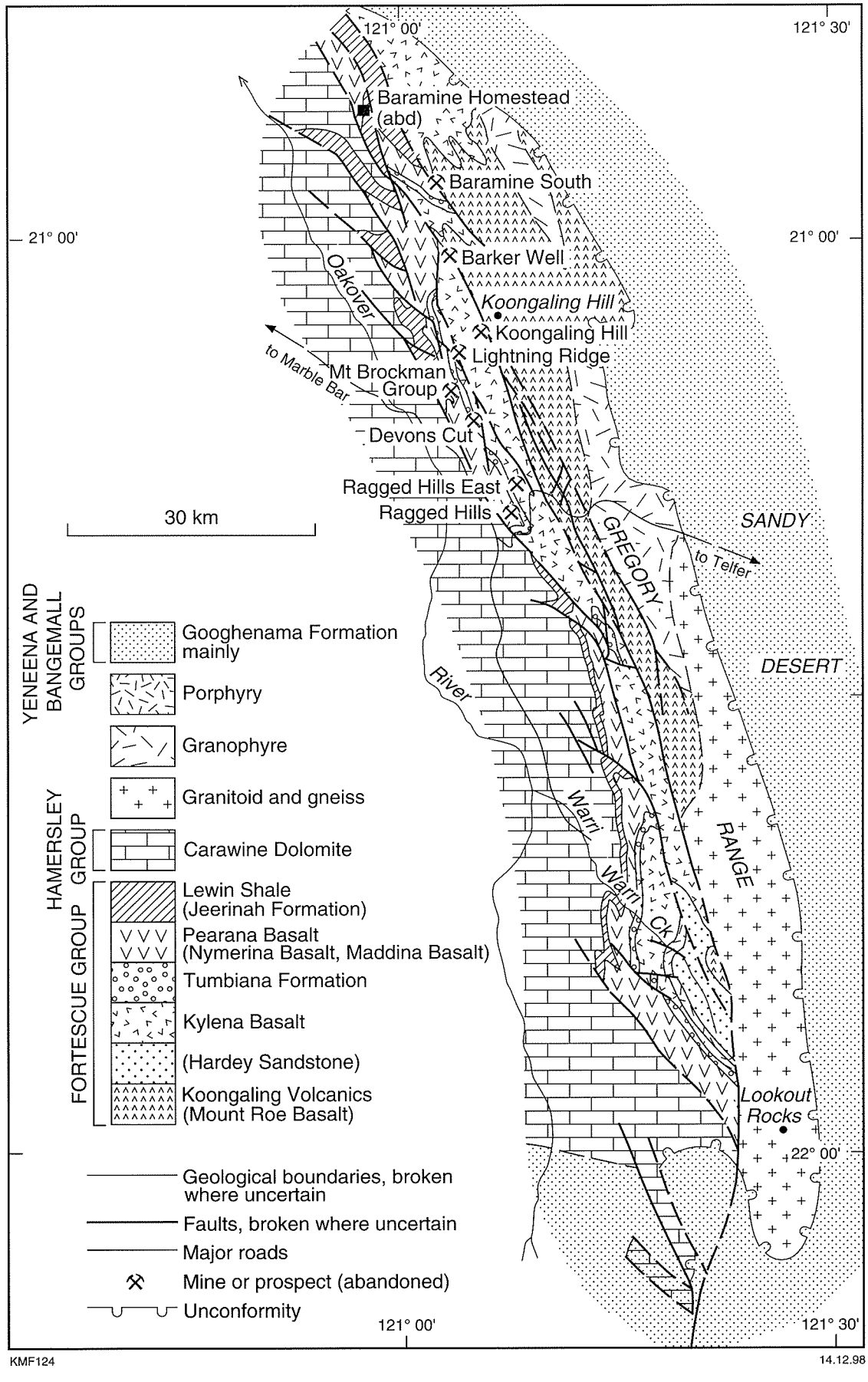


Figure 101. Gregory Range area: geology and base-metal mines and prospects (*modified after* Trendall, 1991)

4.2 m wide in a cymoid loop split on the western fault. The mineralization forms massive lenses or disseminations in quartz and quartz-filled breccia and is mainly galena with small amounts of sphalerite, chalcopyrite, bornite and pyrite. Cerussite, anglesite and malachite are present in the oxidized zone. An average of 22 ore samples gives 27.2% Pb and 110.72 g/t Ag. A best drill intersection gives 1.8 m at 8.1% Pb, 4.6% Zn and 6.2 g/t Ag. Copper is present in the southern shoot and is enriched at the surface (2.00% Pb, 1.9% Zn and 6.1% Cu).

The deposit was worked over 150 m along strike and to 46 m depth between 1925 and 1928, and from 1950 to 1959, for a total production of 2927.16 t of lead, 24.44 t of zinc and 87 090 g of silver. Anglo Westralian, who conducted the bulk of the underground mining in the 1950s, also drilled three diamond holes (*see* intersection quoted above). Associated Mins. (1970–71) examined the effect of country rock lithologies on ore development in the fault-veins and on the potential of geochemically anomalous acid porphyry horizons. Samples (?rock-chip) gave up to 2.00% Pb, 1.9% Zn and 6.1% Cu. WMC (1969–72) carried out stream-sediment and rock-chip sampling in the area and recorded lead up to 64% in veins and zinc up to 2.00% in small veins. Hancock and Wright (1974–82) carried out mapping, ground magnetic and geochemical surveys in the area. At Ragged Hills they considered the high assays to be due to supergene enrichment. Esso (1980–82) examined the Lewin Shale for sediment-hosted, stratiform targets with discouraging results. Newmont (1988) explored gold/platinum potential in the volcanic/sedimentary sequence with stream-sediment and rock-chip sampling, but with poor results.

References: Blockley (1971), Marston (1979), Hickman (1983), GSWA-WAMEX - I 256, I 966, I 2491, I 3224, I 3743.

Ragged Hills East

Abandoned mine: Pb; Ag; Zn
Location: 21°16'40"S, 121°08'50"E; 65 km southeast of Warrawagine

A line of en echelon faults north-northeast of the Ragged Hills Mine hosts north-northwesterly trending, steep easterly dipping quartz veins in coarse dolerite. Six separate shoots are described by Blockley (1971). A sample taken from the No. 3 shoot opencut in 1968 assayed 50.6% Pb, 0.22% Zn and 223.94 g/t Ag.

Between 1949 and 1958, production from this group was 68.1 t of lead, 0.63 t of zinc and 8962 g of silver from 106.49 t of ore.

Reference: Blockley (1971).

Devons Cut

Abandoned mine: Pb; Zn; Ag
Location: 21°12'30"S, 121°05'40"E; 10.5 km north-northwest of the Ragged Hills mine

Anglesite, cerussite and oxidized zinc and copper minerals are seen in the workings over 30 m of a quartz reef striking at 325° and dipping 80–85° east. The reef has been worked to 18.2 m depth and samples indicate lead up to 30.59%, zinc up to 12.6% and silver up to 102 g/t. Total production from the periods 1926–28 and 1955–56 is 34.5 t lead and 7464.7 g silver.

Reference: Blockley (1971).

Mount Brockman Group

Abandoned mines: Pb; Zn
Location: 21°10'30"S, 121°04'20"E; 4.8 km north-northwest of Devons Cut

Three small mines are located on three veins striking at 320–330° and dipping at 75–80° east. Assay results were up to 54.8% Pb and 108.23 g/t Ag in separate samples. Production from the group between 1947 and 1955 was 52.8 t of lead and 17 604.2 g silver.

Reference: Blockley (1971).

Lightning Ridge (Moxom Well)

Abandoned mines: Pb; Zn; Ag
Location: 21°07'25"S, 121°04'E; 11 km northeast of Braeside Station (abandoned)

These mines follow a quartz-filled subvertical fault over 1.07 km at 290°. Mining has been restricted to a few richer patches at the western end of the reef and extends over 30 by 6 m. Galena, chalcopyrite, bornite, covellite and malachite are present in ore dumps. Separate samples gave up to 33.8% Pb, 1.32% Zn and 49.8 g/t Ag. Production between 1949 and 1954 was 19.3 t of lead and 2674.7 g silver.

Reference: Blockley (1971).

Koongalin Hill

Abandoned mine: Pb; Zn
Location: 21°06'20"S, 121°05'30"E; 3.2 km east-northeast of Lightning Ridge

The mine is on a 0.3 m-wide quartz vein striking at 300° that links two barren veins trending 340°. Work has taken place over 180 m in two shafts and several opencuts. The average of 11 samples is 31.7% Pb and 118.18 g/t Ag. Production in the periods 1925–27 and 1949 was 34.5 t of lead and 279.9 g of silver.

Reference: Blockley (1971).

Bellary Dome

Occurrence: Pb; Cu
Location: 23°09'30"S, 117°39'E; 4 km northwest of Paraburdoo

The Bellary Dome, one of a number of domes reflecting basement horsts near the southern margin of the Hamersley Basin, hosts lead mineralization in a minor occurrence located by Hamersley Exploration (1980–83). A quartz vein with massive galena (replaced by anglesite) and associated copper, silver and minor gold occurs in late

Archaean metasedimentary rocks of the Bellary Formation in the Fortescue Group. The vein has an easterly trend subparallel to axial-plane cleavage. Mineralization exists on both sides of the vein. Rock-chip sampling gave up to 10.45% Cu, 10% Pb and 868 g/t Ag. Costeaning indicated no significant dip extension.

References: Blight (1985), Thorne et al. (1991), GSWA-WAMEX - I 1969.

Belvedere (Belfry, Blacks, Metawandy)

Abandoned mine: Au; Ag; Cu; Pb
Location: 22°36'50"S, 116°17'20"E; 11.2 km north-northeast of Wyloo Homestead

At Belvedere a northerly trending mineralized vein (No. 1 reef), dipping 45° to the west is offset by a second, northeasterly trending, fault-controlled quartz vein, dipping 50–70° west (No. 2 reef) within the Mount Roe Basalt of the Fortescue Group in the Wyloo Dome. The Belvedere mineralization (gold, copper and lead) occurs in these veins within a 120 m-thick, west-northwesterly striking, southerly dipping, quartz-intruded horizon of mafic metavolcanic rocks and silicified chert of the Mount Roe Basalt. The Blacks (or Belfry) copper mine also lies within this horizon 3 km to the east. The mineralization at Belvedere is characterized by surface enrichment and is present as bunches of galena, cerussite, beudantite and plumbojarosite. Copper minerals were reported by Marston (1979).

The 0.6 m-wide vein was mined over 46 m and to a depth of 15 m. Production in 1949 of 1.77 t of lead and 2488.2 g of silver probably came from dumps. Placer (1968) carried out soil and stream-sediment sampling and diamond drilling near Belfry with only poor results. Whim Creek (1974–77) collected rock-chip samples with up to 6.00% Pb and 4.4% Cu in quartz veins in the general vicinity of the Belfry and Belvedere mines. Channel samples at Belfry gave up to 2.87% Pb and 1.3% Cu. Mineralized veins are typically associated with the Belvedere–Belfry horizon (silicified chert).

References: Blockley (1971), Marston (1979), Blight (1985), GSWA-WAMEX - I 289, I 1125.

Robe River

Occurrence: Pb; Ag
Location: 21°40'S, 116°25'E; 0.23 km east of Deepdale Homestead

Galena occurs in a quartz vein within the Mount Jope Volcanics of the Fortescue Group. A surface sample contained 47.4% Pb and 115.7 g/t Ag.

Reference: Blockley (1971).

Beasley River

Occurrence: Pb; Cu
Location: 22°47'S, 117°12'E; 60 km northwest of Paraburdoo

Thin, mineralized, generally conformable quartz veins characterize pyritic/graphitic shale units (20 m thick) over a strike length of 15 km in a tuff/greywacke sequence that forms part of the Hardey Sandstone, at the base of the Fortescue Group on the western flank of the Rocklea Dome. The veins are up to 4 m thick and contain up to 40% sulfides. Fresh argentiferous galena is associated with limonitic boxworks and minor malachite and cerussite. Rock-chip samples gave up to 20% Pb, 0.5% Zn, 13.5% Cu, 340 g/t Ag and 3.29 g/t Au. The best intersection in percussion drilling was only 1 m at 0.575% Pb.

Amax (1979) carried out rock-chip sampling, costeaning and percussion drilling in an unsuccessful attempt to locate stratiform mineralization.

Reference: GSWA-WAMEX - I 1119.

Coppin Pool

Prospect: Pb; Cu (Ag; Hg; V)
Location: 22°53'S, 117°08'E; 1.3 km southwest of Coppin Pool on Turee Creek

Galena, with a range of other primary and secondary minerals, is contained in a vuggy quartz vein cutting a dolerite sill within the Hardey Sandstone on the southern side of the Milli Milli Dome. The vein, which strikes at 290° and generally dips 40° south, can be traced over a considerable distance, but mineralization is concentrated in a flat-plunging pod formed where the dip flattens locally to 10°S. (Blockley, J. G., 1995, pers. comm.).

Associated minerals include minor chalcopyrite and tetrahedrite in the primary ore and in the supergene assemblage the minerals are cerussite, anglesite, pyromorphite, malachite, azurite, chrysocolla, chalcocite, covellite, vanadinite, mottramite and cinnabar, together with a number or rarer species (Nickel, 1985).

Past work by an unknown prospector consisted of shallow trenching and stripping over a distance of 5 m. The vein is about 80 cm wide where excavated, but ranges up to 5 m wide elsewhere. No production has been reported.

Richards and Blockley (1984) report a lead-isotope age of about 2.4 Ga for the primary mineralization.

References: Nickel (1985), Richards and Blockley (1984).

Ashburton Basin

The geological framework of the Ashburton basin has been outlined in **Chapters 6** and **7**.

Mineralization

Small quantities of gold, silver, copper and lead have been extracted from the Ashburton Basin since the latter part of the nineteenth century (Table 22). Thorne and Seymour (1991) pointed out that most of these minerals exist as vein-hosted sulfides in west-northwesterly and north-

Table 22. Lead and silver production from the Ashburton Basin (to December 1986)

Mine or group	*Lead ore and concentrate (t)*	*Lead (t)*	*Silver (kg)*
Belvedere	4.0	1.8	2.5
Aerial	155.0	100.0	27.1
Silent Sisters	162.0	116.0	13.8
Kooline	3 638.0	2 679.0	868.4
Total	**3 959.0**	**2 896.8**	**911.8**

NOTE: *from* Thorne and Seymour (1991)

northwesterly trending D_2 dextral wrench faults. Gold is present with pyrite or arsenopyrite. Fracturing along these trends is considered to have taken place fairly late in the tectonic evolution of the area, following deposition of the Capricorn Formation and intrusion of the Boolaloo Granodiorite. The D_2 faults cut across F_2 folds and are aligned parallel to, or at an acute angle to, the trend of the principal wrench faults which bound the northeastern margin of the Ashburton Basin. Several small deposits also occur on northerly to northeasterly trending fissures in the Mount Bruce Supergroup and lower Wyloo Group (e.g. Aerial, Belvedere, and Silent Sisters). These fissures seem to be synthetic and antithetic faults also related to the D_2 dextral wrenching event.

Syngenetic epithermal gold and silver (with associated, subordinate lead and copper) mineralization at Mount Clement, distal volcanogenic copper, lead and zinc mineralization at Yarraloola, stratiform lead and copper at Mount Stuart, and possible syngenetic, stratiform mineralization at Slate Bore are the only examples of pre-D_2 mineralization.

Indications from the dating of mineralization through geochronological studies support a late-stage event. Dates from the west-northwesterly fractures at Kooline and the Gorge, and from northerly to northeasterly faults and veins in the Wyloo Dome and Duck Creek Dolomite, indicate an age of about 1.55 Ga for mineralization. (Richards et al., 1981; Thorne and Seymour, 1991).

Most lead deposits are restricted to the central part of the basin within the Ashburton Formation and the Duck Creek Dolomite. Mineralization in the Kooline centre lies within a suite of submarine-fan deposits derived from an area to the south of the Ashburton Basin. The location of lead and silver veins in the upper part of the Duck Creek Dolomite at Aerial and Silent Sisters suggests that wall-rock reactions with dolomite may have some effect in localizing mineralization.

Exploration

Only early exploration in the Ashburton Basin, from the late 1940s to the early 1970s, specifically targeted vein-type lead and zinc. This was mostly in the known lead areas such as the Kooline and Ashburton Downs fields. The Kooline field was opened up and mined for lead and silver between 1948 and 1959. Ashburton (I 3227) (1960–63) discovered and opened up the Ashburton Downs field and mined copper from the Bali Lo, Bali Hi and Ledge mines between 1963 and 1966. Westfield Minerals, in collaboration with Ashburton, carried out air blast drilling at the Aerial Mine to define areas of surface enrichment, drilled a gossan at Silent Sisters and put down an inclined shaft at Bali Hi, all in the early 1960s. PMI carried out limited drilling in the Ashburton Downs area in the latter part of the 1960s and ACM drilled at the Aerial mine for secondary copper and silver at the watertable.

By 1968, EZ (I 2603) was exploring the Aerial and Silent Sisters mine areas for stratabound targets in the Duck Creek Dolomite using stream-sediment and rock-chip geochemistry. BHP (I 3099) also targeted carbonate-hosted mineralization in these areas in the early 1980s, and sampling defined anomalism related to veining in fault zones. Exploration in the Ashburton Downs area by Esso in the late 1970s (I 1282) and UAL/Barrack (I 5944) in the 1980s was primarily to assess uranium and gold potential in the vein systems. Ground magnetic and radiometric surveys and geochemical sampling were followed by extensive drilling of the shear system and definition of subeconomic lead and copper resources at Bali Hi and Bali Lo. UAL also carried out regional exploration for uranium related to base metals, with negative results. In the late 1980s, Golden Deeps (I 3746) explored in the Kooline area, specifically seeking gold in a quartz-veined greywacke unit of the Ashburton Formation. Magnetic surveys and stream-sediment sampling failed to define RAB targets. For other exploration in relation to stratabound targets see **Chapters 6** and **7**.

The Mount Clement gossans were discovered by a kangaroo shooter in the early 1970s and shown to BHP (I 6434) who carried out ground-magnetic surveys, geological mapping, surface geochemistry and drilling. Difficulties with the interpretation of this highly altered and deformed prospect led to various changes in the approach to its exploration by different operators. Newmont recognized the epithermal nature of the deposit and carried out extensive percussion drilling to establish a gold–silver resource.

The discovery and elucidation of the Mount Clement deposit led to further exploration for this type of target by others, including Command/West Coast Holdings in the Capricorn Range in the early 1980s. Regional stream-sediment sampling also included stratabound sulfides as a potential target. Four anomalies were located, two with exhalative gold potential, one with stockwork gold potential, and one with exhalative base-metal potential in rocks of the Capricorn Formation. Austamax/Billiton also investigated epithermal gold/base-metal potential in the late 1980s in the Marboo Well, Kunda Creek and Paddy Well areas. Stream-sediment sampling located two weak anomalies in the Marboo Well area but ground magnetics and detailed soil geochemistry failed to define significant potential.

Deposits, prospects and occurrences

Aerial Mine

Abandoned mine: Pb; Ag; Sb; Cu; As
Location: 22°53'S, 116°37'E; 44 km east-southeast of Wyloo Homestead

Mineralization at Aerial is in a 15 m-wide, northeasterly trending fault zone that cuts the Upper Duck Creek Dolomite 1 km south of the east-southeasterly trending anticlinal axis which is a southeasterly continuation of the Wyloo Dome. Galena with cerussite, anglesite, malachite and azurite occurs in pods in quartz–kaolin silicified dolomite gangue within the fault. Lead is also disseminated in quartz veins up to 1.2 m wide, and minor copper, zinc, antimony and silver are associated with the mineralization. The mineralized shoots lie parallel or subparallel to the fault zone. A chip sample over a 1.1 m shoot gave 2.66% Pb, 9.33 g/t Ag and less than 0.01% Zn.

The mine workings cover about 350 m of the fault zone. Most of the ore came from two opencuts up to 6 m deep, and production over the period 1949–53 was 100.17 t lead and 27 152.9 g silver. Westfield (1961–67) drilled 63 airblast holes to test for near-surface secondary enrichment of lead; a possible ore shoot 60 m long and running 18% Pb was outlined. Soil and stream-sediment sampling to define further targets was unsuccessful. EZ (1968–70) carried out further stream-sediment sampling but located only minor anomalies. ACM (1970) drilled six diamond holes in the fault zone targeting secondary copper and silver at the watertable. Narrow zones grading up to 9% Pb, 22% Cu and 100 g/t Ag were defined, although poor core recovery limited interpretation of their features. BHP (1980–83), exploring for possible stratabound or stratiform MVT type mineralization, defined anomalism in fault zones, quartz veins, silica breccias and Tertiary silcrete. Rock-chip sampling in the main Aerial fault zone gave up to 29% Pb, 0.3496% Zn, 0.2180% Sb and 85 g/t Ag in separate samples and a parallel fault/vein gave 3.58% Pb. The company found no evidence for primary stratiform mineralization.

References: Blockley (1971), Thorne et al. (1991), GSWA-WAMEX - I 2603, I 3099, I 3227.

Silent Sisters

Abandoned mine: Pb; Ag; Zn
Location: 22°52'40"S, 116°27'30"E; 24.1 km southeast of Wyloo Homestead

Five lead-bearing quartz veins trending northeast to northwest, and dipping steeply either east or west, cut Duck Creek Dolomite south of the Wyloo Dome. Most are tension-gash fillings rather than veins on well-defined shears. Galena and sphalerite occur in a gangue of quartz, silicified dolomite, barite and calcite. Anglesite and cerussite are also present with traces of azurite and malachite. A chip sample from the main lode gave 2.74% Pb, 7.15 g/t Ag and less than 0.01% Zn. There is intense folding to the north and east of the mine but the dolomite is relatively undisturbed in the mined area.

The deposit was discovered in 1947 and worked between 1949 and 1953, with 115.8 t of lead and 13 778.6 g of silver produced from workings in opencuts and adits. Westfield Minerals drilled a gossan body but located only iron minerals at depth. Electrolytic Zine (1968–70) explored for stratabound MVT-style mineralization but found only mineralized quartz veins. Stream-sediment and rock-chip sampling gave discouraging results.

References: Blockley (1971), Thorne et al. (1991), GSWA-WAMEX - I 2603.

The Bali Hi group (Ashburton Downs Station)

The Bali Hi, Bali Hi East, Bali Lo and Ledge deposits lie about 13 km southwest of Ashburton Downs Homestead and are all in shear planes related to the Bali Shear at, or close to, the unconformable base of the Capricorn Formation on the Ashburton Formation (Fig. 102). The Ashburton Formation in this area consists of lithified deep-water trough sediments; predominantly slate and siltstone with 'mud flow' conglomerate, greywacke and tuff horizons. The Capricorn Formation consists of shelf-facies conglomerate, dolomite and greywacke with minor tuff.

The mineralized zones were discovered between 1960 and 1963 and opened up by Ashburton Mining, with 129 t of copper ore averaging 8.84% Cu having been mined from Bali Lo, Bali Hi and the Ledge between 1963 and 1966. The mineralized zones contain copper, lead, zinc and silver mineralization with pyrite, galena, chalcopyrite, bornite, digenite, covellite, tetrahedrite and skutterudite recognized in primary ore. A complex assemblage of secondary minerals near the surface includes adamite, antlerite, bayldonite, beudantite, bindheimite, brochantite, caledonite, carmintite, cerussite, chlorargyrite, chrysocolla, cinnabar, diaboleite, goethite, hematite, hemimorphite, hydrozincite, jarosite, lavendulan, linarite, malachite, mimetite, olivenite, plattnerite and rosasite.

Bali Hi (Anticline)

Deposit: Pb
Location: 23°24'30"S, 116°56'E; 8.5 km west-southwest of Ashburton Downs Homestead

Bali Hi lies 1.2 km east-southeast of Bali Lo within the same shear zone, the Bali Shear. At this location the shear is about 2 m wide, dips 50° south and is sporadically mineralized for 700 m in silicified, kaolinized felsic tuff, sandstone and minor dolomite of the Capricorn Formation, and chloritic slate, mudstone and greywacke of the locally folded and boudinaged Ashburton Formation. The shear coincides with a zone of leaching with kaolin and silica alteration. Narrow pods or shoots of mineralization located along the shear zone contain disseminated pyrite, galena, chalcopyrite, bornite, digenite, covellite, tetrahedrite and skutterudite with malachite, azurite and cerussite at the surface. The best intersections in drilling for individual base metals are 2 m at 9.2% Pb, 2 m at 2.16% Cu and 2 m at 1.22% Zn.

The workings consist of a few pits and an inclined shaft (Fig. 103), which encountered primary ore when

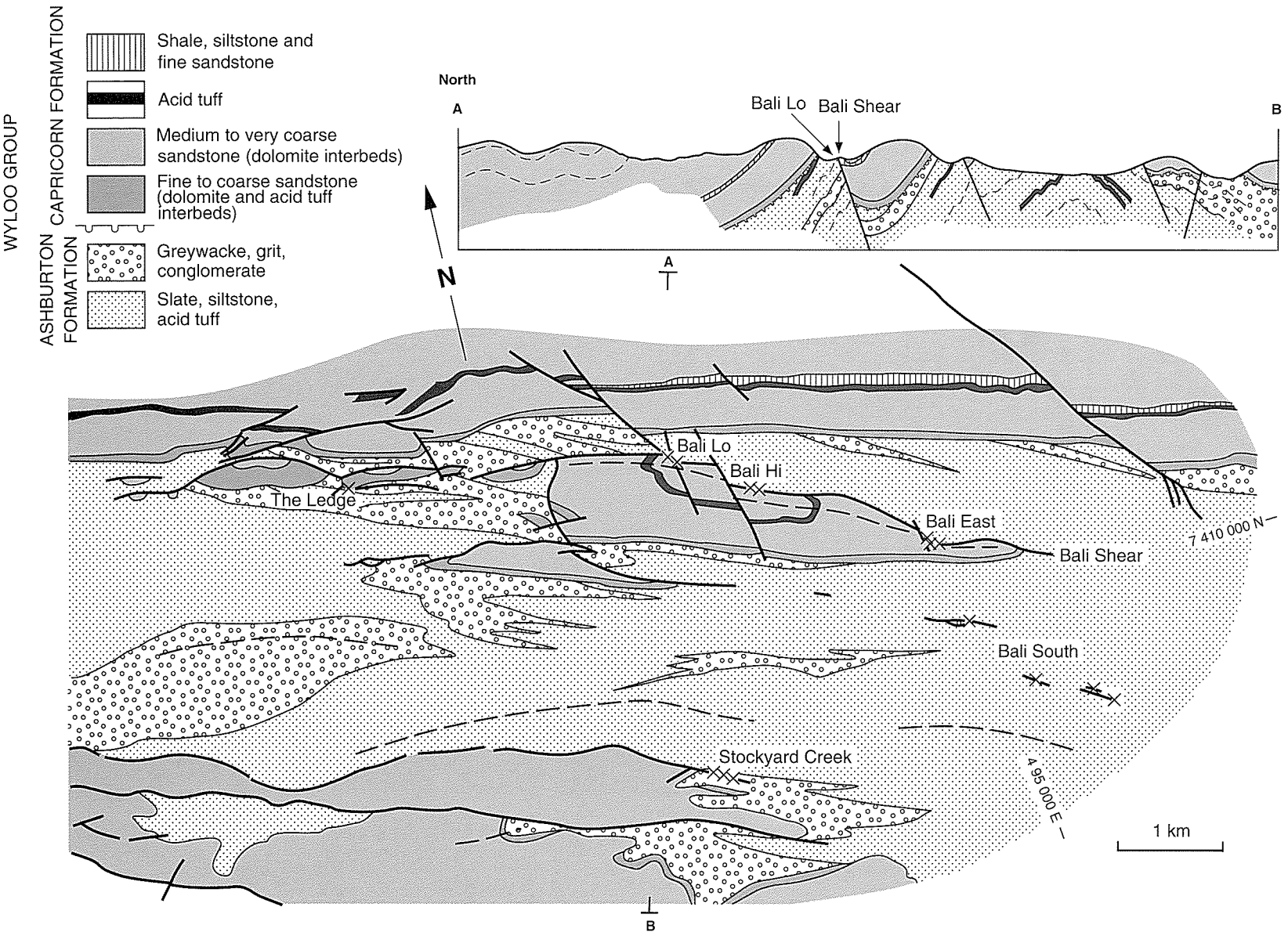
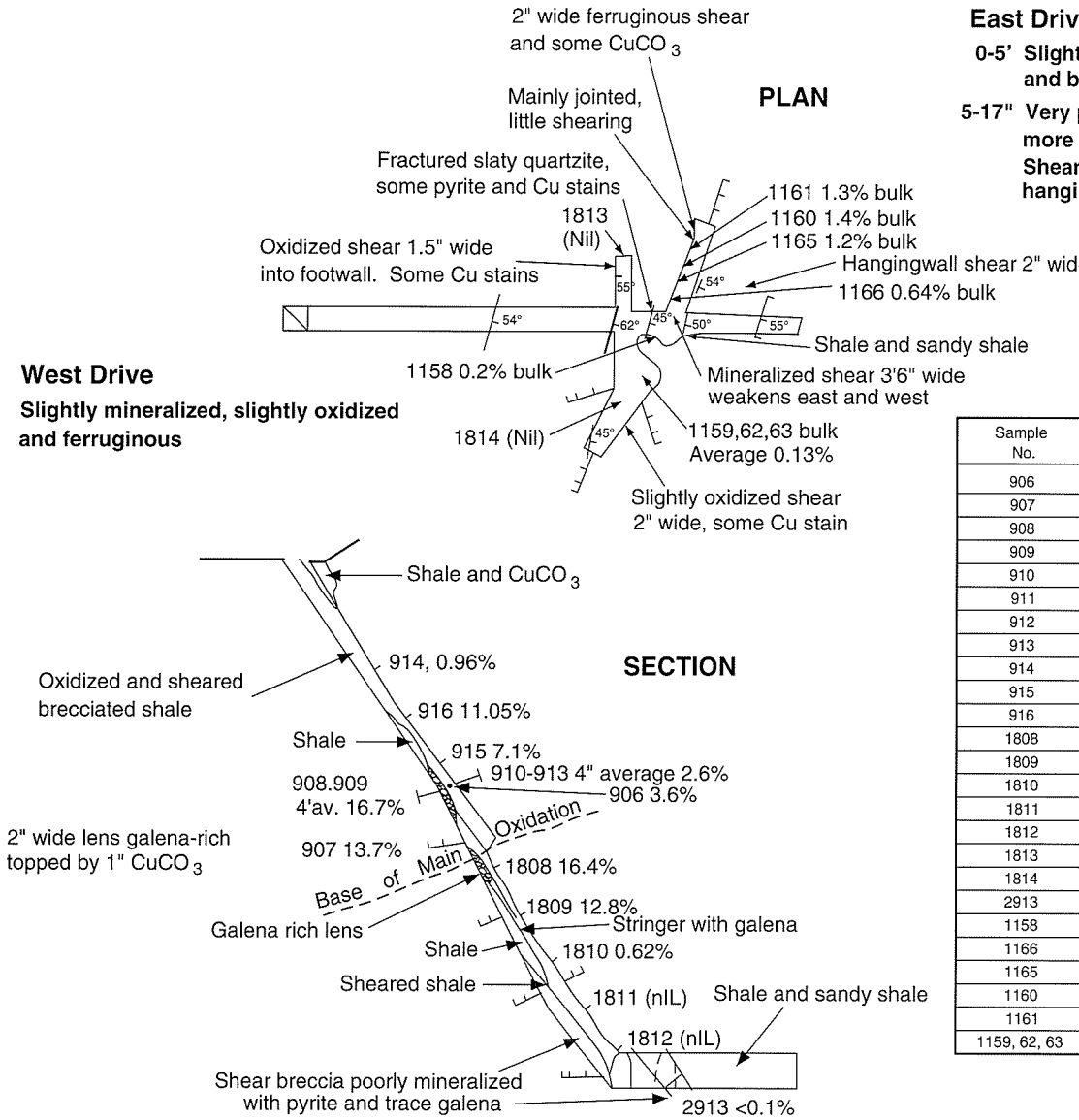


Figure 102. Ashburton Downs base-metal prospects: geology and location (*after* Uranerz)



Sample No.	Sample Type	Sample Footage	Pb%
906	Channel	3' wide	3.6%
907	"	"	13.7%
908	Sample hole	0-3"	19.08%
909	"	3-4"	9.89%
910	"	0-1'	3.7%
911	"	1-2'	2.06%
912	"	2-3'	0.7%
913	"	3-4'	4.1%
914	Bulk	20-30'	0.96%
915	"	40-50'	7.1%
916	"	30-40'	11.05%
1808	"	60-70'	16.4%
1809	"	70-80'	12.8%
1810	"	80-90'	0.62%
1811	"	90-100'	Nil
1812	"	100-110'	Nil
1813	"	East Drive	Nil
1814	"	West Drive	Nil
2913	Channel	Back -Sth Drive	0.1
1158	Bulk	0-3' WSE Drive	0.2
1166	"	0-3' ESE Drive	0.64
1165	"	3-6' ESE Drive	1.2
1160	"	6-9' ESE Drive	1.4
1161	"	9-12' ESE Drive	1.3
1159, 62, 63	Bulk average		0.13

Figure 103. Bali Hi: exploration shaft and section plan (*after* Westfield Minerals, *revised by* Barrack, 1988)

sunk to 34 m by Westfield Minerals (1962–66). A diamond hole west of the shaft drilled by PMI (1967–68) encountered sheared and brecciated sedimentary rocks with pyrrhotite but only minor base metals between 91 and 106 m. Esso (1966–78) recorded a surface sample of 50% Pb and 0.335% Zn. Shallow drilling was carried out to test uranium potential. Barrack/UAL (1983–89) conducted mapping, surface and underground sampling and RC drilling (results quoted above). Barrack calculated an inferred resource of 95 000 t at 2.08% Pb and 0.2 g/t Au, estimating the core of the mineralized body (>1% Pb) to be 80 m long and up to 4.5 m thick.

References: Blockley (1971), Marston (1979), Thorne et al. (1991), GSWA-WAMEX - I 1282, I 2704, I 3227, I 5944.

Bali Hi East

Prospect: Pb; Zn; Bi; Ag; As; U
Location: 23°24'20"S, 116°57'E; 10 km west-southwest of Ashburton Downs Homestead

Bali Hi East is 2.8 km southeast of, and similar to, Bali Lo. The Bali Shear at this location cuts Ashburton Formation. The mineralized portion of the shear is 280 by 2 m at the surface and contains malachite, azurite, chrysocolla and traces of chalcocite. Rock-chip samples show up to 27% Cu with anomalous amounts of lead, zinc, bismuth, arsenic, silver and uranium.

Barrack (1983–89) conducted rock-chip and soil sampling over 1 km of the shear between Bali Hi and Bali East. The best copper values (≤1.93%) were obtained near Bali East. High lead (≤2.79%) was only located close to Bali Hi.

References: Marston (1979), Thorne et al. (1991), GSWA-WAMEX - I 5944.

Bali Lo (Casleys)

Deposit: Cu; Pb; Ag; Zn
Location: 23°24'S, 116°55'E; 11 km west-southwest of Ashburton Downs Homestead

Bali Lo is located at the western end of the mineralized zone on the Bali Shear close to the hinge of a major west-northwesterly trending anticline that closes to the west. Mineralization occurs over a 240 by 3 m chloritized and brecciated zone occupying the steeply southerly dipping unconformity between the Ashburton and Capricorn Formations. The dominant mineralization is copper in quartz veins parallel to foliation, disseminations in the country rock (felsic tuff, dolomitic slate and mudstone), and small pods of limonite with disseminated malachite, azurite, chrysocolla and copper arsenates. Metazeunerite (a uraniferous copper arsenate) occurs as fracture coatings within the Capricorn Formation at the eastern end of the mineralized zone.

Copper was produced from the openpit workings between 1962 and 1963. Pickands Mather (1966–68) drilled one diamond hole. An intersection of 5.7 m at 1.2% Cu, 50ppm Pb and 460 g/t Au probably represents a true width of about 2.7 m at a depth of some 40 m. Russgar Minerals (1972–73) channel sampled the opencut to obtain 1.7% Cu, 0.3% Pb, 240 ppm Zn and 6 g/t Ag. Esso (1977) examined the uranium potential with a percussion-drilling program. Intersections of up 2 m at 1.8% Cu, 0.05% Pb, 0.0185% Zn, 6.5 g/t Ag and 219 ppm uranium and 2 m at 5.05% Cu, 0.89% Pb and 0.075% Zn were obtained in tuff of the Capricorn Formation. Barrack/UAL (1983–89) obtained rock chips containing up to 4.93% Pb between The Ledge and Bali Lo. Thirteen percussion holes were drilled at Bali Lo with intersections of up to 6 m at 1.0% Cu; an inferred resource of 90 000 t at 1.3% Cu was estimated. The company considered this group of prospects to be of marine-shelf volcanogenic origin, with the mineralization remobilized by shearing to form deposits in dilation zones.

References: Blockley (1971), Marston (1979), Thorne et al. (1991), GSWA-WAMEX - I 1282, I 2704, I 3227, I 5944.

Ledge

Prospect: Cu; Pb
Location: 23 23'40"S, 116°53'40"E; 13 km west of Ashburton Downs Homestead

The Ledge prospect lies 2.8 km west of Bali Lo, on the Bali Shear, in Capricorn Formation mudstone, siltstone and fine to coarse sandstone trending at 280° and dipping north at 80°. The 2 m-wide silicified shear zone strikes at 285° and dips 80° south. Four separate pods (50 m long) of malachite, chrysocolla, chalcocite, tenorite, cuprite, and cerussite lie within the limonitic, quartz-filled breccia matrix of the shear. Lead is concentrated towards the western end and Blockley (1971) reports a chip sample with 31.3% Pb, 0.08% Zn, 6.8% Cu and 112 g/t Ag.

Minor copper production in the 1960s came from trenches and opencuts. Esso (1977) located minor uranium in a cupriferous quartz vein and in a thin quartzite horizon. Rock-chips gave up to 9.55% Pb. Barrack/Uranerz (1983–89) conducted rock-chip sampling between the Ledge and Bali Lo.

References: Blockley (1971), Marston (1979), Thorne et al. (1991), GSWA-WAMEX - I 1282, I 5944.

Kooline deposits (Gift, June Audrey, Bilrose)

Abandoned mines and deposits: Pb; Ag; Ba
Location: 23°06'S, 116°26'E; 25.7 km southeast of Kooline Homestead

An area 7.2 by 2.4 km covering Ashburton Formation mudstone, siltstone and sandstone on the north limb of a large upward-facing D_2 syncline contains 17 mines (Blockley, 1971) and ten miscellaneous deposits. Mineralization is in the form of galena-bearing quartz–calcite veins mainly intruded parallel to the vertical axial-plane cleavage trending at 280°. The Gift, June Audrey, and Bilrose mines account for 65% of the production from the area. The veins are up to 1.2 m thick and 60 m long and are commonly arranged en echelon. Ore shoots consist of galena, cerussite, malachite, calcite and barite,

are of limited width and extent, and do not seem to be controlled by host-rock lithology. Ore minerals may either be disseminated through quartz or restricted to narrow seams of sulfide or carbonate. Approximate grades are in the range 10–12% Pb and 31.1–46.6 g/t Ag. The deposits are commonly of limited extent with little potential for further development at prevailing lead prices. For details of the individual mines and deposits, *see* Blockley (1971).

The 17 mines and ten miscellaneous deposits were worked between 1948 and 1959 for 2679 t of lead and 825 kg of silver. Carr Boyd (1969–71) examined the potential for stratabound mineralization. Uranerz (1981–82), as part of a regional assessment, chip-sampled most of the prospects in the area including Gift Mine (27% Pb) and Bilrose (7.9% Pb). Nero Exploration (1986–90), again from rock-chip reconnaissance, found general levels of over 20% Pb and 100 g/t Ag in veining up to 2 m thick. Golden Deeps (1987–88) conducted reconnaissance with a gold focus and obtained an isolated result of 38 g/t Au.

References: Thorne et al. (1991), Blockley (1971), GSWA-WAMEX - I 2543, I 2775, I 3746, I 5357.

North Kooline

Abandoned mines: Pb; Ag
Location: 22°58'S, 116°21'E; 35 km southeast of Wyloo Homestead

Two small deposits were worked in this area within the Ashburton Formation. One occurs in a vein trending at 165° and dipping 80° west. The vein is 18 m long and contains galena and cerussite at levels up to 34.4% Pb, 0.01% Zn and 49.76 g/t Ag. A second vein follows a shear trending at 135° and dipping 80° west with disseminated galena seen in pits over a strike length of 18 m.

Production between 1954 and 1958 was 22.3 t of lead and 5132 g silver. Golden Deeps (1987–88) obtained up to 33.2% in rock-chip samples collected from veins.

References: Blockley (1971), GSWA-WAMEX - I 5357.

Big Chief

Abandoned mine: Pb
Location: 23°11'30"S, 116°35'15"E; 16 km southeast of Kooline

Uncharacteristically for the Kooline area, this deposit is hosted by the Capricorn Formation. The mineralized zone is 12 m long on a strike of 285°, parallel to bedding, and dips 60° south. The richest galena and cerussite is in a narrow bed of sheared mudstone and siltstone between major sandstone beds. Traces of lead were found over 120 m of strike with disseminated cerussite in both the footwall and hangingwall. Ore dump samples gave up to 24.1% Pb and 26.44 g/t Ag, with less than 0.01% Zn.

The deposit was worked to a depth of 4.5 m between 1954 and 1958 for 8 t of lead and 404.3 g of silver. Carr Boyd (1969–70) carried out surface sampling, and West Coast Holdings (1981–83) described Big Chief as 'Galena . . . disseminated in a sandstone devoid of quartz veining . . . exhalative, stratiform'.

References: Blockley (1971), Thorne et al. (1991), GSWA-WAMEX - I 1047, I 2704.

Gorge Creek (The Gorge, Independence)

Occurrence: Pb; Ag; Au
Location: 23°22'32"S, 116°37'10"E; 25 km south-southeast of Mount Dawson

The Gorge Creek occurrence consists of an auriferous lead-rich quartz vein up to 1.8 m wide containing galena and cerussite. A 12 t ore sample collected in 1937 contained 55.3% Pb, 196.88 g/t Ag and 7.59 g/t Au. Gold up to 44.32 g/t was also reported.

Command/W Coast Holdings (1981–83) carried out surface sampling for gold targets. Uranerz (1981–82) obtained 6.35% Pb during regional rock-chip sampling.

References: Blockley (1971), Thorne and Seymour (1991), GSWA-WAMEX - I 2543, I 2704.

Station Creek

Occurrence: Ag; Cu; Pb
Location: 23°26'12"S, 117°01'48"E; 5.6 km south of Ashburton Downs Homestead

Low-grade lead mineralization follows an irregular shear trending 290° in fine-grained conglomerate and shale of the Ashburton Formation. Copper occurs in sedimentary rock in a stockwork of quartz veinlets up to 1 m from the vein on the footwall side.

The occurrence has been opened up in pits over 21 m. Rock-chip and stream-sediment samples were taken in the area by UAL (1981–82) during its uranium search. One sample gave 25.6% Cu, 17% As, 7.05% Sb, 1120 ppm Bi, 1420 ppm Zn and 2.4 g/t Au. Other separate samples in the general area gave up to 5 g/t Au, 6.35% Pb and 5.64% Cu.

References: Blockley (1971), Marston (1979), Thorne et al. (1991), GSWA-WAMEX - I 2543.

Cane River

Occurrence: Pb
Location: 22°13'S, 116°02'30"E; 32.1 km north of Mount Stuart

A narrow, small leader of lead occurs in Ashburton Formation sedimentary rocks (Blockley, 1971).

Billiton (1987–89) conducted surface sampling in the general area for gold and base-metal stratabound targets, and Aberfoyle (1989–90) located copper-stained dolomite with 1.52% Pb and 5.99% Cu in a channel sample.

References: Blockley (1971), Thorne et al. (1991), GSWA-WAMEX - I 3804, I 4365.

Mount Clement (Main, East)

Prospect: Au; Ag; Pb; As; Cu; Bi; Sb
Location: 22°49'50"S, 116°06'46"E; 20 km southwest of Wyloo Homestead

The Mount Clement deposit lies within slightly metamorphosed, deep-marine sedimentary rocks of the Ashburton Formation (Fig. 104). The deposit is in the form of two lenses or shoots, the Main and East prospects, both of which occur in mudstone, siltstone, and subordinate thin- to medium-bedded, partly conglomeratic sandstone. In the Mount Clement area the two main phases of deformation that have affected the Ashburton Formation (D_1 and D_2) are reflected in the interference between southwesterly trending F_1 folds and northwesterly trending F_2 folds. This has produced an upward-facing, large-scale dome-and-basin geometry in which F_2 folds are associated with a strong, penetrative cleavage. The sedimentary rocks have been metamorphosed to lower greenschist grade and are cut by two northeasterly trending post-D_2 dolerite dykes, one of which cuts the Main prospect. The prospects are interpreted as being the result of submarine, hot-spring activity and a mixture of epigenetic and syngenetic processes.

The Main prospect is within a conformable, triangular to lenticular body of hydrothermally altered sedimentary rocks in the core of a fold dome. Bedding dip varies from vertical to about 45° south to southwest. The hydrothermal lens is divided into a lower, mineralized sequence of iron-rich chert (banded iron-formation), siltstone, breccia, talc rock and dolomite. The upper part comprises chert, quartz-pebble siltstone and conglomerate. The mineralized sequence is 450 m thick and extends 1.2 km along strike. It is enriched in silver, arsenic, gold, bismuth, cerium, copper, mercury, lanthanum, lead, antimony, thorium, thallium, uranium, tungsten and zinc. The mineralization is generally stratabound and arsenopyrite and pyrite appear to be the dominant sulfides. Pyrrhotite and chalcopyrite have also been observed. The presence of significant silver, antimony and copper suggests that a sulfosalt of the tetrahedrite–tennantite series may have been present. Lead occurs in bindheimite. Anomalous gold is associated with chert breccia, gossan, massive talc and ironstone. Oxidation extends to below 100 m in the mineralized zones and surface mineralization is dominated by green arsenate minerals. Most of the mineralization is in the oxidized zone.

The East prospect is 2 km to the southeast of Main on the flank of the dome forming a linear zone 1 km long and subparallel to strike. This prospect lies about 400 m above the Main prospect in the stratigraphic sequence. Mineralization is in a 3 m-wide zone cross-cutting the bedding at an angle of about 5°. Secondary lead minerals (bindheimite, carminite and philipsbornite) and scorodite are identified in the gossan. Below 3 m, arsenopyrite, pyrite, pyrrhotite, boulangerite, galena, chalcopyrite and ullmanite are encountered. Pyrite is dominant below 33 m. Mineralization is mostly in irregular cross-cutting quartz veins striking 260°. Lead grades are up to 1.7%, and there is enrichment in silver, arsenic, gold, copper, molybdenum, antimony and tin. Recrystallization in shear zones has produced small, discrete pods of sulfide.

Deuterium-isotope data from talc indicating mineralizing fluid temperatures of 350–400°C, in conjunction with brecciated hydrothermal zones and trace-element assemblages, suggest an epithermal, hot-spring origin. At the East prospect sulfides have filled a fracture formed by dextral faulting in the Ashburton Formation. Davy et al. (1991) suggest a common source for the mineralizing fluids in both prospects, released during burial metamorphism of the supracrustal sequence and transported along major fractures.

BHP/WMC/Newmont/Norseman Gold (1974–1992) have explored the prospects to ore reserve estimate level. BHP carried out initial testing with four diamond holes, and a maximum of 21.1 m at 2.66 g/t Au and 219.8 g/t Ag was intersected in the Main prospect. WMC interpreted the mineralization as discontinuous pods or erosional remnants. Newmont recognized the epithermal nature of the prospects and carried out extensive percussion drilling to establish openpit potential of 0.8 to 1 Mt at 2.5 g/t Au. Norseman Gold reassessed the data, drilled four more holes and drove an adit into the Main prospect. An indicated resource of 480 000 t at 2.2% Au and 30 g/t Ag was defined. Further drilling was planned but did not proceed.

References: Thorne et al. (1991), Doust (1984), Davy et al. (1991), Louthean (1993), GSWA-WAMEX - I 6434.

Gascoyne Complex

Geological framework

The Gascoyne Complex consists of high-grade metasedimentary rocks, orthogneiss and granitoids in the western part of the Capricorn Orogen and is unconformably overlain to the north and east by the sedimentary rocks of the Bangemall Group. To the south, the Complex passes into a zone of tectonic interleaving with the early Archaean Narryer Gneiss Complex. To the north, the metasedimentary rocks are interpreted as passing into their lower grade equivalents, the Ashburton Formation of the Wyloo Group in the Ashburton Basin. To the southeast, the complex passes beneath the sedimentary succession of the Glengarry basins (Fig. 72).

The geology of the complex was the subject of a mapping project and study by GSWA in the early 1980s (Williams, 1986), and to a subsequent revision in the light of more recent geochronology and mapping (Myers, 1990c). From south to north, Myers subdivided the complex into five major zones (Fig. 72).

Zone A, in the south, consists predominantly of a foreland of Archaean gneiss (3.7–3.3 Ga) associated with granitoid (2.7 Ga), which was complexly deformed and metamorphosed over a long period prior to the Capricorn Orogeny. During the Capricorn Orogeny, east-northeasterly to east-southeasterly trending shear zones developed, associated with dolerite dykes. These shear zones transported tectonic slices of the foreland to the south. Zone B lies north of a steep shear zone and a belt of intensely deformed schist and consists of essentially allochthonous basement interleaved with younger gneiss

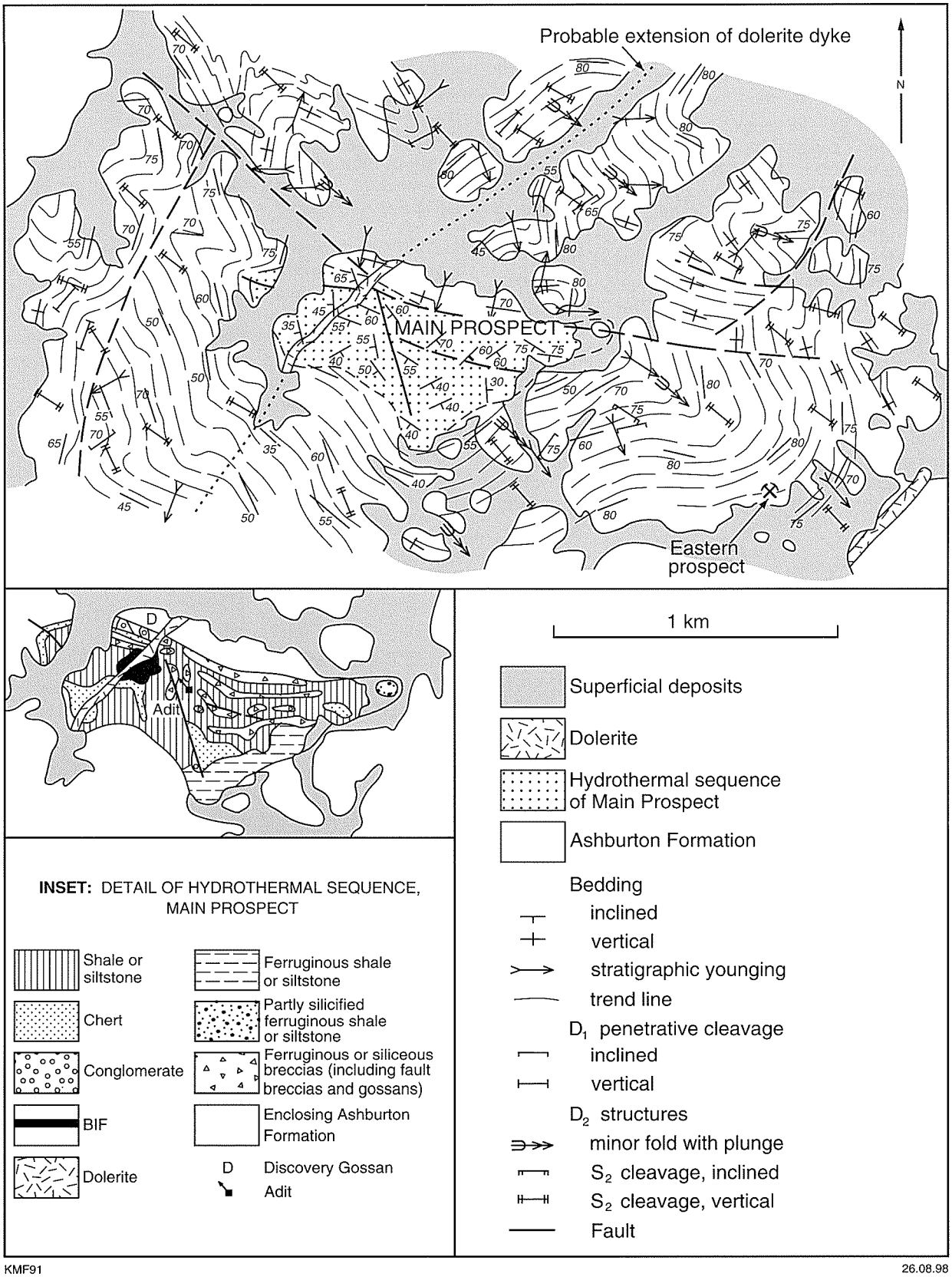


Figure 104. Local geological setting of the Mount Clement Main and Eastern prospects (*after* Davy et al., 1991)

and metasedimentary rocks of the Morrissey Metamorphic Suite. These high-grade pelitic and psammitic rocks are strongly deformed and show signs of partial melting. Gneissic granitoid in this zone gives an Sm–Nd model age of 2.47 Ga (Fletcher et al., 1983). Zone C consists of metasedimentary rocks of the Morrissey Metamorphic Suite mantling granite–gneiss domes with Sm–Nd ages at about 2.24 Ga. In this zone the metasedimentary rocks are interleaved with large bodies of mafic volcanic-derived amphibolite. Zone D consists of the 230 by 35 km Minnie Creek Batholith (Sm–Nd age of 2.06 Ga), emplaced into the metasedimentary rocks and granitoid gneiss, and ranges in composition from tonalite to granite. The northernmost zone E consists of extensively migmatized rocks of the Morrissey Metamorphic Suite intruded by I- and S-type granitoids. The metamorphic grade decreases to the north from amphibolite to greenschist facies and the rocks pass into Wyloo Group sedimentary rocks.

In the light of evidence suggesting that the Pilbara and Yilgarn Cratons evolved separately prior to the collision event which produced the Capricorn Orogeny, the tectonic evolution of the Gascoyne Complex has been re-interpreted (Tyler, 1991; Thorne and Seymour, 1991) as conforming to a B-subduction model. On the basis of Sm–Nd model ages for Gascoyne Complex gneiss and granitoid, Fletcher et al. (1983) and Thorne and Seymour (1991) suggest a timescale of 2.4 to 2.0 Ga for the collision.

In the early phase of collision and subduction of oceanic crust below the Yilgarn Craton, island-arc volcanism would be expected at the northern margin of that craton. The mafic and ultramafic lavas and breccias of the Narracoota Volcanics, within the Glengarry Group, are proposed as reflecting this with the Thaduna Greywacke deposited in a back-arc basin (Tyler, 1991). The sedimentary rocks, which became the Morrissey Metamorphic Suite (2.2–1.8 Ga), are considered to be partly equivalent to the Glengarry Group and were deposited in a shallow sea. As subduction progressed an active foreland basin developed in which Wyloo Group was deposited. Collision produced extensive deformation, crustal thickening and high-grade metamorphism in the Gascoyne Complex. This was accompanied by the intrusion of large volumes of granitic magma, including the Minnie Creek Batholith (2.06 Ga; Fletcher et al., 1983). Suturing may explain the steep metamorphic gradient that marks the boundary between the Morrissey Metamorphic Suite and the Wyloo Group.

Mineralization

The bulk of lead–zinc–copper occurrences located in the Gascoyne Complex is in veins within the Morrissey Metamorphic Suite. Pelitic and semi-pelitic schists predominate in this unit with lesser, but substantial, sequences of paragneiss and relatively minor calc-silicate gneiss and mafic to intermediate volcanic rocks. Migmatite is extensively developed in the paragneiss.

The prospects and abandoned mines are all of limited size and were worked by small groups in the early 1900s and in the 1950s and 1960s.

MC Mining (I 3706) in the mid-1980s used Landsat images to study lineaments in the southeast corner of the YANREY 1:250 000 sheet, in the northern part of the complex. This study found a dominant northerly trend in lineaments with related trends between 330° and 340°, and between 040° and 050°. Mineralization is associated with each of these trends and also reflects the density of lineament intersections (Fig. 105). Farther south, in the Mangaroon area, Regional Resources NL (I 4835) recognized the major northerly fault direction with related shear-link structures trending between 060° and 090°. Quartz stockwork zones were also associated with the shear links. Sulfide stockworks were found both in the main northerly trending shears and in the link structures.

Myers and Barley (1992) suggest that the granitoid intrusions (~2.0 Ga), abundant particularly in the suture zone between the Pilbara and Yilgarn Cratons, are associated with the widespread minor molybdenum, tungsten, bismuth, lead, barium, uranium and beryllium mineralization in the Gascoyne Complex.

Lead-isotope determinations on a number of deposits indicate ages of mineralization ranging from 1.4 Ga (Mangaroon) to 1.7 Ga (Range). Some deposits give anomalously young ages, due probably to the presence of uranium in the lodes or host rocks (Mount Alexander, Rose Find).

Exploration

The relatively small vein-type lead–zinc–copper deposits, mostly in the Uaroo Group in the northwestern part of the complex, were worked sporadically until the mid 1950s (Fig. 4). Blockley (1971) gives details of the mine workings.

Exploration for extensions of the known deposits began in the 1960s with Ashburton/Westfield (I 3227) examining the Mangaroon workings and conducting a drilling program at the Turtle mine. Also at Mangaroon, Kennecott (1966) (I 111) carried out a stream-sediment survey to locate extensions of the mineralization. Union Miniere (I 2136) considered reopening the Uaroo/Rainbow/Silver King workings in 1968–1970. Jododex/Homestake (I 1120) explored the Range and Turtle deposits between 1969 and 1971 with a variety of ground-geophysical surveys including magnetics, IP, SP and EM, and drilling to establish a resource at Turtle. The results of the geophysical surveys were neither significant nor conclusive except for a correlation of IP anomalism with pyrite in the shear zone at Range.

The next phase of exploration was driven by the recognition of uranium potential in the complex. Between 1969–1972, Leopold Minerals (I 391) carried out reconnaissance mapping and radiometry in the vicinity of the Range, Emu and Nanutarra mines without locating any significant extensions. Radioactivity proved to be thorium biased. Between 1972 and 1983, Esso (I 664) carried out regional exploration which included examination of the Rainbow, Coober Peedy, Nanutarra, Mundong Well and Monte Carlo mines and prospects. Geophysics was confined to radiometric surveys. All the main prospects

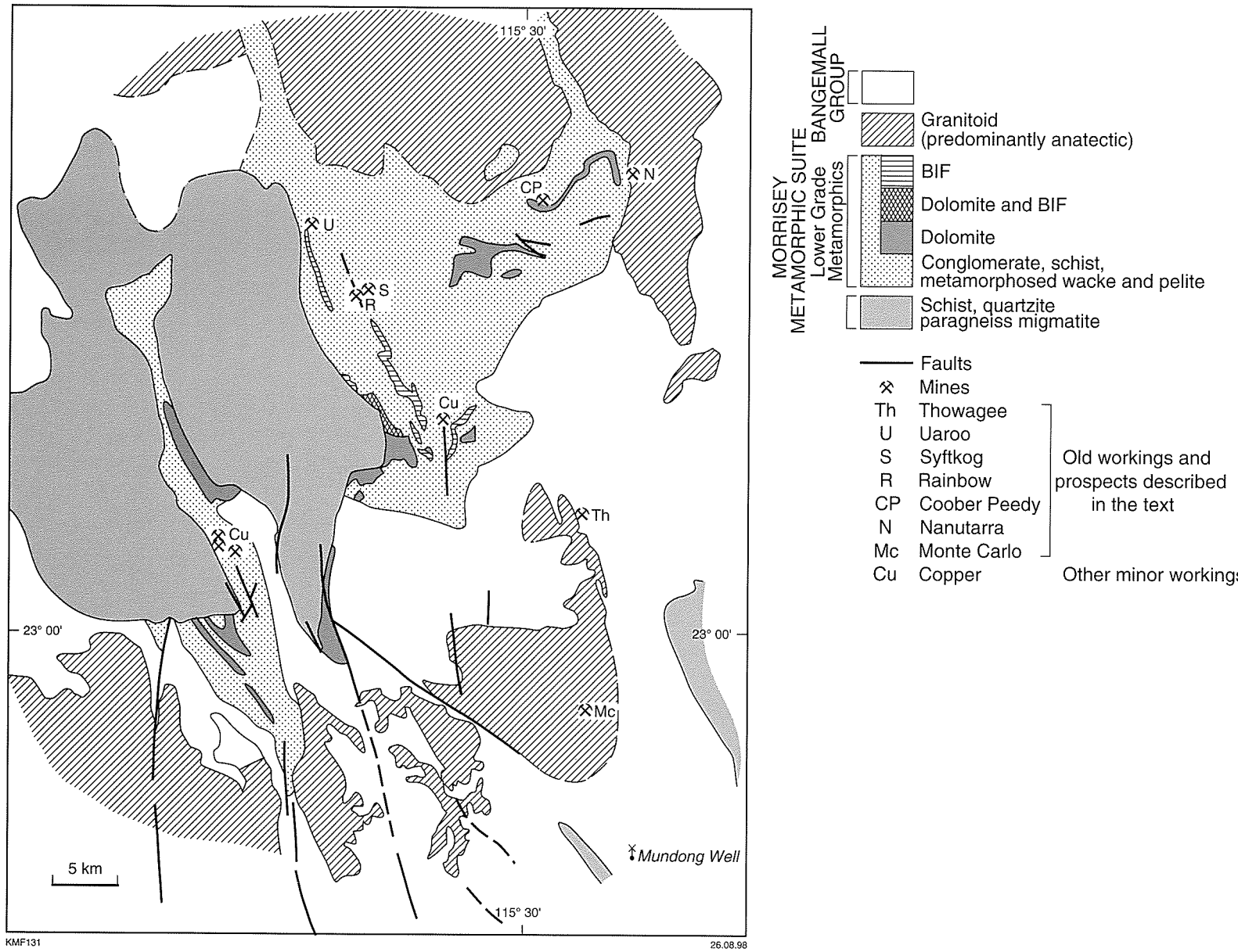


Figure 105. Gascoyne Complex: geology and prospects of the Uaroo–Mount Alexander area (*after* GSWA 1:250 000 mapping and MIM Exploration Pty Ltd)

except Rainbow and Coober Peedy were tested to drilling level with the most extensive studies at Mundong Well. Lead–silver mineralization was the focus in the vicinity of the Monte Carlo mine, where a resource was defined. CRA (I 3835) carried out regional uranium exploration in the Uaroo area between 1985 and 1988, including a variety of target types but mainly testing unconformity-related situations. No significant finds were reported.

Regional geochemical exploration for stratiform base metals and gold was carried out by Australian Anglo in 1978 (I 1284). Sampling of gossans, stream sediments, soils, ironstones and heavy minerals suggested that the Uaroo area had low potential for this type of mineralization. Jays Exploration (I 5185) drilled the Turtle and Range deposits to establish copper and lead potential in the early 1980s. The company upgraded the geological interpretation and resources were estimated for both deposits. WA Metals/Delta (I 6534) followed up in the late 1980s carrying out aeromagnetic surveys over both deposits, with sampling and limited drilling at Turtle.

Other more recent studies include rock-chip sampling in the Mangaroon area by Regional Resources (I 4835) during a gold search in the late 1980s, stream-sediment sampling by BHP (I 6473) in the Uaroo–Thowagee area in 1991–92, and regional, gold-biased sampling and RAB drilling by Newcrest/Newmont (I 6438) in the Mount Gifford area between 1989 and 1992. No anomalies beyond the known deposits were found. Detailed sampling of the Rainbow/Silver King workings by Ibbotson (1986–89) (I 3896) suggested that there is still potential for further development in the vicinity of the mine. Structural analysis of the Uaroo area by MC Mining (I 3706) has been described above.

It has recently been reported (Metals Gazette, December/January, 1993/94) that Matlock Mining NL and Lydia Exploration Pty Ltd, are following up reconnaissance rock-chip sampling in the Gascoyne Complex, southwest of Mount Augustus, in high-grade rocks of the Morrissey Metamorphic Suite. The rock types suggest similarities with the Broken Hill region. A number of gossan zones, over an extensive area, are anomalous in base metals.

Deposits, prospects and occurrences

Coober Peedy

Prospect/abandoned mine: Pb; Zn
Location: 22°42'S, 115°29'E; 16 km northeast of Uaroo

A lead-bearing quartz vein trending 090°, dipping 70–80° south, and up to 0.23 m wide, is present in a shear 2 m wide in amphibolite and dolomite of the Morrissey Metamorphic Suite. The vein contains coarse-grained galena, cerussite and sphalerite. A grab sample from a small dump contained 42.6% Pb, 5.92% Zn, 203.72 g/t Ag.

Coober Peedy was mined, in 1950, from two shafts 50 m apart and 10 m deep, and from a shallow cut; no details of production are available. Esso (1977) included the area in its uranium exploration.

References: Blockley (1971), GSWA-WAMEX - I 664.

Emu

Abandoned workings: Pb; Ag; Cu
Location: 22°47'S, 115°33'E; 14.4 km south-southeast of Mount Alexander

Two parallel quartz veins trending 305° and dipping 75° west in gneiss and amphibolite of the Morrissey Metamorphic Suite contain lead along 240 m. The western vein is up to 1.2 m wide and the eastern vein up to 0.46 m. They carry disseminated galena and a little chalcopyrite and chrysocolla. Seven samples gave 15–80% Pb, up to 0.09% Zn and up to 198 g/t Ag.

The veins were worked in trenches and opencuts in 1952 for 2.54 t lead and 560 g silver. Leopold Minerals (1972) included the area in regional uranium/base-metal reconnaissance.

References: Blockley (1971), Marston (1979), GSWA-WAMEX - I 388.

Mangaroon

Abandoned workings: Pb; Ag; Au; Cu
Location: 23°51'30"S, 115°45'40"E; 14.4 km south of Mangaroon Homestead

Three narrow but high-grade quartz veins in quartz–feldspar–biotite gneiss of the Morrissey Metamorphic Suite contain galena, cerussite, malachite, azurite, chrysocolla and free gold. They trend at 360°, dip 10–15° east, are individually up to 30 cm thick, and contain up to 75% Pb (with an average ~15%).

The veins have been worked over 14 m length and opencut to 9 m depth. Production from intermittent mining between 1956 and 1960 was 8.43 t lead, 141.6 kg copper, 3937 g silver and 1524 g gold. The mine area was included in regional exploration by Ashburton/Westfield (1961–67) and Kennecott (1966) carried out stream-sediment sampling. During extensive regional gold reconnaissance, Regional Resources (1987–89) collected rock chips in the vicinity of the Mangaroon lead workings and the Star of Mangaroon gold mine, about 1.6 km south of the Mangaroon lead workings. The company obtained between 0.37% and 65% Pb, and up to 869 g/t Au, 284 g/t Ag, 12.5% Cu and 14 g/t uranium in 29 samples. The samples came from zones of quartz–sulfide mineralization in north-trending shear zones. These zones range in size from 1 to 10 m wide and 20 to 200 m long and are characterized by stockworks rich in galena, malachite, covellite, azurite, cuprite, chrysocolla, free gold, scheelite, and pyrite, plus copper oxalate and tungstenate minerals. Also recognized were hornblende–epidote–quartz pegmatoids in association with mafic lopoliths in northerly and northeasterly trending shear zones, which contain chalcopyrite and pyrite and are anomalous in copper, lead, gold and silver. These are up to 2 m wide and extend for several kilometres.

References: Blockley (1971), Marston (1979), GSWA-WAMEX - I 111, I 3227, I 4835.

Monte Carlo (Hancock)

Abandoned mine: Pb; Ag
Location: 23°03'S, 115°32'30"E; 32 km south-southeast of Uaroo

A silicified, cherty breccia in a shear zone within granite contains quartz veins with coarse galena in two areas of weaker silicification. The shear strikes north-northeast over 3 km and dips to the west at 65–75°.

The workings, a number of shallow shafts and pits at the southern end of the shear zone, extend 120 m on a 1 m-wide reef. Farther north there is another section of workings over a length of 90 m. Production between 1948 and 1953 amounted to 47.7 t of lead and 8211 g of silver. Esso/Griffin/Newmex (1972–83) drilled four percussion holes in the vicinity of the mine and intersected up to 4 m at 5.5% Pb, 1.06% Zn and 8.07 g/t Ag. Surface samples gave up to 44% Pb and average grades in the pits were between 11% and 12%. Some zinc was also encountered with a maximum intersection of 2 m at 1.06%. From the drilling results Atkinson and Partners, for Newmex, estimated a resource of 3654 t at 3.7% Pb in the northern body. A potential resource of 93 752 t at 22% Pb was estimated to 122 m for the two bodies: i.e. 20 625 t of lead.

References: Blockley (1971), GSWA-WAMEX - I 2364.

Mundong Well (Elizabeth R)

Prospect: U; Cu; Pb; Ag; Au
Location: 23°06'50"S, 115°35'E; 70 km east-southeast of Barradale

Uranium at Mundong Well is associated with copper–lead sulfides in xenoliths of semi-pelitic and amphibolitic gneiss of the Morrissey Metamorphic Suite within pegmatitic leucogranite. The xenoliths are within curving, generally northwest-trending, vertical shears which also contain foliated quartz. Small amounts of malachite and chrysocolla are visible at the surface. The main mineralized vein (seen in the Elizabeth R pit) measures 150 by 1 m and coincides with a zone where the metasedimentary rocks are faulted and sheared in at least two directions, producing a highly altered and fractured zone. A similar zone is seen in the Petes and Georges prospects farther south. Mineralization occurs as kasolite, cerussite and anglesite encrusted galena, hematite, jarosite, sphalerite, fluorite, calcite, chalcocite, digenite and chalcopyrite in a gangue of intensely kaolinized quartz–mica schist and magnetite, jaspilite and chert, cut by quartz veinlets and pegmatite. The best assay obtained from surface material is 3.6% U, 5.38% Cu, 5.97% Pb, 54.2 g/t Ag and 1.84 g/t Au.

Esso (1972–83) examined the uranium potential of the prospect with a 34-hole percussion drilling program covering both main prospects. The maximum value was 6 m at 0.25% U_3O_8 beneath the Elizabeth R pit. Thickening of the metasedimentary sequence in the drill profiles was interpreted as reflecting the cross-structure control of mineralization. The best lead intersection was 2 m at 2.6%.

References: Blockley (1972), Marston (1979), GSWA-WAMEX - I 2364.

Nanutarra

Abandoned mine: Pb; Cu
Location: 22°41'S, 115°33'E; 15 km southeast of Nanutarra Homestead

Lead and copper are present in a quartz vein 1.2 m wide, part of a zone of veining within a subvertical shear zone 3 m wide and 137 m long. The veins are transitional into muscovite–tourmaline pegmatite. The northern, easterly trending part of the vein, within granite, is the richest. The southern part, trending 190°, is in schist of the Morrissey Metamorphic Suite. The ore occurs as galena, cerussite, chalcopyrite, malachite, sphalerite and kasolite in quartz with well developed comb structures. The best drill intersections (Esso) are 8 m at 3.1% Pb, 2.2% Zn, 12 g/t Ag and 4 m at 6% Pb, 0.9% Zn and 18 g/t Ag.

The mineralization is exposed in a 4.5 m-deep shaft and in a small pit 300 m to the north of this. Production between 1956 and 1957 is recorded as 9.2 t of lead. Leopold Minerals (1972) carried out a uranium and base-metal search, obtaining high grades from quartz veins. In 1971, Esso drilled nine percussion holes during uranium exploration.

References: Blockley (1971), Marston (1979), GSWA-WAMEX - I 388, I 664.

Perseverance Well

Occurrences: F; Pb; Cu
Location: 24°31'30"S, 116°15'E; 17 km north-northeast of Yinnietharra Homestead

Two fluorite-bearing quartz dykes, carrying disseminated lead and copper in galena, malachite and chrysocolla, occur within porphyritic tourmaline granite.

Reference: Williams et al. (1983).

Rainbow 2 (Uaroo, Silver King, Silver Star)

Abandoned mine: Ag; Pb; Au
Location: 22°46'40"S, 115°21'15"E; 1.2 km northwest of Uaroo Homestead

A mineralized quartz vein striking 320–340° and dipping 70° east cuts northwesterly trending, easterly dipping, chloritic slate and greywacke of the Wyloo Group. The vein is 240 m long and, between 30 and 100 m from the southern end of its outcrop, bifurcates to form a cymoid loop structure. The main ore zone is on the western branch of this and is up to 1.2 m wide. The lode consists of massive galena with pyrite, chalcopyrite, cerussite, anglesite and malachite. Samples from the mine averaged 33.5% Pb and 267 g/t Ag, with a maximum of 1.75 g/t Au.

An adit extends 129 m in from the east side of the hill on a 230° bearing and workings extend to about 44 m depth.

Intermittent production between 1901 and 1953 yielded 2100 t of lead and 1210.7 kg of silver. Lead grades were in the range of 50% to 66% and silver averaged 336 g/t. Union Min (1968–70) investigated the feasibility of reopening the mine. Esso (1972–83) conducted uranium exploration in the general area and Anaconda (1981–83) explored stratabound base-metal targets in the Wyloo Group but obtained indifferent results. Ibbotson (1986–89) sampled the workings and suggested that potential remained at depth and in the general area. Samples gave up to 68% Pb , 1000 g/t Ag, 0.33% Zn, 5.1% Cu and 1.78 g/t Au. MC Mining (1984–88) carried out structural analysis which highlighted the Uaroo/Rainbow area.

Isotopic determinations on samples of galena and cerussite by J. R. Richards and I. R. Fletcher gave model-lead ages of about 1.65 Ga (Blockley, J. G., 1995, pers. comm.).

References: Blockley (1971), Marston (1979), GSWA-WAMEX - I 2136, I 2364, I 3706, I 3896.

Range (Copper Ridge)

Abandoned mine: Pb; Ag; Cu; Zn
Location: 22°12'S, 115°25'E; 60 km southeast of Onslow

The Range Mine occupies a silicified, chloritized, shear zone trending between 060° and 070° over 340 m in granodiorite. The main worked lode is 75 m in length by 1.5 m wide and dips 80° south. The ore is in veins or lenses of massive galena, with pyrite, pyrrhotite, tetrahedrite, cuprite and chalcopyrite, associated with jarositic and chalcedonic silica gangue. Disseminated ore of variable grade is also present between the massive lenses. Malachite and cerussite are present at the surface. Pinch and swell has affected continuity in the shear zone. Jays Exploration estimated a depth limit of about 100 m for the mineralization. Dump and shaft samples give 15–35% Pb, up to 0.33% Zn and about 132 g/t Ag; a maximum of 20.4% Pb was encountered in drilling.

The ore has been worked in a number of pits and costeans also in four shafts to a depth of 9 m. K. Stubbs reportedly produced 25 t of high-grade lead ore in 1968. Leopold Minerals (1969–70) explored the surrounding area with 'no base-metal mineralization noted'. Drilling of two diamond holes by Jododex (1969–71) suggested that the mineralized zone did not extend much below the surface workings because no mineralization was intersected. Newmex (1978) drilled three percussion holes south from the main shaft and gave a poorly constrained estimate of ore potential of 40 823 t at 22% Pb and 78 g/t Ag. Jays Exploration (1981–84) drilled 18 percussion holes and established an inferred resource of 44 000 t at 45–55% Pb plus 15 000 t at 15% Pb and 9000 t at about 5% Pb. Their report emphasized pinch and swell in the mineralized zone and suggested the possibility of extensions at depth. Zinc and copper were seen to be in the range 0.2 to 0.4% and silver in the range 150 to 400 g/t. Both massive and disseminated ores were recognized, the latter in a separate parallel shear to the south measuring 100 by 50 by 5 m. Structural interpretation suggested 'a parallel group of lensoid bodies centred about one or two strong shears'. WA Metals/Delta (1989–90) reviewed exploration to date and carried out mapping and an aeromagnetic survey over the area of the Turtle and Range deposits. Follow-up sampling and drilling was carried out on Turtle only.

References: Blockley (1971), Marston (1979), GSWA-WAMEX - I 391, I 1120, I 2354, I 5185, I 6534.

Turtle (Copper Ridge)

Abandoned mine: Cu; Pb
Location: 22°11'40"S, 115°24'30"E; 7.5 km north of Range Homestead

Three parallel, en echelon, jarositic and chalcedonic silica lodes containing pyrite, pyrrhotite, galena, chalcopyrite and minor cuprite (cerussite, malachite and azurite in the oxidized zone) are hosted by a quartz–chlorite shear zone within a highly siliceous stockwork in quartzofeldspathic gneiss/schist of the Morrissey Metamorphic Suite, close to a small adamellite stock. The mineralized shear zone trends at about 230°, dips steeply southeast and is about 210 m long and up to 50 m wide. The southernmost of the three main lodes is some 50 m by 3.6 m. Northeast of this a second lode has been worked in an 8.2 m deep shaft. A third, less well defined lode lies to the north of this. Quartz and quartz–chlorite horizons alternate within the shear zone with sulfide stronger in the latter. A pit sample contains 6.81% Pb, 0.02% Zn, 3.39% Cu and 146.18 g/t Ag.

The mine was worked in 1962 and yielded 45.86 t of ore at 4.43% Cu. Westfield Minerals (1964) drilled 18 percussion holes, only two of which intersected mineralized lodes. A best intersection contained 12 m at 4.6% Pb and 121.3 g/t Ag including 2.4 m at 3.7% Cu in the southern lode. Jododex (1969–71) interpreted the deposit as being hosted by a pendant of metasedimentary rocks and minor metavolcanic rocks within granodiorite, roughly corresponding with the low hill of outcrop. Six diamond holes were drilled with best intersections of 1.5 m at 0.9% Pb and 0.9% Cu; a potential resource of about 200 000 t at 1.45% Cu was suggested. Jays Exploration (1981–84) considered the mineralization to be hosted by strongly sheared and pervasively altered, medium- to coarse-grained biotite granite, with gneiss showing remnants of granitic oligoclase. As a result of percussion drilling, a resource of 90 000 t at 2–3% Cu, 10–15% Pb and <2000 g/t Ag was estimated to a depth of 60 m. WA Metals/Delta (1989–90) carried out an aeromagnetic survey, surface geochemistry, detailed mapping and the drilling of four RC holes. This work clearly defined the three main lodes and seems to support a granitic host. A best drill intersection of 8 m at 4.31% Cu, 1.98% Pb and 348 g/t Ag was recorded and further diamond drilling was recommended.

References: Blockley (1971), Marston (1979), GSWA-WAMEX - I 1120, I 3227, I 5185, I 6534.

Tabletop Well

Prospect: Pb; Cu
Location: 24°01'30"S, 116°19'E; 10 km east-northeast of Mount Gifford Homestead

A lens of sheared porphyritic granitoid intruding migmatized paragneiss carries disseminated galena and copper carbonate.

Newcrest/Newmont (1989–92) carried out regional sampling and RAB drilling in the general area but no significant gold or base-metal anomalies were reported.

References: Williams et al. (1983), GSWA-WAMEX - I 6438.

Thowagee

Abandoned workings: Pb; Zn; Ag
Location: 22°56'S, 115°32'E; 21 km southeast of Uaroo Homestead

Two lines of narrow lenticular quartz veins occur in mica–chlorite schist of the Morrissey Metamorphic Suite. One trends north-northeast and the other northwest. The north-northeast line is 370 m long and contains ten en echelon veins. The northwest line is 260 m long. The veins contain galena and cerussite. A sample from the north-northeast line gave 17.4% Pb, 3.87% Zn and 99.52 g/t Ag.

The veins were worked in various pits and cuts. A total of 15.2 t of lead and 5878.4 g of silver were extracted from these in 1956. Ground magnetics and grab sampling by Academus (1970–71) found no indications away from workings. CRA (1985–88) carried out regional exploration in the general area for a variety of target types to the level of RC drilling but with no significant success. BHP (1991–92) did not find any stream-sediment anomalism associated with the prospect.

References: Blockley (1971), GSWA-WAMEX - I 936, I 3835, I 6473.

Ti Tree Well

Occurrence: Pb; Cu; Mo; W
Location: 24°21'S, 116°05'30"E; 36 km south-southwest of Gifford Creek Homestead

Intersecting, mylonitized easterly to east-southeasterly trending shear zones in granodioritic rock contain pervasive disseminated pyrite with minor to accessory galena, chalcopyrite and molybdenite. A suite of quartz–pyrite veins was drilled by Amax.

Australian Minerals Inc (1972–73) drilled disseminated sulfides in a 'porphyry copper environment' within post-tectonic granitoid for a maximum of only 0.2% Cu over 1.5 m. Amax (1979–83) explored the prospect and surrounding area to diamond-drilling level. Best results were up to 0.17% Cu over 9 m and 0.125% Pb in a surface sample.

References: Williams et al. (1983), Marston (1979), GSWA-WAMEX - I 2062, I 2257.

Roses Find

Prospect: Pb (Cu; U)
Approximate location: 22°35'S,115°31'E

Some shallow pits about 8 km north of Mount Alexander expose galena and cerussite, together with secondary copper and uranium minerals, contained within sheeted zones of narrow, comb-structured quartz veins cutting weathered biotite granite. At least two parallel sets of veins are present, each about 1 to 1.5 m wide. Individual veins within the sets vary in thickness from 5 cm to 20 cm. The veining strikes northwesterly and dips steeply to the southwest. There is no record of past production.

A lead-isotope determination by I. R. Fletcher gave anomalous results, due probably to the uranium content of the deposit. Apart from its different host rock, Roses Find is similar in mineralization style to the Mount Alexander (Emu) deposit (Blockley, J. G., 1994, pers. comm.).

References: Blockley, J. G., 1994, pers. comm.

Potential

It is considered that the main potential for a lead–zinc–silver deposit of economic grade and dimensions in the Gascoyne Complex lies with the syngenetic clastic-hosted type within the Morrissey Metamorphic Suite (~2.2–1.8 Ga).

The Morrissey Metamorphic Suite is present in zones B to E of the complex and consists of pelitic and psammitic schist, with layers and lenses of quartzite and calc-silicate gneiss in the south, and large bodies of amphibolite after mafic volcanics in zone C (which also contains a thick arkosic sequence). The suite is extensively migmatized with partial melting in the south and is also strongly deformed, showing complex fold-interference structures. To the north, amphibolite-grade metamorphism gives way, in zone E, to greenschist grade where the rocks pass into the Wyloo Group of the Ashburton Basin.

The tectonic setting of the sedimentation that produced the Morrissey Metamorphic Suite is not clearly defined at this stage. Williams (1986) has suggested that both trough and shelf sedimentary rocks are represented, the former as thick interlayered sequences of pelitic schist and fine-grained paragneiss (after greywacke), and the latter as quartzite, meta-arkose, pelitic schist, calc-silicate gneiss, marble and metachert. This suggests analogies with the setting of the lower grade metasedimentary rocks of the Glengarry Basin, which are approximately coeval. Williams (1986) examined the subduction, back-arc marginal-basin model, later applied by Thorne and Seymour (1991) to the Capricorn Orogen as a whole, whereby early extensional tectonics would allow the accumulation of the necessary great thickness of ensialic sediments. In the collision-related compressional phase, further deepening would be achieved by subsidence in a foreland-basin setting (Ashburton Basin). The crustal derivation of large volumes of granitoid would be explained by this model. There appears, however, to be little evidence for the expected volcanic arc adjacent to the marginal basin. Thorne and Seymour (1991) conclude that in view of the high structural levels exposed in the Gascoyne Complex, the lack of direct evidence of arc volcanism is not a severe problem.

If extensional tectonics were an important part of at least the early basin sedimentation in the Gascoyne Complex then potential exists for the location of stratiform lead–zinc–silver mineralization. The degree of deformation and metamorphic grade have probably hampered adequate exploration of the complex in the past. The situation of the Broken Hill mineralization in the high-grade metamorphic rocks of the Palaeo- to Mesoproterozoic Willyama Block might provide some useful exploration strategies. Regional and detailed lithological and structural mapping will clearly be necessary to establish prospective elements in the depositional environment.

Northampton Complex

The first mining operations in Western Australia were based on the lead–silver and copper, vein-type deposits in the Northampton Complex. Over 100 deposits were worked in the complex between 1850 and 1973 in three principal centres: Northampton, Galena and Narra Tarra. The overall production was at least 77 000 t of lead, 4268 t of copper, 42.3 t of zinc and 212.3 kg of silver.

Geological framework

The Northampton Complex is a partially fault-bounded horst within the Pinjarra Orogen (Myers, 1990d). The Pinjarra Orogen, on the western margin of the Yilgarn Craton, has undergone repeated orogenic activity during the Proterozoic and was the site of rifting during the separation of India and Australia in the Gondwana breakup in the Mesozoic.

Within the complex three main rock types predominate: granulite, granite and migmatite (Fig. 106). These form large-scale open folds with northwest axes that plunge mainly southeast. Within the granulites are bands of mafic granulite, sillimanite gneiss, graphitic schist and quartzite. They are considered to derive largely from metagreywackes (Peers, 1971; Blockley, 1971). Little is known about the age or environment of their deposition although Fletcher et al. (1985) report an Nd-model age which implies that the metagreywackes were derived from material that separated from the mantle around 1.8 Ga. The last metamorphism of the granulites is dated at around 1.05 Ga and the metasedimentary rocks have been intruded by a thick sheet of porphyritic granite which is surrounded by an envelope of migmatite containing abundant rafts of granulite. The granite is dated at 1.00 Ga. These rocks are intruded by a north-northeasterly trending tholeiitic dyke swarm dated at 0.65 to 0.8 Ga. The dykes follow a set of fractures which mostly dip steeply west. The dykes are unaffected by the regional metamorphism

Mineralization

All of the lead–silver and copper mines are located in areas dominated by gneiss and are associated with the same north-northeasterly fault system that has controlled the intrusion of the dolerites. Thirty percent of the deposits are in contact with dolerite dykes. The overall trend of the fracture system is 038° whereas that of the dolerite dykes is 030°. Byrne and Harris (1993) have recently reviewed the deposits of the Northampton Complex in the light of current theories based on experimental fault and shear zone models, and studies of mineralization within wrench systems. They define the fractures as brittle–ductile shear zones. The northeasterly trending dykes and shear zones are cut, and sinistrally offset by up to 1 km, by north-northwesterly trending shears, particularly in the northern part of the complex (Fig. 106).

The brittle–ductile shear zones trending 038° contain brecciated wallrock (predominantly gneiss with pegmatite and dolerite) cemented by quartz, usually with disseminated sulfides. The vuggy nature of the quartz and other minerals suggests that some of the infilling took place in dilatent zones. In some cases the breccias are cement supported which suggests syntectonic mineralization. Byrne and Harris (1993) cite other evidence from growth textures in the mineralized veins to suggest syntectonic crystallization.

The mineralized lodes within the shear zones also fill open fissures and fault breccias. Most deposits are in simple veins associated with the opening of slight bends in the faults. The larger deposits are in more structurally complex situations, where faults intersect, or in cymoid loops (Blockley, 1971). Most commonly the sulfide vein zones are located near the margins of the shear zone though they have sometimes formed within the breccia zone. The ore commonly takes the form of boudins or lenses suggesting 'pinch and swell' under the influence of post-mineralization tectonism. Blockley (1995, pers. comm.), however, points out that the galena shows no sign of deformation. In some cases mineralization has extended into the country rock beyond the shear zones. Individual veins within deposits may be up to 1 m wide and deposits, or ore shoots, may be up to 9 m wide, 270 m long and 150 m deep (Blockley, 1971).

Galena, sphalerite, pyrite, marcasite and chalcopyrite are the main sulfides, with galena dominant, within a gangue of quartz, carbonate and barite. In the copper lodes chalcopyrite is dominant but sphalerite seems to be more commonly associated with the lead mines (Byrne and Harris, 1993). Michael and Groves (1977) have pointed out, on the basis of sulfur-isotope evidence, that sphalerite and galena are not in equilibrium with the other sulfides, and may therefore be of different origin.

Wallrock alteration haloes are commonly associated with the deposits. This involves silicification, chloritization and kaolinization of the gneiss, pegmatite or dolerite. This alteration is generally considered, on petrographic and chemical evidence, to be related to the mineralizing event (Richards et al., 1985).

Byrne and Harris (1993) have recognized two main types of ore shoot, partially controlled by their structural environment. The first type, predominantly the lead deposits, is divided into four structural varieties.

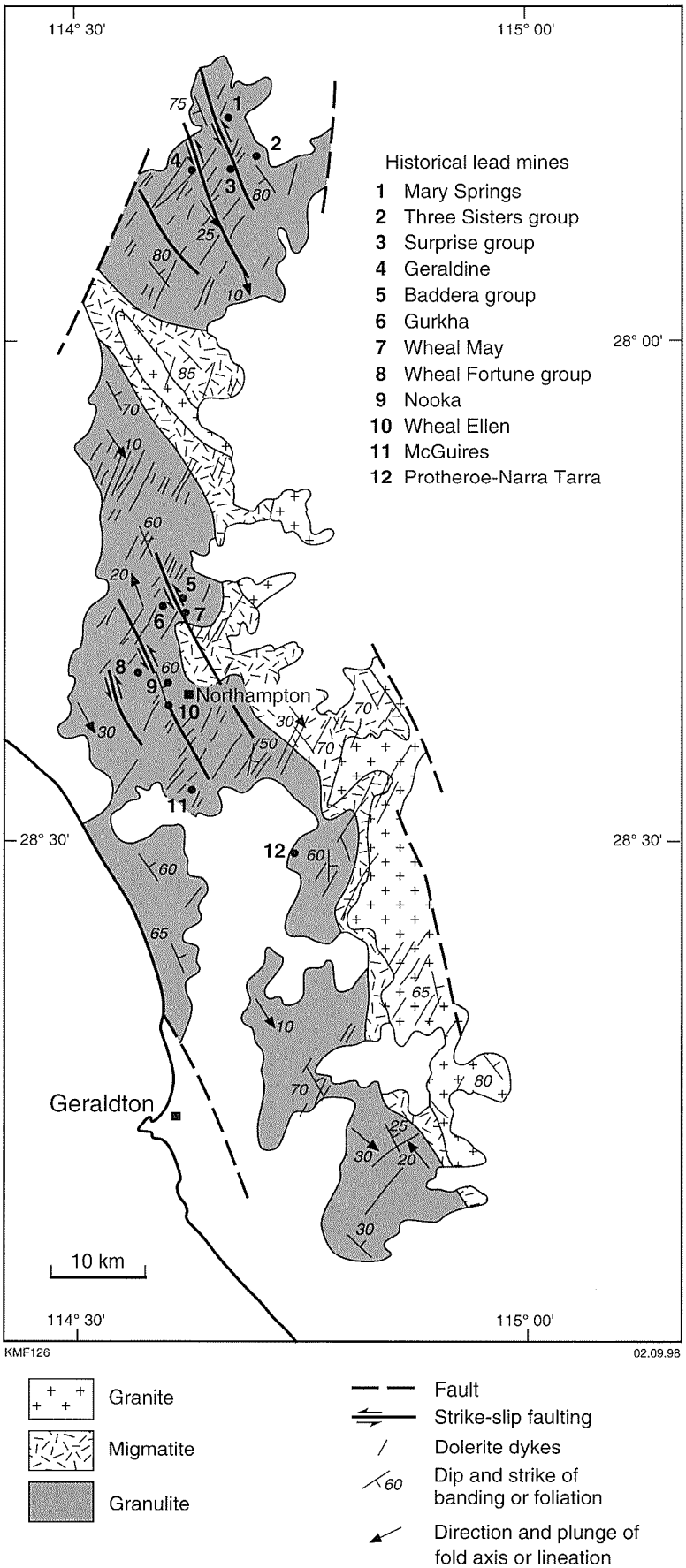


Figure 106. Northampton Complex: geology and deposit and prospect locations (*after* Myers, 1990d; Byrne and Harris, 1993)

(1) lens structures,

(2) shear-breccia link-shear structures (Campbell, 1952; Blockley, 1971),

(3) intersecting lodes, and

(4) curved lodes (Byrne and Harris, 1993).

In (1), a bifurcation of the shear, containing a brecciated lens of country rock, is mineralized; e.g. Protheroe and Narra Tarra. In (2), two parallel shear zones are connected near their ends by linking oblique shears (Fig. 107). Under extension the linking shears dilate; e.g. Surprise, Galena and Surprise North. In (3), breccia develops at the intersection of two shears. There are examples of east-northeasterly trending shears intersecting northeasterly and northerly trending shears; e.g. Deebles and Baddera respectively. In (4), ore forms within the curved section of a shear. This variety is more rare but the Nooka mine provides an example.

The second main type of shoot is associated with copper deposits. These are subhorizontal within the shears as a result of their primarily supergene nature and relationship to the watertable. Malachite and azurite predominate here whereas much lower grades of copper in the form of chalcopyrite and covellite are present at depth.

Campbell (1952) considered that the sinistral shear zones (trending 330°) control the location of ore deposits by their intersection with the 038° shears. Only four such intersections are seen in mines, however, and on the balance of evidence from mines such as Wheal Fortune, Byrne and Harris (1993) concluded that the shears trending 330° post-date the mineralization. This is disputed by Blockley (1995, pers. comm.), who points out that at least one shear trending 330° is mineralized and suggests that the old observation from Wheal Fortune is suspect or at least atypical.

Some early workers have suggested a genetic relationship between the dolerite dykes and the mineralization based on their joint association with the 038° shears. However, only 30% of the deposits are in contact with dykes and none of the larger deposits are associated with dolerite. Isotopes studies by Michael and Groves (1977) indicate a high $^{207}Pb/^{204}Pb$ ratio, suggesting a felsic (crustal) source for the lead rather than a magmatic source.

Establishing the age of the mineralization is fundamental to any genetic hypothesis. A number of attempts have been made (Prider, 1958; Michael, 1977; Michael and Groves, 1977; Richards et al., 1985) and these are summarized by Byrne and Harris (1993). The mineralization is younger than the dolerite dykes which have been dated (Schmidt and Hamilton, 1990) at between 0.5 and 0.75 Ga (K–Ar). According to Byrne and Harris (1993), mineralization is older than the north-northwesterly trending sinistral shears that cut the mineralization in the Wheal Fortune mine and have been related to the north–south sinistral movement along the Darling Mobile Belt around 0.5 to 0.65 Ga. The mineralization, by this argument, is therefore constrained between 0.65 and 0.75 Ga. However, Rb–Sr data from wallrock alteration, presented by Richards et al. (1985), indicates an early Silurian age for the mineralization (427 Ma).

In relation to the mode of formation of the mineralization, Richards et al. (1985) suggested two stages in the mobilization of lead from the greywacke precursors of the granulites. During regional metamorphism at 1.02 Ga, heating and compression would have contributed to the mobility of strontium, lead and uranium. As a second stage, they suggested circulation of aqueous fluids in the early Silurian which extracted lead from the granulites and redeposited it in the orebodies seen today. Michael and Groves (1977) used oxygen-isotope data to suggest low-temperature meteoric water as the mineralizing fluid. They also suggested a connection with seawater derived from the overlying Silurian to early Devonian Tumblagooda Sandstone. As indicated above, this conflicts with the view of Byrne and Harris (1993), based on structural analysis, that the ore zones are cut by north-northwesterly trending shears which predate the deposition of the Tumblagooda Sandstone, being related to sinistral movement along the Darling Mobile Zone between 0.5 and 0.65 Ga.

Byrne and Harris (1993) suggest that the main mineralizing event occurred between 0.65 and 0.8 Ga within the 050° trending brittle–ductile shears formed in a north–south dextral wrench system at least 100 000 years after the intrusion of the dolerite dykes. Some remobilization of the mineralization into late extension veins may have occurred during deposition of the Tumblagooda Sandstone and development of the Perth and Carnarvon Basins.

Exploration

Most lead–zinc–silver exploration in the Northampton Complex has involved detailed sampling and drilling around known abandoned mines, looking for extensions at depth or along strike. These include the programs of Anglo Westralian Mining in the 1950s (Campbell, 1952), Tycho Mining at Ethel Maude, Tin Creek Mining at Lady Sampson, Eastmet at the Mendip mine, Samin at Mary Springs and ACM at Galena.

The work of Dresser (1973–75)(I 2099) was more regional and conceptually based. An area of about 50 km^2 in the Poison Hill area south of Wheal May was mapped, and aerial magnetic and EM surveys were carried out with follow-up ground IP and chip sampling. A number of prospective zones were outlined based of geology, and IP and EM anomalism. The EM targets were within fault breccias associated with the known Wheal May and Baddera mines. A significant number of other targets, however, were within four newly recognized fault breccia zones trending around 045°. Silicification, chloritization and kaolinization of host rocks were recognized in association with the mineralization. The area is occupied by an anticlinal structure, the Poison Hill anticline, and the Baddera and Wheal May mining centres were

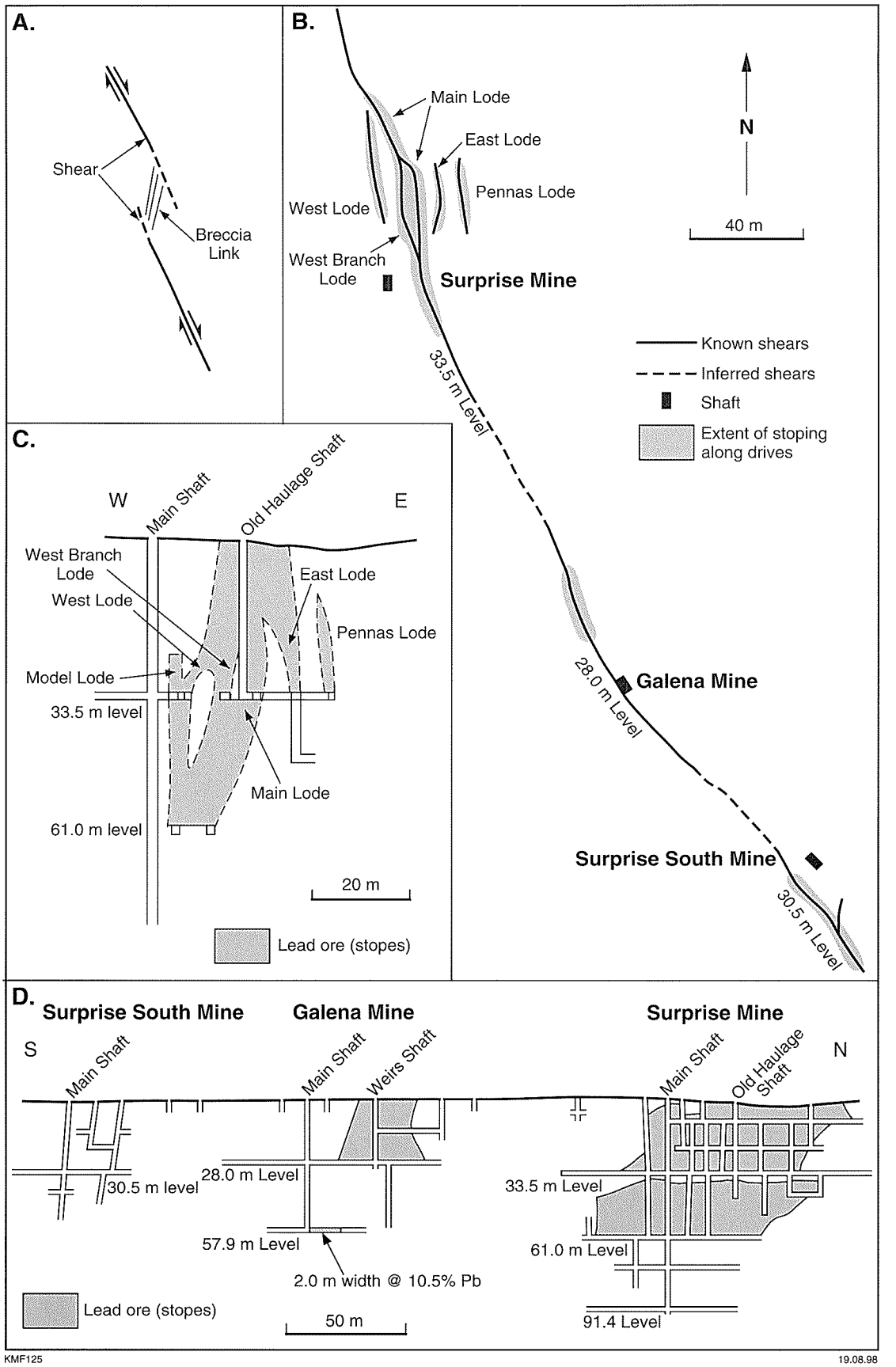


Figure 107. Shear-breccia link structure in the Surprise group of mines, Northampton (*after* Campbell, 1952; Byrne and Harris, 1993)

recognized as occupying the nose of the anticline. Breccias were recognized only where there is considerable displacement along the fault zones. Dresser considered that two high-volume breccia zones located by geological mapping had good potential for large mineralized bodies. Dresser argued a possible 1 to 2 Mt of ore at 10% Pb at depth; however, the surface expressions located were fairly modest.

Allied Minerals (I 3054) carried out regional stream-sediment geochemistry in the complex in 1972–74. They located 'numerous anomalies' but did not follow up the results.

Esso appears to have been the first company to consider the possibility of the occurrence of stratiform lead–zinc(–copper) in the Northampton Complex. In the period 1980 to 1982, in the largely covered, northern part of the complex, Esso (I 2917) conducted a program of regional and detailed geophysics with follow-up geochemical sampling and drilling. The regional work was to define and locate conductors in more favourable lithologies than those seen farther south. Regional soil sampling was hampered by the widespread presence of pisolitic laterite. Forty aeromagnetic anomalies were followed up on the ground with SIROTEM and ground magnetics, and confirmed conductive zones were RAB drilled. Four anomalies, with up to 1.45% Pb and 550 ppm Zn, were each followed up with a diamond hole. Drilling intersected psammitic gneisses with minor felsic breccia zones and related veins of pyrite and galena.

Exploration by CRA (1991–92)(I 6150) of the faulted eastern margin of the complex beneath the Perth Basin sedimentary sequence, northeast of Northampton, examined the possibility that Siluro-?Devonian vein-style lead–zinc might occupy the fault zone and have led to the development of sediment–hosted deposits in the Silurian Tumblagooda Sandstone. Airborne magnetic and GEOTEM surveys were carried out to define structurally and stratigraphically favourable areas, and followed by ground magnetics and RAB geochemistry. Four sites were tested with diamond drilling, which confirmed block faulting and located hematite alteration, thus providing some evidence for fluid movement on the Proterozoic–Silurian unconformity.

West Australian Metals (I 6808), in association with CRA, explored a large area in the northern, south to southeastern parts of the complex between 1986 and 1992. They tested mainly stratiform (Broken Hill-style) targets and, to a lesser extent, vein-type targets and possible mineralization related to the faulted eastern margin of the complex. In their own right, CRA are also exploring in the bulk of the remaining eastern part of the complex. Reporting from surrendered portions of this work confirms that vein-type targets are considered to be subeconomic at present, whereas similarities between the Northampton and the Willyama Complexes favour emphasis on stratiform targets. Literature review by West Australian Metals suggested that mineralization controls in the complex were not well understood and that modern exploration in the area has been insufficient and possibly misdirected.

Deposits, prospects and occurrences

GURKHA (Alma)

Abandoned mine: Pb; Ag
Location: 28°16'30"S, 114°37'E; 8 km north of Northampton

The mineralization is within a shear zone striking 030° and dipping 60–75° west in gneiss. The shear is up to 1.8 m thick over some 150 m and was mined to about 75 m depth. It contains lenses of solid galena up to 0.6 m thick in a silica gangue that contains some barite. Pyrite and marcasite are also present. A sample of pyrite contained 0.54% nickel.

Production in 1859 and between 1952 and 1961 totalled 34 500 t of ore for 5323 t lead and 18 660 g silver from workings which operated at four levels to a depth of 73.1 m.

Reference: Blockley (1971).

NOOKA (Chiverton, Lucky Lou, Nooka South, Nooka West)

Abandoned mines: Pb; Ag
Location: 28°20'40"S, 114°37'45"E; 2 km west of Northampton

Mineralization has been mined in five deposits within a group of shears striking generally north, dipping 70° west, but with a number of variations in attitude. It is present at the surface for about 1 km and curves westward towards the southern end. The centrally placed Nooka mine is located on a curve or bend where the main shear cuts a quartzite band in the granulites. Veins of galena with sphalerite, pyrite and chalcopyrite occur in a siliceous breccia over 76 m and to at least 85 m depth. Nooka South, 300 m to the south, hosts copper only over 30 m in a lode 0.6 m wide. At Nooka West, 300 m northwest of Nooka, cerussite ore has been produced from workings over 30 m to a depth of 6 m. At the Lucky Lou Prospect, south-southeast of Nooka West, bulldozing has exposed weak mineralization on a sheared dolerite contact. The Chiverton mine lies about 240 m southwest of the Nooka mine and is developed on an arcuate link structure in a northerly trending shear worked over 45 m in cerussite and galena.

Production occurred during the 1870s, from 1916 to 1918, and again from 1960 to 1967. The total for the Nooka group is 11 580 t of ore for 1239 t lead and 5007.5 g of silver.

References: Blockley (1971), Richards et al. (1985), Byrne and Harris (1993), Louthean (1992).

BADDERA (Baddera North, South Baddera)

Abandoned mines: Pb (Ag; Zn)
Location: 28°16'20"S, 114°38'10"E; 8 km north of Northampton

At Baddera, discontinuous galena lenses exist within a lode shear (2.5 m wide), striking 050° and dipping 73° to the west, in granulite, pegmatite and quartz. No dolerite is associated with the mineralization. The individual lenses vary greatly in width and length and the degree of boudinage may reflect post-ore formation ductile shearing. Blockley (1971) describes the ore bodies as being associated with cymoid loop structures, which have formed where two bands of massive quartz (veins or ?recrystallized quartzite) trending at 300° are intersected by the shear. A branching lode striking 175° and dipping 65° west, and a 175° trend at the south end of the lode, indicate intersecting shears on this trend, parallel to the metamorphic banding. Baddera North is on the same 050° lode shear, 600 m to the northeast.

The ore bodies comprise quartz, galena, sphalerite, pyrite and minor chalcopyrite either as open-space filling, as narrow veins, or within finely brecciated or powdered rock.

The Baddera deposit was discovered in 1873 and worked for ten years. Subsequent mining between 1910 and 1920 produced 132 000 t of ore at 11% Pb giving 14 200 t lead. The shear zone was mined over about 300 m and to a depth of about 135 m. The branch lode was worked along about 70 m. At Baddera North between 1946 and 1954, 15 200 t ore at 5% Pb were produced for 731 t of lead. Two branching lodes were mined over at least 80 m and to a maximum depth of 46 m.

References: Blockley (1971), Richards et al. (1985), Byrne and Harris (1993), Louthean (1992).

Narra Tarra

Abandoned mine: Pb; Cu
Location: 28°30'35"S, 114°44'50"E; 21 km southeast of Northampton

The Narra Tarra deposit lies within a 030° trending shear lode, the most westerly of three parallel lines of lode in the Protheroe Group. Dipping at 70° east within highly sheared gneiss, the lode is about 1.2 m wide and almost totally occupied by galena. The country rock comprises garnet gneiss, granulite and concordant pegmatite. The deposit has formed on a split-shear lens (or cymoid loop) with major ore shoots on link structures between the arms of the shear. The ore occurs in pinch-and-swell (and possibly boudinaged) lenses. The ore material is often vuggy and contains chalcopyrite, cerussite, pyromorphite, malachite and chalcocite, mostly subordinate to the galena. Oxidation extends to a depth of about 30 m. Copper tends to predominate at the southwest end of the shear lode in a relatively distinct zone, whereas lead is concentrated at the north end.

The deposit was first worked between 1874 and 1880. Later mining between 1913 and 1928 produced 129 312 t of ore for 12 707 t of lead. The workings are 259 m long and extend to 168 m below the surface, at which depth the grade in the most favourable link structure decreases markedly.

References: Blockley (1971), Byrne and Harris (1993).

Protheroe

Abandoned mine: Pb
Location: 28°30'30"S, 114°45'05"E; 21 km southeast of Northampton

The Protheroe deposit lies near the north end of a 035° trending lode, the central of three parallel lines of lodes constituting the Protheroe Group and dipping 70° west. The shear zone has been traced for 1.37 km by geophysical methods. The main ore zone is located on a linking structure in a split-shear lens in garnet gneiss and granulite, similar to the situation of the Narra Tarra deposit. Ore was also mined from the bounding shears, however, and from the main shear outside the split section. Galena, chalcopyrite, cerussite, pyromorphite, malachite and chalcocite were present in the ore, with oxidation extending to a depth of 30 m.

The Protheroe mine was worked between 1946 and 1958 over about 350 m and to 162 m depth and yielded 86 868 t of ore for 13 839 t lead. Diamond drilling was carried out by Anglo Westralian P/L in the early 1950s with thirty holes intersecting the main lode to depths of about 230 m. Only three holes intersected significant lead (up to 2.28 m at 3.6% Pb and 0.6 m at 19.2% Pb) and the favourable link structure was not intersected at depth.

References: Blockley (1971), Byrne and Harris (1993), Louthean (1992).

Wheal Ellen (Wheal Ellen North)

Abandoned mine: Pb; Zn
Location: 28°22'05"S, 114°37'E; 2.5 km southwest of Northampton

The lode shear at Wheal Ellen strikes at 035° and dips west at 60–80° following the west contact of a thin dolerite dyke in granulite. The main ore is associated with a link structure in the lode which offsets the shear. The strongest mineralization is on the offset ends of the shear rather than in the link. Galena, sphalerite, cerussite, copper carbonates and pyrite are present in a gangue of quartz and siliceous breccia. Alteration and silicification of the wall rocks is prominent. The mine contains a significant amount of zinc but only one assay (12.4% Zn) is recorded.

The mine operated in two periods, from 1872 to 1882 and from 1917 to 1967, in two sets of workings 175 m apart. The maximum depth is 82 m and workings extend over about 380 m. Production from 1872 to 1882 was approximately 1000 t of lead and from 1917 to 1967, 23 545 t of ore for 1935 t lead. The average grade realized since 1899 is 8.25% Pb. Anglo Westralian PL in the early 1950s sampled the lowest level of the new workings to outline two shoots, one 117.3 m long and the other 52.1 m long, over a width of about 1 m. They estimated the potential of the two shoots to be about 220 t of lead per vertical foot (~ 0.30 m).

References: Blockley (1971), Byrne and Harris (1993)

Wheal Fortune (Wheal Fortune Extended, Paringa)

Abandoned mines: Pb; Cu; Ag
Location: 28°20'10"S, 114°35'10"E; 5 km west-northwest of Northampton

The three deposits of the Wheal Fortune Group lie within a line of shearing trending at 040–050° and dipping at least 70° southeast. The trend is believed to be made up of a number of parallel, en echelon shears and the richer zones occur where the shears intersect pegmatite. Individual ore shoots pitch southerly and ore widths are up to 1.2 m. The ore minerals are galena, sphalerite, chalcopyrite and pyrite in the primary zone, and cerussite, malachite, azurite, chalcocite, covellite and native copper in the oxidized zone.

At Paringa, the most northerly of the deposits, the ore is in shears of between 030° and 040° strike cutting garnet granulites invaded by pegmatite. Shears with associated mylonite trending at 050° cut the lodes in this mine but may not be involved in localization of the ore. At another location the 030° to 040° shears cut the 050° trend. Byrne and Harris (1993) suggest, on the basis of this kind of evidence, that most of the brittle–ductile shearing formed during the same deformation event.

Wheal Fortune, the most southerly of the deposits, was mined over 223 m to 90 m depth and connected with Wheal Fortune Extended at the 55 m level extending for another 22 m to the north. The Paringa deposit was worked over 200 m and to 97.5 m depth. Wheal Fortune operated from 1862 to 1968 for 3015 t of lead ore at 75% Pb and 2681 t copper ore at 17% Cu. The production for the whole group from 1899 was 44 753 t ore for 4428 t lead and 28 428 g of silver. Allied Mins (1972–74) carried out stream-sediment sampling for lead(–zinc) targets in the area but did not follow up anomalies.

References: Blockley (1971), Richards et al. (1985), Byrne and Harris (1993), Louthean (1992), GSWA-WAMEX - I 3054.

Wheal May

Abandoned mine: Pb; Cu
Location: 28°17'30"S, 114°38'30"E; 6 km north of Northampton

The Wheal May deposit follows a shear lode (1.2 m wide) trending 040°, dipping west at 80° and parallel to a dolerite dyke in metasedimentary rocks. Ore is concentrated where the shear cuts a thick bed of quartzite that strikes at 330°. A galena vein (0.5 m wide) was reported to have persisted over the 210 m length of the workings. Galena, cerussite, chalcocite and copper carbonates were seen in the ore dumps.

Prior to 1899, the deposit was worked over 180 m and to about 25 m depth from a number of shafts. Production in this period was 2240 t of ore at 75% Pb.

Reference: Blockley (1971).

Surprise (Galena, Surprise South, Two Boys)

Abandoned mines: Pb; Zn; Ag
Location: 27°50'S, 114°41'05"E; 56 km north of Northampton

Surprise, Surprise South and Galena are located on a sinistral tear fault with a lateral displacement of 900 m, striking at 340° and dipping 70° west in granulite (Fig. 107). Ore shoots occur on bends and en echelon offshoots. Two Boys is on a parallel fault 170 m to the east, also in granulite country rock. A copper mine has been worked on a parallel shear 90 m west of the Galena mine. There is much brecciation and alteration in the lodes and wall rocks. Primary minerals present in the lodes are galena, sphalerite, marcasite, chalcopyrite, barite and quartz.

At the Surprise mine, the largest and most northerly of the group, six lodes were worked in an intensely crushed and fractured zone, described by Blockley (1971) as an en echelon offset of the north-northwesterly trending fault. Both cymoid loop and diagonal link structures have provided loci for ore mineralization. The average grade was 11% Pb. Byrne and Harris (1993) proposed a dextral movement on the north-northwest brittle–ductile shear zone to explain the parallel lodes at Surprise, based on the angle of the linking shears (northerly rather than north-northeasterly). The Galena mine is 150 m south-southwest of Surprise on the same shear with Surprise South a further 120 m beyond Galena.

Surprise was worked over 100 m to a depth of 90 m between 1918 and 1926, and Galena was worked over 52 m to a depth of 58 m between 1946 and 1958. Surprise South was of similar dimensions but the smaller workings at Two Boys extended only over 24 m and to a depth of 40 m. Total production from the group between 1918 and 1965 (mostly from Surprise) was 119 518 t of ore for 15 142 t lead, 19.83 t zinc and 21 461 g silver. Two diamond holes were drilled by the WA Department of Mines in 1928 to test Surprise at depth. No definite lodes were intersected and core recovery was poor. Aust Consol Mins (1973–76) carried out geological mapping, surface sampling, ground EM and auger drilling in the vicinity of the Galena mine.

References: Blockley (1971), Byrne and Harris (1993), GSWA-WAMEX - I 233

Geraldine

Abandoned mine: Pb; Zn
Location: 27°50'30"S, 114°38'E; 55 km north of Northampton

The mineralization follows a west-dipping shear zone trending 035° in granulite, parallel to nearby dolerite dykes. The ore body is nearly 300 m long at the surface and consisted (in 1848) of sheared, brecciated, chloritized garnet granulite containing solid galena with sphalerite, pyrite, cerussite, chalcopyrite and quartz. Drilling results indicate that galena tended to be concentrated on the hangingwall with sphalerite on the footwall. At depths of about 98 m the ore averaged between 65 and 75% Pb.

In 1850, Geraldine became the first deposit discovered and mined in the Northampton field. It was worked to about 90 m depth and 300 m along strike. The main production occurred between 1867 and 1878 and, by 1899, totalled about 6500 t of ore concentrate. GSWA diamond drilling below the workings in the 1960s encountered only very narrow (≤0.17 m) intersections of high-grade galena and sphalerite. Aust Consol Mins (1973–76) carried out geological mapping, surface sampling, ground EM and auger drilling in the vicinity of the mine.

References: Blockley (1971), Byrne and Harris (1993), GSWA-WAMEX - I 2332.

Three Sisters (Grand Junction, Three Sisters North, Three Brothers, Lady Maude [or Victory])

Abandoned mines: Pb
Location: 27°50'30"S, 114°42'10"E; 59 km north of Northampton

All the mines, except Three Sisters North, are on the west contact of a dolerite dyke trending 040° and dipping 70–80° west. Rich ore forms in zones of brecciation located on offsets and bends in the lode shear where it has intersected bands of more massive country rock within the granulite gneiss. Three Sisters North lies on a line of shearing on the west contact of a basic granulite band which would intersect the main shear farther south. Three Sisters, the main mine of the group, is situated where the shear is offset by a quartzite band and the mine is reported to have averaged 12% Pb. At Grand Junction three lodes occur in an en echelon offset of the lode where it cuts a pegmatite dyke. The main, or western lode, is on a brecciated link structure connecting the opposite ends of the main shear. The Three Brothers mine is 300 m south-southwest of Three Sisters on the same line, and Three Sisters North is 520 m north of Grand Junction. The mineralized zones within the group consist of galena with pyrite, chalcopyrite, copper and lead carbonates, with some sphalerite also at Three Sisters.

Three Sisters was worked over 140 m to a depth of 30 m, and Grand Junction over 37 m also to a depth of 30 m. Total production from the group between 1899 and 1955 was 17 480 t of ore for 1390 t lead and 342 g silver. In 1957, Anglo Westralian PL drilled three diamond holes at Three Sisters for a best intersection of 8.3 m at 2.6% Pb at about 50 m depth.

References: Blockley (1971), Byrne and Harris (1993).

McGuires (Isseka)

Shut down mine: Pb
Location: 28°27'23"S, 114°38'49"E; 11 km south of Northampton

This mine is located on two parallel shear lodes about 600 m apart trending approximately 045° and dipping east. The main workings are on the West Lode in quartz and galena; the East Lode consists of sheared and brecciated gneiss containing disseminated cerussite and sphalerite.

The West Lode was worked over about 190 m and to 70 m depth. Although McGuires is an old mine, production is recorded only from 1950 to 1959 and from 1965 to 1966 with 45 465 t of ore for 582.65 t lead and 4852 g silver. Anglo Westralian PL drilled three diamond holes at West Lode and six at East Lode, beneath the workings, but with negative results. The mine is presently held by Tycho Mining (1973 on) who have established a reserve of 14 000 t at 9.6% Pb.

Reference: Blockley (1971).

Mary Springs (Chequers, Gallaghers, Kingdom Come)

Abandoned mine: Pb; Zn
Location: 27°45'27"S, 114°41'51"E; 65 km north of Northampton

Three parallel ore shoots have been mined at Mary Springs in garnet, quartz–feldspar gneiss (granulite) and dolerite. The two main shoots flank a dolerite dyke (18 m wide) and the third lies 50 m to the west. The shoots trend 030° and dip 70° west. At depth the dips are shallower and the widths and grades increase. The ore zones contain quartz, galena, sphalerite, chalcopyrite and pyrite. In the eastern or footwall shoot dolerite is reportedly mineralized to ore grade. At Gallaghers, near the Mary Springs mine, two lodes trending 035° and 050° contain galena with anglesite and pyromorphite.

The Mary Springs mine has been worked over 120 m to a depth of 30 m and over a maximum width of 3.3 m. In 1908 and between 1947 and 1967 a total of 7620 t of ore for 1300 t lead had been produced, mostly from the Mary Springs mine. Canadian Southern Cross Ltd diamond drilled the footwall shoot to establish dimensions of 90 m by 1.7 m to a depth of 76 m, and the hangingwall shoot for 97.5 m by 1.5 m by 90 m depth. The company estimated a resource of about 80 300 t at 17% Pb in the two shoots. Subsequently a new shaft was sunk and crosscut to the lodes at the 60 m level, after which development work was suspended. Samin (1972–88) drilled below the old workings to outline an estimated resource of 95 600 t of ore at 18.05% Pb in two shoots. A best intersection gave 0.5 m of 25% Pb with maximum grades for other metals of 4.46% Zn, 600 ppm Cu and 6.4 g/t Ag. Samin also tested geophysical targets beyond the mine workings locating subeconomic mineralization. Aust Consol Mins (1973–76) carried out geological mapping, surface sampling, ground EM and auger drilling in the vicinity of the mine.

References: Blockley (1971), Byrne and Harris (1993), GSWA-WAMEX - I 2332, I 3438.

Potential

At present metal prices, and considering the geometry of most deposits, further development of vein-type mineralization in the Northampton Complex must be considered to be uneconomic for the foreseeable future.

As mentioned above, West Australian Metals and CRA have been investigating the potential of the metasedimentary rocks for clastic-hosted, Broken Hill type stratiform lead–zinc–silver mineralization, based on a proposed similarity between the Northampton and Willyama Complexes. Little is known about the environment of deposition of the metasedimentary rocks, although the presence of considerable volumes of metagreywacke suggests a flysch or rift-basin setting, and the presence of graphitic schist indicates the presence of suitable host rocks for this type of target. Moreover, the very limited use of modern mineral exploration techniques in the complex provides additional grounds for optimism.

Rudall Complex

Geological framework

The geological framework, occurrence of mineralization and an outline of exploration for the Rudall Complex in relation to both vein-type and stratabound targets, have been discussed in **Chapter 7**.

Deposits, prospects and occurrences

Gunanya

Occurrence: Cu; Pb; Zn
Location: 23°00'10"S, 122°58'20"E; 30 km southeast of Mount Connaughton

A thin cupriferous quartz blow is emplaced in amphibolite in granitoid gneiss of the Rudall Complex. Malachite, limonite and pyrite occur in patches in the quartz. A surface sample gave 5.68% Cu, 5300 ppm Pb, 2200 ppm Zn, 730 ppm nickel and 17 g/t Ag.

Reference: Marston (1979).

Lead Hills

Prospect: Pb; Ag; Cu; U; Zn
Location: 22°20'30"S, 122°02'40"E; 3 km east of the Kintyre uranium deposit

At Lead Hills, 3 km southwest of Tracy, base-metal sulfides occur in a chlorite–quartz schist and chlorite–carbonate–quartz schist and chert of the Yandagooge Formation within the Rudall Complex. Lenticular siderite veins up to 0.5 m in width contain galena and sphalerite over a 200 m zone. A picked specimen of vein material gave 14.4% Pb, 13% Zn, 156 g/t Ag and 90 ppm Cd with minor associated copper and uranium.

The prospect was discovered and chip sampled by Otter (1971–79). Lead contents, however, were later considered to be uneconomic by CRA (1979 on), who remain the tenement holders. CRA discovered uranium in association with the base metals in 1985 and consider the prospect to be geologically similar to Kintyre.

References: Marston (1979), Hickman and Clarke (1993), GSWA-WAMEX - I 973.

Minder

Prospect: U (Pb; Cu; Zn; Bi)
Location: 22°46'50"S, 122°20'22"E; 33 km southeast of Rudall Crossing

Uranium mineralization at Minder is associated with lead, copper, zinc and bismuth sulfides in albite-altered shear zones within iron-rich metapelite at, or near, pegmatite margins. Mineralized fractures show signs of hydrothermal activity. The mineralization includes traces of galena, chalcopyrite, sphalerite and Pb–Bi sulfides. The prospect lies within the informally named Graphite Valley sequence of the Yandagooge Formation and was located by CRA.

Reference: Hickman and Bagas (in prep.).

Cassandra

Prospect: U; Au; Ag; Cu; Pb
Location: 22°44'18"S, 122°20'26"E; 30 km southeast of Rudall Crossing

Uraninite and coffinite, with subordinate gold, silver, copper and lead, occur as veins in D_4 fractures and shears. Mineralization is associated with silicified pegmatite and chlorite, sericite, hematite and albite hydrothermal alteration within the Graphite Valley sequence of the Yandagooge Formation. The prospect was located by CRA.

Reference: Hickman and Bagas (in prep.).

Bilbo and Dione

Occurrences: U (Pb; Cu; Ni; Co; Bi; Sb)
Location: 22°41'51"S, 122°18'35"E and 22°52'18"S, 122°16'36"E; 21 and 25 km, respectively, southeast of Rudall Crossing

These occurrences, which were found by CRA, are restricted to flat-lying layers in regolith material, and may have formed by precipitation from near-surface groundwater. They contain uraninite with traces of pyrite, galena and chalcopyrite. The area is underlain by the Graphite Valley sequence of the Yandagooge Formation.

Reference: Hickman and Bagas (in prep.).

Albany–Fraser Orogen

Geological framework

The Albany–Fraser Orogen, exposed along the southern and southeastern margins of the Yilgarn Craton, lacks a comprehensive synthesis based on detailed mapping. Myers (1990e) summarized published work at that time and incorporated this, along with aeromagnetic data, in a new interpretation of the extent and nature of the orogen. The orogen, a zone of continental collision between the

Yilgarn Craton and a craton to the east which lies beneath the Eucla Basin (Myers and Barley, 1992), has been divided into two parts called the Biranup and Nornalup Complexes (Myers, 1990c).

The Biranup Complex is made up of high-grade quartzofeldspathic gneiss and layered basic intrusions which appear to be tectonic slices of deep continental crust emplaced at a high crustal level between 1.2 and 1.1 Ga. The portion of this that is made up predominantly of granulite-grade metagabbro is called the Fraser Complex, which is located in the northeastern part of the orogen. The Nornalup Complex, in the southwest of the orogen, comprises less-intensely deformed high-grade orthogneiss and paragneiss, intruded by sheets of granite at about 1.1 Ga. No remnants of oceanic crust are recognized in the orogen and derivatives of basic volcanics seem to be rare. It is speculated that the Biranup Complex may combine reworked Yilgarn Craton material and younger rocks whereas the Nornalup Complex is mostly younger than the Yilgarn Craton.

The northern foreland of the orogen, in the Yilgarn Craton, is characterized by a dense swarm of dolerite dykes subparallel to the margin, which extends about 100 km into the craton, and by thrust sheets of psammitic and subordinate pelitic metasedimentary rocks that include the Stirling Range Formation, the Mount Barren Group and the Woodline Beds. During the formation of the orogen, oblique collision and dextral movements continued between the converging cratons.

Exploration

Little significant Pb–Zn mineralization has been found in the Albany–Fraser Orogen. At Southdown, high-grade magnetite ore is present in granulite facies banded iron-formation. Minor amounts of copper, nickel and platinum have been found in a large body of gabbro in the Fraser Complex. This mineralization was located during a comprehensive regional appraisal of the complex by Newmont between 1965 and 1972 (I 1429). This followed conceptual modelling by Wilson (1969), who suggested that metals such as nickel and copper might be released from mineral lattices during metamorphism and concentrated at structurally favourable sites. Newmont carried out extensive aeromagnetic surveys, geological mapping, rock-chip and soil sampling, covering an area of about 45 000 km^2. More than 20 prospects were drilled after detailed follow-up with IP, magnetic and gravity surveys, mapping and gossan sampling. The subeconomic Cu–Ni mineralization is disseminated in mafic–ultramafic intrusives and is best developed in strongly sheared sections.

Both Goldfields Exploration and Pancon explored the complex for PGEs in the mid-1980s. Following their review of previous work, Growth Resources (1987–89) (I 6401) carried out regional aeromagnetic and radiometric surveys to define lithology and structure. Regional lithochemical sampling was carried out for multi-element assessment but no particular potential for lead–zinc targets was recognized in this work.

Central Norseman (1979–81)(I 2541) explored the granulite in the Salmon Gums area on the western side of the Fraser Range for a number of possible targets including stratiform lead–zinc(–copper). Drilling penetrated the extensive Tertiary cover to assess potential but no base-metal anomalism was encountered.

Occurrences

Bremer Bay

Occurrence: Pb
Location: 34°17'S, 119°22'E; 8 km north of Bremer Bay

Cerussite and anglesite in quartz within the Mesoproterozoic Kybulup Schist (1.3–1.1 Ga) was discovered in 1928 but not mined. The area is presently under tenement to Arimco/Cyprus/ Forrestania Gold (1975 on).

Reference: Blockley (1971).

Halls Creek and King Leopold Orogens

Geological framework

The geological framework of the Halls Creek and King Leopold Orogens has been outlined in **Chapter 6**.

Mineralization

Vein-type lead–zinc–copper mineralization exists predominantly in the western part of the Halls Creek Orogen and in the King Leopold Orogen and tends to take the form of small but high-grade occurrences.

Of the Mount Amherst Group of lead-rich veins, the Black and Glidden and Mount Amherst prospects appear to occupy structures related to the regional, east-northeasterly trending Glidden Fault. This D_3–D_4 structure is probably coeval with the intrusion of the suite of mafic to felsic intrusives, including the McIntosh Gabbro and the Bow Batholith (~1.86 Ga). The shears and veins cut both the Halls Creek Group and the post-tectonic granite of the Bow Batholith and are probably genetically related to that intrusive/deformational event.

Pirajno et al. (1994) describe mineralized hydrothermal quartz veins in granitic rocks at Gnewing Bore (Cu–Pb–Zn(–Au–Ag)), Five Mile Bore (Cu–Pb–Au) and Lady Helen (Au–Ag) in the Halls Creek Orogen. An epithermal origin is indicated by wallrock alteration, dominated by phyllitic assemblages (quartz–sericite–microcline), intense silicification and pyrite, and the ore-mineral assemblage including pyrite, arsenopyrite, chalcopyrite, galena, sphalerite and gold. Mineralization occurs in late structures (~1.1–1.3 Ga) which post-date granitoid emplacement.

The Grants Creek gold-associated mineralization occurs in the Biscay Formation and is related to post- or late D_2 structural permeability (Plumb, 1990).

In the King Leopold Orogen stratabound and vein-type Cu–Pb–Zn occurrences and prospects are located in the Richenda Anticline, a D_2 structure equivalent to D_3 in the Halls Creek Orogen. The Lead prospect and Top Springs prospect are both related to D_2 northwesterly trending shears within Ruins Dolerite, or on Marboo Formation–Ruins Dolerite sheared contacts. The combination of stratigraphic and structural trends in this group of prospects suggests that the stratabound mineralization (whether volcanogenic or sedimentary exhalative, or related to the intrusion of the Ruins Dolerite) may have been partially remobilized during D_2-related shearing around 1.86 Ga.

Other minor prospects in the King Leopold Orogen are veins either in Whitewater Volcanics or related granitoids of the Hooper Complex and probably relate to that ~1.86 Ga intrusive/extrusive event.

The Emull polymetallic body appears to be a metasomatic concentration in favourable host rocks (calc-silicate rocks) assimilated within a mafic–ultramafic sill.

Exploration

The Mount Amherst group of vein-type prospects were stream, soil and chip sampled by Serem (I 778) and Dampier/Stratem (I 738A) in the period 1968 to 1973, but they were not considered to have economic potential. Roebuck (I 7144), however, re-evaluated and resampled the prospects in 1990–93 with the aim of establishing a viable resource for a number of veins in aggregate, or a stockwork zone. Once again results were discouraging.

A number of companies have explored the unusual lensoid and stockwork mineralization at Emull since 1961. Following discovery of the gossanous zone, exploration was predominantly a matter of surface sampling, auger, percussion and diamond drilling, with only minor use of ground geophysics including magnetic, IP, resistivity and VLF EM surveys. Later work by West Coast Holdings (I 5594) used ground magnetics and IP to reinterpret the geometry of the ore shoots.

Exploration by WMC/Richenda and WMC in the King Leopold Orogen, of the vein-type and stratabound prospects in the Richenda Anticline, has been mentioned in **Chapters 6** and **7**. The Lead prospect and Top Springs prospects received attention initially, in the early 1970s, for lead–zinc–copper but more specifically in the 1980s for their gold potential. Regional stream-sediment geochemistry was successfully used to confirm the main prospects. Other anomalies were of limited size. Ground magnetic, IP, resistivity and TEM surveys were used from the early stages to help define conductors beyond and beneath the gossans.

Deposits, prospects and occurrences

The Mount Amherst group

A group of base-metal veins occurs within Halls Creek Group metasedimentary rocks and intrusive granitoid in the area of Mount Amherst Homestead, south of the Mueller Range. Both granitoid and Halls Creek Group are unconformably overlain by rocks of the Kimberley Group.

The Black and Glidden, and Mount Amherst prospects are located in shears close to the major east-northeasterly trending Glidden Fault. The Halls Creek Group lies mostly to the north of the fault whereas granitoid and Kimberley Group sedimentary rocks lie to the south. The fault cuts all these units.

The Dead Horse Creek prospect is in a north-northwesterly trending zone of small veins within the Halls Creek Group about 18 km northwest of the Mount Amherst prospect.

Black and Glidden

Prospect/abandoned mine: Pb; Cu
Location: 18°23'30"S, 126°58'30"E; 75 km west-southwest of Halls Creek

A shear zone cuts arkose, greywacke and amphibolite of the Halls Creek Group. Mineralization is within a 12 by 1.8 m stockwork of thin quartz veins striking 240° with a steep northerly dip. The thin veins, which make up about 15% of the lode, contain galena, cerussite and copper carbonate.

The lode is exposed in two shallow opencuts from which Black and Glidden produced 6.34 t of lead and 1045.68 g of silver between 1948 and 1952. Serem Aust (1968–71) sampled in the Mount Amherst area as did Dampier/Stratem (1971–73) and Roebuck (1990–93).

References: Blockley (1971), Marston (1979), GSWA-WAMEX - I 738A, I 778.

Dead Horse Creek

Prospect: Pb; Zn; Ag; Cu
Location: 18°18'30"S, 126°55'50"E; 78 km west-southwest of Halls Creek

The Dead Horse Creek prospect lies in a north-northwesterly trending fault zone cutting granite, migmatite and Halls Creek Group biotite-rich paragneiss with lenses of calc-silicate and ultramafic material. The fault zone trends at 155° and dips steeply west. The lode contains narrow veins of quartz and calcite with galena, cerussite and secondary copper minerals (including malachite) and is 500 m long by 100 m wide. The northern extension of the zone is obscured by the overlying units of the Kimberley Group; to the south the vein system becomes less pronounced. The main mineralized zone, at the northern end is about 94 by 3 m on the east side of the shear and has been investigated in a trench and small pits. Samples collected by Jones (1938) and Simpson (1951) contain up to 37.7% Pb, 2.74% Zn, 0.25% Cu and 186 g/t Ag.

Serem Aust sampled in the area between 1968 and 1971. Roebuck (1990–93) mapped the area and carried out rock-chip and stream-sediment sampling (maximums 7.5% Pb, 8.4% Zn, and 28 g/t Ag in separate samples). Their report discussed the possibility of the mineralization being preceded by a phreatic explosive event creating a

breccia-pipe style deposit with the possibility of more significant sulfide accumulation at depth. On the basis of outcrop, however, the report concluded that there was 'not even the remotest chance of the veins constituting, in aggregate, an economic orebody'.

References: Jones (1938), Simpson (1951), Blockley (1971), Marston (1979), GSWA-WAMEX - I 778.

Mount Amherst (Mount Amhurst)

Occurrence: Pb; Cu
Location: 18°21'45"S, 127°03'E; 6 km east-northeast of Mount Amherst Homestead

Several mineralized shears are associated with the Glidden Fault (trending 200°) in the Bow River Granite close to its contact with phyllitic metasedimentary and calc-silicate rocks and basalt of the Halls Creek Group. In some cases the metasedimentary component may be remnants within the granite. There is an offset in the Glidden Fault at Soda Springs, where a north-northeasterly trending cross-fault cuts through. East of this intersection the mineralized vein fractures form an en echelon trend over some 3.5 km. The veins form zones of intense chloritization and quartz, are locally gossanous and in one locality consist of massive carbonate. Gold and base metals are associated with the gossanous zones. The three main veins at this locality were examined by Jones (1938). The western two veins coincide with the 'South Prospect' *of* Jones and are, from west to east, his No. 1 and No. 2 reefs. The third vein, farther east, coincides with the 'North Prospect' *of* Jones.

Dampier/Stratem (1971–73) located and sampled the prospect. Sample results for the 'No.1 reef' gave 49 g/t Ag, 6.4 g/t Au and 0.52% Pb from coarse quartz breccia with a ferruginous cement. The 'No. 2 reef', in a zone of veins characterized by malachite-stained limonite gossan, 150 m by 60 m, gave 5.6% Cu and 0.215% Pb. The eastern vein, the North Prospect, forms a gossan zone sporadically developed over 60 m but most strongly developed in a gossan 9 by 1.2 m. Rock-chip sampling gave up to 3.1% Cu, 6.9% Zn, 15.5% Pb, 180 g/t Ag and 8.0 g/t Au in separate samples. The variably carbonate-rich gossan lies close to parallel bands of calc-silicate rock in the metasedimentary material. Further work was recommended. Roebuck (1990–93) saw indications of percussion drilling at the two western reefs. Sampling at No. 1 reef gave up to 15 g/t Au and 1.3% Pb. Mapping by Roebuck indicated an overall length of 2 km for the North Prospect in granite and sediments. Galena was noted in outcrop and rock-chip sampling gave up to 27% Pb, 9.5% Zn, 120 g/t Ag, 0.4% Cu and 1.8 g/t Au. Roebuck saw no indication of an orebody sized stockwork.

References: Jones (1938), GSWA-WAMEX - I 738A, I 7144.

Other prospects

Emull (Lamboo, Loadstone Hill, Location 5)

Deposit/prospect: Zn; Cu; Pb; Ag (Au; As; Bi; Cd)
Location: 18°26'S, 127°17'10"E; 50 km southwest of Halls Creek

Sulfide mineralization is present in two locations within a differentiated gabbroic sill on an easterly trend and dipping at between 50 and 70° to the south. The sill is intruded into, and also incorporates, volcaniclastic rock and tuff of the Halls Creek Group. The Emull and Location 5 prospects lie about 800 m apart, on strike, within a 1.5 km anomalous zone.

At Emull, sulfide mineralization occurs in ultramafic rocks that have been altered to serpentinite and to a diopside–carbonate–chlorite rock originally interpreted as an ultramafic differentiate of the sill, but later considered by Shell to represent assimilated country rock. The mineralization forms broad, heavily disseminated zones containing patchy massive and sub-massive sulfide bands. Pyrite and pyrrhotite are found with sphalerite, galena and some chalcopyrite, plus high silver, gold, bismuth and cadmium in a zone about 500 m long by 150 m wide. Individual bands of massive galena–sphalerite reach 1 m in thickness.

At Location 5 the gabbro sill is much thinner and contains two zones of gossanous ironstone and stockwork veining which are anomalous in copper, lead, zinc and silver. Patchily developed disseminated and submassive lenses present at depth are associated with shearing, xenolithic fragments and calc-silicate bands, indicative of post-magmatic effects. Pyrite, pyrrhotite, chalcopyrite, sphalerite and galena are also noted.

In both prospects Shell reported that the mineralization occurred in calc-silicate rocks occupying a zone near the base of the gabbro, which lies between an upper sulfide-rich gabbro (pyrite–pyrrhotite) and a lower oxide-rich gabbro. Shell concluded from the lithological and mineralogical associations that the lead–zinc–silver sulfide phase had been introduced into the partially crystallized, sulfidic gabbro.

Peko (1961–63) discovered the gossans. PMI (1965–71) drilled the gossan at Emull, obtained a best intersection of 15 m at 1.6% Zn, 0.9% Pb and 0.63 g/t Ag, and established indicated reserves of 6 Mt at 2.0% Zn and 0.34% Cu. PMI/Shell (1977–78) mapped and sampled the prospective horizon and carried out percussion and diamond drilling at Location 5 with a best intersection of 1.58 m at 2.07% Zn, 0.58% Cu, 0.27% Pb and 13 g/t Ag. They quoted a resource of 7.8 Mt for Emull at 2.9% Zn and 0.3% Cu plus lead, silver, cadmium and bismuth. BHP (1979–80) briefly examined and sampled the gossans, obtaining up to 1.1% Cu, 9.5% Zn and 11.5 g/t Au, but considered the grade and size too low. WC Holdings (1981–91) tested the supergene zone with indifferent results and no extra potential was outlined. As a result of ground magnetic and IP surveys they reinterpreted the zinc zones as en echelon, steeply east-dipping shoots, and defined the demonstrated, in situ ore resource as 4.7 Mt at 4.5% Zn, 0.33% Cu, 0.2% Pb and 19 g/t Ag.

References: Marston (1979), Louthean (1992), GSWA-WAMEX - I 732, I 2683, I 5594.

Grants Creek (Star of Kimberley, Perseverance)

Prospects: Au; Ag; Pb
Location: 17°50'08"S, 127°55'50"E; 48 km northeast of Halls Creek

East-northeasterly trending quartz reefs in basalts and metasedimentary rocks of the Biscay Formation host gold–silver–lead mineralization in small, high-grade deposits. The Star of Kimberley reef is 143 by 1.7 m in schist showing vertical or steep dips to the northwest. Rock-chip samples contain up to 58% Pb, 754 g/t Ag and 38 g/t Au (Finucane and Jones, 1939) with an average gold grade of 13 g/t. Sampling by Australian Mineral Ventures in 1979–80 gave up to 4.3% Pb, 24 g/t Au and 76.5 g/t Ag. The quartz reefs contain pyrite, galena, chalcopyrite, anglesite, cerussite, malachite, azurite and limonite.

The Star of Kimberley was briefly worked in the late nineteenth century for gold from a shaft, and a diamond drillhole has penetrated beneath the workings but no details are recorded. Aus Min Ventures (1979–80) carried out further rock-chip sampling. Dominion/Southern Ventures (1981 on) currently hold the Grants Creek Group and have reported a demonstrated resource for the group of 66 000 t at 4.97 g/t Au, 16.28 g/t Ag and 0.73% Pb.

References: Finucane and Jones (1939), GSWA-WAMEX - I 6027.

Osmond Creek (Osmund Creek)

Prospect: Pb; Ag; Cu
Location: 17°13'37"S, 128°19'E; 22 km east-southeast of Mabel Downs Homestead

A quartz vein carrying galena and chalcopyrite occurs in the Olympio Formation. A sample contains 52.1% Pb, 241 g/t Ag and minor Cu.

References: Blockley (1971), Marston (1979).

Bigelleas Yard

Occurrence: Pb
Location: 17°38'S, 125°53'E; 73 km northeast of Fitzroy Crossing

This occurrence lies at the southern end of a ridge formed by en echelon northerly trending quartz veins. Galena occurs in thin veinlets in a brecciated, massive quartz gangue within granite. There has been minor production in the past.

Reference: Blockley (1971).

Macs Jump-Up

Occurrence: Pb
Location: 17°09'S,125°00'E; 30 km east-northeast of Napier Downs Homestead

Galena in quartz veins is associated with barite, fluorite and pyrite in a fault zone within Whitewater Volcanics.

Reference: Derrick and Playford (1973).

Old Leopold Downs (Leopold Downs Station)

Occurrence: Pb
Location: 17°50'S, 125°56'E; 54 km northeast of Fitzroy Crossing

A quartz reef with crystals and patches of galena, is located 5 km northeast of the homestead. This occurrence is about 0.5 m wide and may be traced over 600 m, striking north in sheared granite and schist of the Lamboo Complex.

Reference: Blockley (1971).

Lead Prospect (Lead Show)

Prospect: Pb; Ag; Cu
Location: 17°23'15"S, 125°16'45"E; 60 km east-southeast of Napier Downs Homestead

A northwesterly trending galena, quartz, limonite gossan (1.3 km × 6 m) appears to reflect subparallel mineralized veins in sheared Woodward Dolerite, on the Sandy Creek Fault Zone (Fig. 70). Individual veins can be up to 250 by 0.5 m. Rock-chip sampling of the veins by WMC showed up to 0.25% Cu, 15.75% Pb, 155 g/t Ag, 0.46% Sb and 0.18% As. The marginal dolerite showed up to 0.17% Cu, 1.43% Pb and 0.46% Zn in separate samples (WMC).

WMC/Richenda (1973–74) carried out surface sampling and percussion drilling (with possible contamination) for best intersections of 1.5 m at 9.2% Pb and 8 m at 3.9% Pb between 42 and 50 m. WMC (1982–84) undertook stream-sediment and rock-chip sampling with a gold focus as did Century Mining from 1987 to 1988. Century obtained up to 0.11% Cu, 0.8% Zn, 66% Pb, 1260 g/t Ag and 0.28 g/t Au. Moonbeam, Pancontinental and Normandy are currently exploring in the area.

References: GSWA-WAMEX - I 780, I 1200, I 3614.

Top Springs

Prospect: Cu; Pb; Zn; Ag; Au
Location: 17°23'50"S, 125°17'10"E; 66 km east-southeast of Napier Downs Homestead

Top Springs prospect lies 3 km northwest of Turtle Creek (Fig. 70). A gossan (270 × 6 m), overlies a quartz stockwork. Mineralization is malachite and azurite in a sheared phyllite–metadolerite contact related to the Sandy Creek Fault Zone. The phyllite represents carbonaceous metasedimentary and felsic volcanic rocks of the Marboo Formation. Surface sampling by WMC showed up to 0.51% Cu, 0.9% Pb, 0.1% Zn, 2.35% As, and 6 g/t Ag. Century recorded 16.5% Cu, 1.05% Zn, 4.65% Pb, 6.43 g/t Au and 206 g/t Ag in separate samples. The mineralization seen in drillcore contained pyrite and pyrrhotite with chalcopyrite. In polished section the following were identified: sphalerite, bournonite, galena, tetrahedrite–tennantite, jamesonite, tetradymite, arsenopyrite, boulangerite, jordanite, and fine-grained stibnite.

WMC/Richenda (1973–74) carried out percussion and diamond drilling to define a continuous zone 100 m long by 10 m to a depth of 80 m. A maximum of 6.5% Pb and 347 g/t Ag was encountered in percussion drilling whereas the best diamond intersection was 2.38 m at 2.1% Cu, 3,5% Pb, 4.2% Zn and 162 g/t Ag representing two bands of massive sulfides in a laminated, graphitic siltstone.

WMC (1982–84) undertook stream-sediment and rock-chip sampling with a gold focus and Century (1987–89) also sampled rock chips for gold and reported earlier sampling that has been carried out by Moonbeam Nominees. Moonbeam and Pancontinental are currently exploring in the area.

References: Marston (1979), Griffin et al. (1992), GSWA-WAMEX - I 780, I 1200, I 3614.

Bangemall Basin

The geological framework of the Bangemall Basin has been detailed in **Chapter 7**.

Mineralization

Lead–zinc mineralization in the Bangemall Basin is found predominantly in minor vein-type occurrences such as Maroonah, Teano Range and Keep It Dark. Most of these exist within small quartz veins in the Irregully Formation within the western facies of the basin. Koorabooka Creek, Maroonah and Teano Range are examples of this type and Joy Helen may also belong to this group. The primary sulfides are galena and chalcopyrite. Muhling and Brakel (1985) considered the metals to have been concentrated from the surrounding carbonate.

Most of these occurrences are within the Edmund Fold Belt, which formed under an extensional regime during sedimentation with related development of growth faults in the basement. Post-depositional, open to tight folding in the belt was followed by a later phase of tight folding, with reactivated growth faults and shear zones, reflecting north–south compression.

Copper with lower lead content is also associated with dolerite in minor occurrences with little potential for significant tonnages.

The Quartzite Well Fault lead–zinc mineralization has been interpreted (Davy, 1980) as being derived from remobilization of the nearby stratabound mineralization in the Jillawarra Formation.

The Keep it Dark prospect lies at a higher stratigraphic level in shales of the Mucalana Subgroup and in a structural domain characterized by open folds and block faulting. There may have been a volcanogenic association at the Prairie Downs prospect, located on the faulted margin of the Bangemall Basin where arenite and conglomerate lie against mafic volcanics of the Fortescue Group.

Exploration

Exploration in the Bangemall Basin from the 1960s has been largely for stratabound or stratiform targets with vein-type lead–zinc encountered only incidentally or examined as an indication of metal mobility.

Exploration of this type was pursued at Koorabooka by BHP (I 4401), at Keep it Dark by BP Minerals (I 2612), at Mount Genoa by Alcoa/Anaconda (I 37) and Inco (I 1111), at Teano Range by Inco (I 643) and Geopeko (I 4642), and at Maroonah by Kennecott (I 69B).

Fault-hosted mineralization in the Jillawara area, at Quartzite Well prospect, was discovered by Amoco in 1975 (I 4641) during reconnaissance geology and rock-chip sampling. Subsequent exploration by Amoco included airborne magnetics and INPUT-EM, which defined numerous anomalous zones. Ground follow-up included EM, IP, gravity and magnetic surveys with extensive soil, rock-chip and RAB bedrock geochemistry prior to deeper percussion and diamond drilling.

The Prairie Downs fault-zone mineralization was discovered by Australian Ores and Minerals in 1969 (I 2180). The mineralization was delineated at the surface by soil geochemistry and self-potential anomalies prior to drilling. More recent mapping, electrical geophysics, soil and auger geochemistry by Sovereign Resources (1991 on) (I 3216) has led the company to reinterpret the prospect as having VMS associations.

Deposits, prospects and occurrences

Koorabooka Creek (Kurabuka Creek, McCarthys Find, Mount Augustus)

Prospect: Pb; Ag; Cu; Zn
Location: 24°03'S, 116°41'E; 1 km southwest of Deep Well

At this prospect a broad, stream-sediment copper–zinc anomaly surrounds coarsely crystalline argentiferous galena, dark, iron-rich sphalerite and siderite in small bedding-parallel veins, pods and quartz stringers along joint planes. Flat-lying Irregully Formation dolomite occurs in the axis of the Woolshed Syncline. Associated products of weathering include limonite, anglesite, covellite, chrysocolla, malachite, smithsonite and hydrozincite. This may be associated with an easterly trending siliceous shear zone (0.6 m wide). Vein samples average 5–10% galena.

Old lead workings (c. 1900) consist of four small pits and one drive. One small excavation follows a steeply dipping quartz vein that trends at 240°. Westfield (1961–67) examined the area during regional exploration. BHP (1984–86) followed up grab-sample anomalies (with maxima of 28.1% Pb, 26.1% Zn and 252 g/t Ag in separate samples) with percussion drilling but results from this were generally poor. Later diamond drilling on geochemical and EM targets was also discouraging, with up to 72 m of Tertiary overburden being encountered in some holes. Newcrest (1990–91) looked for alkaline complexes with associated gold, base metals and rare earth elements. Surface geochemistry was not informative.

References: Blockley (1971), Williams et al. (1983), Chuck (1984), Simpson (1951), GSWA-WAMEX - I 245, I 4401, I 5865.

Keep it Dark

Prospect: Pb; Zn; Cu; Ba
Location: 24°08'40"S, 119°33'E; 18.8 km south of Bulloo Downs Homestead

A shear lode trending 200° and dipping 75° west contains narrow (30 cm) lenses of quartz breccia with galena, cerussite, pyrite and manganese oxides in horizontally bedded Fords Creek Shale. A thin dolerite dyke forms the footwall. Dump material assayed 24.3% Pb, 0.34% Zn and 21.77 g/t Ag.

The prospect was worked over 29 m and to 4.5 m depth in 1949 to produce 4.4 t Pb and 1865 g Ag. CEC (1973) explored for similar targets south of Keep it Dark and BP Minerals (1984–85) explored for stratabound mineralization but also carried out SIROTEM, rock-chip sampling, percussion drilling and diamond drilling on known prospects. One diamond drillhole tested a SIROTEM conductor at Keep it Dark but intersected carbonaceous and pyritic shale. Percussion holes intersected minor elevated lead, zinc and barite (≤0.255%) with arsenic and manganese associated with veining. A previously unrecorded area of southeast and southwest trending quartz–galena–pyrite veins about 6 km south of Koode-Magi Well yielded rock-chip samples showing up to 3.06% Pb, 0.31% Zn and 0.25% Cu.

References: Blockley (1971), Brakel et al. (1982), GSWA-WAMEX - I 1053, I 2612.

Maroonah (Latham Prospect)

Occurrence/prospect: Pb; Ag
Location: 23°31'S, 115°40'E; 18 km east-southeast of Maroonah Homestead

A quartz vein, up to 0.5 m wide, trending 345° and dipping 60° west, occurs in a dolerite sill within Irregully Formation close to its unconformable contact with the Lower Proterozoic Wyloo Group. The vein was traced for 60 m and a rock-chip sample assayed 3.53% Pb, 0.02% Zn and 13.06 g/t Ag.

The occurrence has been worked in a shallow trench over 15 m and along an outcrop for 7.5 m at a depth of 2 m. Kennecott (1966) followed up GSWA gossans in Irregully Formation and considered the mineralization to be of sedimentary origin.

Reference: Blockley (1971), GSWA-WAMEX - I 69B.

Teano Range (Teano River, Postcutters Bore)

Occurrence: Pb; Ag
Location: Teano River 24°30'40"S, 117°51'E; 43 km northwest of Woodlands Homestead Postcutters Bore 24°54'98"S, 117°85'95"E; 33.5 km northwest of Woodlands Homestead

Two quartz vein-hosted lead occurrences have been located in Irregully Formation dolomite.

At Teano River a zone of silicification 3 km long by up to 20 m wide, on an east-northeasterly trend with a vertical to steep northerly dip, contains numerous quartz veins. Sulfide mineralization occurs throughout the length of the zone. A 1 km-long northeasterly trending branch of the zone, is also mineralized. Galena is the dominant sulfide, particularly in the east–west zone and some chalcopyrite and malachite are present in the branch. Grades of up to 40% Pb, 28.5 g/t Ag and 0.187% Cu have been obtained in separate samples collected by INCO and Geopeko.

At Postcutters Bore the zone of lead veining extends over 1 km by 5 m and trends southeast about 6 km southeast of Teano River prospect, again predominantly in dolomite. Disseminated galena (≤1.92% Pb) was observed in quartz veins.

Inco (1977–78) mapped these occurrences and carried out gossan and stream-sediment sampling with the results quoted above. Geopeko (1982–83) carried out further mapping, rock-chip sampling and stream-sediment sampling with follow-up ground magnetic and gravity surveys. Interpretation of a coincident ground-magnetic and gravity high by Geopeko in the Teano River West area indicated sources to a depth of about 800 m.

Samples from Teano River vein were given to J. R. Richards (ANU) for isotopic analysis in 1983: a Pb/Pb model age of 1.50 Ga was obtained (Ruddock, I., 1995, pers. comm.).

References: GSWA-WAMEX - I 643, I 4642.

Mount Genoa (Isabel Well, Mount Isabella)

Occurrence: Pb
Location: 24°23'30"S, 116°59'E; 2 km north of Mount Genoa

At Mount Genoa a thin (0.4 m) vein of anglesite cutting shale of Kiangi Creek Formation contains up to 45% Pb, 2.8% Cu and 150.53 g/t Ag. Apart from massive anglesite the vein contains some quartz, limonite, cerussite, malachite and galena.

Alcoa/Anaconda (1966–67) conducted regional exploration for sedimentary targets. Detailed mapping and diamond drilling suggested that synclines in the area represented original sedimentary sub-basins and that a major northeasterly trending photolineament (Fig. 78) also controlled synsedimentary subsidence (Chuck, 1984). Galena and chalcopyrite in dolomite gave a best intersection of 2 m at 0.44% Pb and an early diagenetic origin was suspected. Inco (1977–79) examined stratiform gossans of limited extent in Irregully Formation dolomitic shale for a maximum of 1.04% Zn at Genoa Bore and 1.7% Zn southeast of Weloo Bore. Inco also obtained 3.7% Zn in a quartz vein with kaolin, malachite and chrysocolla at the contact between Jillawarra Formation dolomitic shale and overlying chert at Mount Candolle, about 8 km southeast of Mount Genoa. They also reported 17.5% Cu from a quartz vein in gabbro in the same area.

References: Blockley (1971), Marston (1979), Williams et al. (1983), Chuck (1984), GSWA-WAMEX - I 37, I 1111.

Quartzite Well Fault

Prospect: Pb; Zn; Ag
Location: 24°39'S, 118°20'E; 29 km northeast of Woodlands Homestead

Pyrite, galena and sphalerite are present in the breccia of the Quartzite Well Fault, an easterly trending reverse fault in which Lower Gap Well Formation (sandstone, dolomite, shale, phyllite) is thrust over the Jillawarra Formation, Discovery Chert and Devil Creek Formation. At the fault, Jillawarra Formation lies against the Lower Gap Well Formation. This fault was probably originally a normal fault marking the northern margin of the Jillawarra basin (Vogt, 1995).

A ferruginous siliceous gossan, 1.4 km long, carries up to 1.85% Pb and 260 g/t Ag at the surface. At depth, galena and sphalerite exist in late-stage silica and pyrite veins.

In 1974, Amoco discovered the gossan and analyses showed that it contained anomalous lead and zinc. Between 1975 and 1978, percussion and diamond drilling had defined the sulfide zone to be dominantly pyritic associated with milky white silica in thin veins (in open-space crustiform structures commonly spheroidal and up to 15 cm in diameter) and in pyrite, silica, and chert breccia of the Jillawarra Formation. Galena and sphalerite are associated with late-stage microcrystalline silica veining of strongly pyritic zones. Traces of copper are found in finely disseminated 'blotches' of chalcopyrite. The best intersection is 34 m at 1.99% Pb, 1.07% Zn and 27.9 g/t Ag. An intersection of 2 m gave 15.4% Pb with 50 ppm Cu, 0.25% Zn and 60 g/t Ag. The best copper grade was 0.11% over 2 m.

Davy (1980) interpreted the mineralization as having been derived from remobilization of nearby stratabound mineralization in the Jillawarra Formation (*see* Quartzite Well prospect).

References: Muhling and Brakel (1985), Davy (1980), Vogt (1995), GSWA-WAMEX - I 4641.

Prairie Downs

Prospect: Pb; Zn; Cu
Location: 23°43'S, 119°17'E; southwest of Newman

Mineralization is in a partly quartz-filled fault zone up to 250 m wide southwest of the Sylvania Dome. The zone trends at 320° and dips steeply northeast. Fortescue Group metamorphosed mafic and komatiitic volcanic rocks on the east side, are faulted against Middle Proterozoic Prairie Downs Formation arenite/conglomerate, intruded by dolerite, on the west side. Along 2.4 km of strike, galena and sphalerite with minor chalcopyrite and pyrite are associated with the shear zone in four en echelon veins, up to 3.6 m wide and 60 m long. Mineralization is very irregular and takes the form of veins and stringers in quartz–barite gangue, disseminations of sphalerite in volcanic breccia and conglomerate and massive pods of solid galena–sphalerite. Surface samples give up to 32.4% Pb, 11.3% Zn and 2.69% Cu.

Australian Ores and Minerals (1969–71) carried out surface mapping, sampling and geophysical surveys prior to percussion and diamond drilling. The best intersection was 8.5 m at 1.28% Pb, 0.2% Cu, 10.1% Zn and 8.8 g/t Ag and resources of 200 000 t at 8% Zn, 1.5% Pb and 7.5 g/t Ag in one shoot and 30 000 t at 3% Cu in a smaller body were defined. Indian Ocean Resources (1984–85) conducted a literature search only and downgraded the prospect. Sovereign Resources (1991 on) conducted surface sampling away from areas of known resources and produced anomalies where Fortescue Group host rocks lie beneath thin surficial cover about 7 km north of the prospect. The association of the mineralization with volcanic units led Sovereign to propose a VMS model for the mineralization, and zones of stockwork brecciation were interpreted as structurally aligned pneumatolytic explosive vents. Major fracturing in these units, it was considered, had been incorrectly interpreted in the past as sedimentary conglomerates.

References: Blockley (1971), Marston (1979), Metals Gazette 8/91, Tyler (1991), Minerals Gazette 11/91, GSWA-WAMEX - I 2180, I 3216.

Kimberley Basin

Geological framework

The Early Proterozoic Kimberley Basin contains an essentially sedimentary sequence. For the most part the units are flat lying and occupy the broad area of the Kimberley Plateau. Along the southeastern and southwestern margins of the basin, however, they are upturned and folded and are included in the Halls Creek and King Leopold Orogens. Included within the sequence is the Hart Dolerite which is up to 3 km thick and forms extensive, anastamosing dolerite–granophyre sills in the Speewah and Kimberley Groups. These sills have an intrusive age of 1.80 Ga based on U–Pb SHRIMP determination on zircon (Griffin and Tyler, 1992). The date and tholeiitic affinities may suggest a connection with the Carson Volcanics (Dow and Gemuts, 1969).

The Speewah Group is the product of a broad transgressive–regressive sedimentation event with fluvial sands giving way to interfingering fluvial and shallow-marine facies, and finally to deep-water silt. The group also includes minor felsic volcanics. The Kimberley Group marks a return to fluvial and shallow-marine sedimentation with tholeiitic basalt (Carson Volcanics).

Mineralization

Vein-type lead(–copper–zinc–silver–fluorite) mineralization in the Kimberley Basin is closely associated with the Hart Dolerite, frequently hosted within or close to this extensive mafic intrusion. The mineralization is also related to northeasterly and north-northeasterly trending sinistral strike-slip faulting in the area of influence of the Greenvale and Ivanhoe Faults. The close association with the dolerite suggests that this rock may be the source of the metals.

Exploration

Only minor exploration has been undertaken in this tectonic unit for vein-type mineralization. Apart from that detailed below in relation to specific prospects, Serem (1968–71) (I 778) explored in the Mount Remarkable area for stratabound targets, using stream-sediment and soil sampling combined with ground radiometry, but found only minor vein-type occurrences. Stratabound copper (–nickel–uranium) was sought in the 1960s and early 1970s and this exploration was followed up by CRA (1991–92) (I 6654) in the Karunji and Grimwood areas.

Deposits, prospects and occurrences

Blackfellow Creek

Prospect/occurrence: Pb; Cu
Location: 18°08'S, 127°07'E; 60 km west-northwest of Halls Creek

An easterly trending mineralized quartz reef (90 m long) occupies a vertical fault in interlayered Carson Volcanics and Hart Dolerite. Separate samples showed up to 1.52% Pb with up to 0.165% Cu; the minerals present are galena as coarse crystals and malachite as staining.

Kia Ora Gold (1970) located and chip sampled the occurrence during a brief reconnaissance.

Reference: GSWA-WAMEX - I 1542.

Coolan Creek Yard

Occurrence: Cu; Pb; F
Location: 17°47'20"S, 126°34'50"E; 114 km east-northeast of Fitzroy Crossing

Chalcopyrite and galena are present in a quartz vein that cuts Hart Dolerite.

References: Marston (1979), Gellatly and Derrick (1967).

Goads Yard East

Occurrence: Cu; Pb
Location: 17°51'40"S, 126°41'E; 110 km west-northwest of Halls Creek

Quartz veins carrying cupriferous limonitic gossan follow a fault in Whitewater Volcanics. Sampling showed up to 0.5% Cu and 0.15% Pb.

Reference: Marston (1979).

Hart Dolerite prospects

The following three prospects and occurrences are all in the Hart Dolerite, a massive composite sill of tholeiitic dolerite and granophyre which intrudes the lower parts of the Kimberley Basin succession, particularly the Speewah Group. The dolerite is dated at 1.8 Ga (Griffin and Tyler, 1992).

The prospects and occurrences are structurally controlled quartz veins containing fluorite and/or lead–zinc–silver mineralization with associated copper. They occur in two groups on the western margin of the Halls Creek Orogen, centred on the Speewah and Shangri La prospects. The associated northeasterly and north-northeasterly trending sinistral faulting and quartz veining are related to D_5 and D_6 deformation. Northerly trending splay faults from the major north-northeasterly trending Greenvale and Ivanhoe Faults are associated with both groups.

Martins Fluorite (Speewah Prospect)

Occurrence: Pb; F
Location: 16°21'S, 127°57'10"E; 11 km north-northwest of Speewah Homestead

Azurite, galena, fluorite and epidote are present in lenticular quartz veins within a northerly trending vertical fault zone (16 km long). The mineralized zone, which lies within Hart Dolerite, extends over only 120 m.

Great Boulder (1972–84) located most of the prospects in this area and tested the fluorite potential of the Speewah Fluorite Prospect (not this prospect) with percussion and diamond drilling. Elmina (1985 on) is continuing to assess the economic potential of the fluorite deposits.

References: Blockley (1971), Marston (1979), GSWA-WAMEX - 2186.

Martins Silver Lead (Duracks)

Prospect: Pb; Ag; Cu
Location: 16°13'S, 127°58'40"E; 27 km north of Speewah Homestead

Small quantities of azurite and malachite are associated with galena and cerussite in a quartz vein (1 m thick), trending at 360° with a shallow easterly dip, on the upper contact of a dolerite–granophyre sill of the Hart Dolerite. The veining may be traced over 250 m. Assays reported for the prospect show up to 72.3% Pb, 1863 g/t Ag, 3.61% Cu, and 4 g/t Au.

The prospect has been costeaned, and Planet (1968–72) drilled 16 percussion holes but intersected only patchy low-grade mineralization.

References: Blockley (1971), Marston (1979).

Shangri La (Costeos, Silver Hills, Donkey Hills South)

Abandoned mine/prospects: Pb; Cu; Zn; Ag; Au
Location: 15°46'40"S, 128°34'10"E; 18 km west of Kununurra

Three prospects are located in the vicinity of the abandoned Shangri La mine. Polymetallic quartz veins pervade the Hart Dolerite, which is intruded into the Valentine Siltstone of the Speewah Group. The sedimentary rocks and the dolerite form an anticline or dome and the mineralized veins are associated with the northeasterly trending axis.

At Shangri La, there are six en echelon, polymetallic quartz veins in a west-northwesterly striking zone in Hart Dolerite. The individual veins strike west to northwest and dip from 10 to 35° north over 300 m. The veins contain galena, sphalerite, chalcopyrite, bornite and tetrahedrite in the primary zone, with azurite, cerussite, anglesite, chrysocolla, chalcocite, malachite, bindheimite, hemimorphite and covellite in the oxidized zone. Gold and silver are associated with the copper minerals. The ore minerals take the form of disseminations or irregular bands and patches. Chlorite alteration is associated with the mineralization. Although samples of ore gave up to 3041 g/t Ag, 73 g/t Au, 4.04% Cu, 24.8% Zn and 34.8% Pb. The average of three samples gave 1.8% Cu, 16.1% Zn and 19.5% Pb. Drilling intersected up to 7.4% Cu, 4.4% Pb and 397 g/t Au (separate intersections).

At Silver Hills, veining similar to that at Shangri La, in Hart Dolerite and Valentines Siltstone (Speewah Group), trends north-northeast and lies east and west of (and parallel to) an associated major fault (the Silver Hills Fault). The veins dip steeply west and contain a mineral assemblage similar to that at Shangri La, with the addition of pyromorphite. Clay alteration is associated with the mineralization. Rock-chip geochemistry gives best values of 23.2% Cu, 9.3% Pb, 0.15% Zn, 10.77 g/t Au and 136 g/t Ag with Cu and Pb averages of 8.8 and 3.2%, respectively.

At Donkey Hills South, a large number of quartz veins cut Hart Dolerite on a west to west-northwest trend over 300 m by 100 m width. The observed mineralization is mainly malachite and galena with most veins having a relatively short strike length. Trench sampling gave 7.4% Cu, 4.4% Pb, 5.95 g/t Ag and 1450 g/t Au.

Conwest Aust/Acmex/Acmin/Geotechnics (1968–72) drilled and mined at Shangri La in two opencuts plus pits and trenches over 30 m and to 5 m depth. No production is recorded. They estimated ore reserves at 34 500 t averaging 7.6% Pb, 301.69 g/t Ag and 5.6 g/t Au within three of the vein shoots. Amax/Auselec/CRA (1972–85) examined the Shangri La mine during regional exploration for MVT targets. Grab samples gave 4% Cu, 27.6% Pb, 0.9% As, 0.11% Ag and 50 g/t Au. Moder (1984–88) examined gold potential in the area and described and sampled (*see above*) the Donkey Hills prospect. Moder mapped and sampled the main prospects in some detail and suggested there was potential at Shangri La for a small opencut in high-grade ore.

Reference: Blockley (1971), Marston (1979), GSWA-WAMEX - I 3167, I 3316, I 3808.

Yerrida Basin

The geological framework, mineralization, and exploration of the Yerrida Basin have been dealt with in **Chapter 7**, in relation to sediment-hosted mineralization.

Diamond Well (Sampsons Bore)

Occurrences: Pb; Zn
Location: 26°17'S, 119°28'E; 13 km south-southwest of Diamond Hill Homestead

Two lead and zinc occurrences are noted in the vicinity of Diamond Well.

At the first, an east-northeasterly trending fault contains malachite, covellite and chalcocite in a quartz reef, the Diamond Well fault gossan. Noranda (1977) chip sampled the fault gossan and found up to 1.05% Pb at the surface. Duval (1982–84) carried out aerial and ground magnetic surveys followed by surface and RAB/percussion drill geochemistry based on sedimentary base-metal targets. The only mineralization located was in the fault zone with best grades from drilling of 1.6% Pb and 15 g/t Ag over 2 m. The average grade is about 0.3% Pb and 2–3 g/t Ag. The mineralization extends over 500 by 2 m at the surface and lies close to the boundary between shelf-facies Findlayson Sandstone and Maraloou Formation shale, and carbonates and cherts of the deeper water facies to the north.

At the second occurrence, south of Sampsons Bore, up to 1.05% Zn in manganiferous shale is probably the result of surface enrichment.

References: GSWA-WAMEX - I 571, I 3103.

Potential of hydrothermal vein-type deposits

The high grade but small size of vein-type lead–zinc mineralization have meant that deposits have generally been discovered and developed at an early stage in the history of mining and exploration throughout Western Australia. More recent exploration has generally been in association with the search for disseminated stratabound or stratiform deposits with an emphasis on the potential of associated feeder/stringer zones beneath these tabular mineralized zones. The economies of scale also dictate that, other than in this situation or in other exceptional circumstances, such as in larger-scale breccia zones associated with large-scale fault or shear zones, they are not viable for modern mining, have little potential, and have therefore not been a focus of active exploration in the modern era. This is particularly true in the remoter areas.

Recent discoveries in the west Pilbara (Orpheus and Elizabeth Hill) and, particularly, in the Eastern Goldfields (Nimbus), however, demonstrate that conventional thinking is rarely unassailable and that mineable high-grade deposits of silver are a viable target. The apparent epithermal system at Nimbus may well represent an overlooked target type in this environment.

Chapter 9

Further development

Targets, tectonic units and potential

Figure 4 shows that the production of lead and zinc in Western Australia since the mid-1960s has been derived entirely from volcanogenic or carbonate-hosted deposits. The dramatic halt in production from vein-type deposits at about the same time was just the last act in a long decline in the viability of high-grade, low-volume, vein-type deposits in the face of declining base-metal prices. Exploration since the 1960s (**Chapter 2**) has concentrated on the large tonnage, moderate- to high-grade target types associated with massive sulfides, either stratabound or stratiform, in volcanic, volcaniclastic or sedimentary host rocks.

Volcanic-associated massive-sulfide deposits

Since the late 1960s the recognition of potential for Canadian-style Archaean volcanogenic mineralization in the Pilbara and Yilgarn Cratons has seen re-evaluation of deposits like Lennons Find and mineralized zones like the Whundo–Yannery area and the Whim Creek Belt in the Pilbara, and the discovery of Teutonic Bore and then Gossan Hill–Scuddles in the Yilgarn. The relative lack of major success in these areas (apart from Scuddles) and the rise of gold prices during the early 1980s saw a shift of exploration away from this target type. However, the recent success of exploration in opening up a new VMS province in the Panorama area of the Pilbara, shows that good potential still exists in both the Yilgarn and Pilbara Cratons. Both the Panorama and Scuddles discoveries emphasise the importance of detailed understanding of the effects of regolith, and of the often complex and deep effects that element redistribution in the oxidized and supergene zones has on the surface geochemical expression of such orebodies.

The present understanding of the distribution of tectonic settings and felsic volcanic suites in the Pilbara Craton, favourable for VMS mineralization, has been summarized in **Chapter 6**. In the East Pilbara, the shallow-water felsic volcanic and volcaniclastic rocks of the Warrawoona Group host relatively small, lead-rich deposits. The lithogeochemical signature and shallow-water setting of these seem to limit their potential for the larger and more typical Canadian-type, or Scuddles-type deposits. The latter are zinc-dominant and were formed in deep-water settings, where boiling of hydrothermal fluids is restricted and the preservation of exhalative mineralization more likely. Farther west, progressively through Big Stubby, Panorama, Mons Cupri and Salt Creek, deeper water environments are indicated, lithogeochemical signatures more favourable, and potential relatively greater for significant deposits. The forthcoming GSWA 1:100 000-scale geological mapping in the west Pilbara will help to detail the potential in this as yet poorly constrained area. Modern geophysical techniques will also be of major importance.

The success of modern, technically and conceptually sophisticated exploration at Panorama suggests that a similar approach may well be successful in the central and west Pilbara. Detailed mapping in the east Pilbara may also reveal more favourable, deeper water settings in the Warrawoona Group, or younger units.

In the Yilgarn Craton, deeper water, lithogeochemically favourable felsic volcanic sequences occur in the Gabanintha and Windanning Formations of the Murchison Province and in arc settings in the eastern Yilgarn. The understanding of tectonic settings and stratigraphic correlations in the latter area is still developing and the clarification of these will have a major impact on assessment of base-metal potential. Studies to date (**Chapter 6 — East Yilgarn**) suggest that the potential of the Black Flag Group in the western part of the Norseman–Wiluna is ambiguous, whereas the rhyolite and dacite in the Teutonic to Kanowna area of the central Norseman–Wiluna belt retains good potential for VMS mineralization. The andestic, shallower water volcanic rocks farther east, for instance in the Duketon and Edjudina areas, have less potential but may be locally more favourable.

In the Southern Cross Province, potential is less clearly defined. The distribution of felsic volcanic sequences in the two major periods of volcanism seems to be relatively limited. There has been little detailed mapping and no comprehensive regional study.

In the Halls Creek and King Leopold Orogens there is no evidence of craton margin settings with B subduction and the development of volcanic arcs. However, A subduction, or intracratonic orogeny, possibly took place in an essentially ensialic regime, coinciding with the Barramundi Orogeny (at ~1.84 Ga). The felsic volcanic, volcaniclastic and sedimentary rocks of the Koongie Park

Formation are associated with this event and contain stratiform mineralization of probable VMS affinity. The potential for further deposits of this type is limited by the relatively restricted outcrop area of the formation. Some potential may exist in the possibly equivalent Whitewater Volcanics in the western zone of the Halls Creek Orogen.

The minor VMS prospects in the upper part of the Biscay Formation, in the Halls Creek Orogen, seem to have formed in a rift basin during the late stages of an extensional regime and probably have little potential for major deposits.

Clastic-hosted deposits

Exploration for clastic-hosted lead–zinc–silver has also expanded since the 1960s, being directed mainly at the Proterozoic orogens, particularly the Capricorn and Paterson Orogens. Potential has been recognized for large-scale deposits such as those at Mount Isa, and in the McArthur River area. This deposit type is particularly associated, both in Australia and globally, with the Mesoproterozoic and with rift basins formed in partially developed or 'failed' intracratonic rift settings, although potential is also seen in craton marginal rifts and, to a lesser extent, in foreland basin rifts. Potential may also exist for the Broken Hill type of deposit in intracratonic rift settings, associated with bimodal volcanism and involving mineralizing fluids of mixed intraformational seawater and hydrothermal origin.

It is perhaps significant that the only relatively major discovery of this target type in Western Australia has been at Abra in the central Bangemall Basin, which is the only truly Mesoproterozoic rift basin in Western Australia. The Bangemall Basin overlies Palaeoproterozoic rocks of the Capricorn Orogen. Abra is associated with the older of the two main subgroups in the central-western basin, the Edmund Subgroup (1.6–1.2 Ga), which was deposited in an extensional rift-controlled environment. The less well known, but probably temporally equivalent, Scorpion Subgroup, in the eastern Bangemall Basin, may have a similar setting but has much more limited exposure. Of the upper subgroups of the basin, the Manganese Subgroup in the northeast also shows evidence of syndepositional faulting in a shelf setting.

Older settings cannot be totally overlooked. Intracratonic basinal settings in the Archaean, which could host Broken Hill-type mineralization, for example, could be present.

Exploration in the Palaeoproterozoic orogens has met with very limited success to date. In the Capricorn Orogen, which includes the Wyloo Group (~2.2–1.8 Ga) of the Ashburton Basin, the approximately equivalent Morrissey metasedimentary sequence of the high-grade Gascoyne Complex and the sequences in the Glengarry basins (2.0–1.8 Ga) of the Nabberu Province, the tectonic setting reflects the closing of an ocean basin between the Pilbara and Yilgarn Cratons with B subduction of oceanic crust to the south beneath the Yilgarn (Hynes and Gee, 1986; Tyler, 1991). The Glengarry basinal sequences are considered to have been deposited on an active continental margin in a rift-related back-arc basinal setting behind an island arc to the north or in a series of pull-apart openings reflecting oblique collision of the Pilbara and Yilgarn Cratons. Farther west a similar situation may have applied to the early sedimentation of what became the Morrissey Metamorphics (Tyler, 1991). At the same time, early Wyloo Group sedimentation took place on a shallow-marine shelf on the southern margin of the Pilbara Craton. Later, as continental collision progressed, further sedimentation was controlled by the subsidence of the Ashburton Trough. Further convergence produced recumbent folding in the southern part of this trough and extensive deformation and crustal thickening in the northern Yilgarn Craton, leading to high-grade metamorphism in the Gascoyne Complex and the generation (1.8–1.6 Ga) of large volumes of granitoid magma. The transition zone from the Morrissey Metamorphics to the sedimentary rocks of the Wyloo Group is therefore a steep metamorphic gradient.

As yet no major stratiform or stratabound base-metal prospects have been located in the Capricorn Orogen. Minor occurrences suggest some potential in the Ashburton Basin while the Gascoyne Complex remains relatively unexplored and poorly known in detail. The Earaheedy Basin (~1.8–1.7 Ga) has recently undergone a major phase of exploration for sediment-hosted base metals. Recent discoveries by RGC, particularly of the epigenetic Magellan deposit, will focus attention on, and help to establish the potential of, this basin and other elements of the Capricorn Orogen.

In the Paterson Orogen the Rudall Complex is tentatively dated between 2.0 and 1.3 Ga on very limited data. The two upward-fining, turbidite–arenite–shale cycles that make up the metasedimentary succession are interpreted as representing a continental-shelf environment behind a volcanic arc to the northeast. This more closely resembles the B subduction association of the northern Yilgarn Craton during the Capricorn Orogeny than the intracratonic settings seen in the Proterozoic orogens of eastern Australia. Suitable source and host lithologies are present within the Rudall Complex for clastic-hosted base metals, and some minor occurrences have been located during uranium exploration. Although some potential exists for this target type, the extent of thrust-related tectonism which the complex has undergone would make any detailed unravelling of the syndepositional litho-tectonic environment difficult.

The Halls Creek Province (1.92–1.80 Ga) contains both extensional rift-basin (Halls Creek Group/Tickalara Metamorphics/Marboo Formation) environments and compressional (Koongie Park Formation/Whitewater Volcanics) environments, each of which hosts volcanogenic sediment-hosted copper–lead–zinc mineralization. Potential for true clastic-hosted, large-scale base-metal deposits seems to be limited, both by exploration results to date and by the relative lack of anoxic siltstone and shale, as potential host rocks, in the rift-basin environment.

The Northampton Complex, which contains metagreywacke and metapelite (some of them graphitic, laid down in a possible flysch or rift basin environment later

than 1.8 Ga and metamorphosed at 1.05 Ga), is considered to have some potential for this target type based on possible similarities with the Willyama Complex in NSW.

The Albany–Fraser Orogen consists of high-grade gneiss and granite formed between 1.3 and 1.1 Ga. The clastic sedimentary and granitic parents of these rocks are of Palaeo- to Mesoproterozoic age (Myers and Barley, 1992), and have been brought to the surface from deep crustal levels. The tectonics, dominated by huge, northwesterly transported thrust sheets, reflect collision between the southern margin of the Yilgarn Craton and a craton to the southeast, now obscured beneath Phanerozoic sedimentary rocks. The difficulties posed by such high-grade and tectonized rocks, the nature of the tectonic setting and the lack of any known prospects leave open at this stage the potential to yield large-scale stratiform base-metal deposits.

The recent, possibly stratabound, Trilogy prospect discovered in 1997 in the Mesoproterozoic Mount Barren Group may have a major impact on this assessment when the nature and extent of the mineralization is fully determined. Even if it is only of moderate dimensions and structurally controlled, it indicates that mineralizing processes occurred within the tectonic setting of the Albany–Fraser Orogen, and produced a significant clastic-hosted accumulation of lead, zinc and silver in association with copper and gold. It may yet, despite some apparent limitations in the regional setting, lead to further important discoveries when the controls on mineralization are understood.

The remaining basins that show, or may have some potential for clastic-hosted deposits are the Neoproterozoic Yeneena Basin and Savory Sub-basin. The Yeneena Basin (~1.1–0.85 Ga) contains up to 8 km of deformed sandstone, siltstone, shale and carbonate rock of the Yeneena Group, considered to have been deposited in fluviatile to deeper shelf environments on the margin of a continent situated to the southwest. There are indications of growth faulting in the lower part of the sequence and favourable host lithologies in the form of carbonaceous and dolomitic shale occur in the Broadhurst and Isdell Formations. Exploration in the late 1970s and 1980s located significant stratabound copper–lead–zinc mineralization in the middle to upper Broadhurst Formation in sulfidic and carbonate-rich shale which may have McArthur River-type or Zambian-type affinities. Potential remains high in this unit. Potential also exists in the Isdell Formation for clastic- or carbonate-hosted mineralization types.

The Savory Sub-basin evolved, in response to adjustments in the positioning of the Pilbara and Yilgarn Cratons, between 0.9 and 0.6 Ga and overlies the eastern parts of the Bangemall Basin and the western margin of the Yeneena Basin. The sedimentary rocks are predominantly arenaceous but the basin also contains a glacigenic sequence and stromatolitic dolomites (Williams, 1992). The first two depositional sequences in the basin reflect growth faulting and subsidence, initially on the southern margin of the basin and later along the northwestern margin of the basin in a situation that suggests some potential for clastic-hosted base metals. Although the rocks are predominantly arenaceous, the first phase shows parallels with the early development of the Bangemall Basin. More-suitable host lithologies are present in restricted areas of the second phase, in the shale and siltstone (in part glauconitic) of the Watch Hill Formation, on the northeastern boundary of the basin, and in the dolomite, chert, siltstone and shale of the Skates Hills Formation in the southeast.

Looking at clastic-hosted potential in terms of the Australia-wide Proterozoic tectonic framework, Rutland et al. (1990) and Wyborn (1988) describe a polygonal arrangement of small Archaean cratons separated by narrow Palaeoproterozoic mobile belts (such as the Capricorn and Halls Creek Orogens) dominated by rift facies clastic, and/or volcaniclastic units of limited areal extent, generated during crustal extension. Basin formation occurred between 2.10 and 1.88 Ga. They consider the pre-1.8 Ga Barramundi Orogeny to have been a widespread compressional event in these orogens related to small-scale mantle convection, still in an essentially intracontinental setting. A major period (between 1.88 and 1.84 Ga) of compositionally uniform felsic volcanism and granite emplacement at is considered to have accompanied the orogeny (Wyborn, 1988). The felsic magmas are predominantly I-type and are LILE-enriched compared with Archaean granitiods. Sawkins (1989b) has proposed that worldwide erosion of these mantle-derived felsic magmas transported major quantities of lead to the rift basins, which formed over the Palaeoproterozoic orogens in response to renewed extensional tectonics in the Mesoproterozoic at ~1.7 to 1.6 Ga. The thick accumulations of lead-rich sediments became the source of the major exhalative stratiform deposits seen in these settings in eastern Australia.

Myers and Barley (1992), however, have pointed out that, rather than Australia-wide uniformity, variations from this scheme suggest a systematic eastward shift in the intensity and style of mineralization in northern Australia during the Palaeo- and Mesoproterozoic. Evidence from recent GSWA mapping indicates that the Capricorn Orogen, the Halls Creek Orogen and possibly the Paterson Orogen, formed as a result of craton collision involving B subduction. Evidence is seen for sedimentation in continental margin and foreland basins rather than in intracratonic rifts. The timing of these orogenies, however, is equivalent to that of the Barramundi event. The intrusion of large volumes of granitic magma in the southwestern part of the Capricorn Orogen, in the Gascoyne Complex, some of which seems to be LILE-enriched, and in the Halls Creek Orogen roughly correlate with the widespread felsic event proposed by Wyborn (1988). Granite-derived orthogneiss from the Rudall Complex may also belong partly to the regional event. However, no information is available on the geochemical nature of these granitoids.

The main implications of this broad tectonic pattern, and the variations from west to east, are that direct parallels with the Mesoproterozoic intracontinental rift basins of eastern Australia are limited. Only the Bangemall Basin offers an approximate correlation. If, as Sawkins (1989b) proposes, the major ~1.88 to 1.84 Ga felsic suite is the major contributor of lead to the large stratiform

deposits in eastern Australia, then the earlier basinal sediments in Western Australia, in the Gascoyne and Rudall Complexes, the Halls Creek Orogen, the Nabberu Province and the Ashburton Basin, were laid down before, or with, the felsic event and may thus be less prospective for this type of mineralization.

Carbonate-hosted deposits

Potential remains for MVT-type targets, and possibly for 'Irish-type' targets, in the Canning, Bonaparte, Carnarvon and Perth Basins, though the remote location of the most favourable areas remains a drawback. Futher exploration success will result from improved structural elucidation and the refinement of genetic models.

Hydrothermal vein-type deposits

Despite negative economies of scale for vein-type base-metal deposits, the two recent discoveries of high-grade silver deposits, in the west Pilbara and eastern Goldfields, offer some potential for creative exploration.

Exploration methods and research

Geological mapping

It would seem to be stating the obvious to assert that high-quality, regional and detailed geological mapping is essential if mineral exploration is to be properly targeted and achieve its full potential for success. Regional mapping at 1:250 000 by GSWA has been completed for the State and many sheets in critical areas have been updated to a second edition. Moreover, 1:100 000 mapping has targeted areas of high mineral potential, or of known deposits, such as the Eastern Goldfields from Norseman to Leonora, the Halls Creek Orogen, the Hamersley Basin, the Paterson Orogen, the Capricorn Orogen, the Hill River area and, currently, the west Pilbara.

The increasing emphasis on, and value of, plate-tectonic models in mineral exploration further underlines the importance of regional studies in defining mineral potential. Recent studies by GSWA and AGSO in the Eastern Goldfields, the Murchison Province, the Paterson Orogen, the Halls Creek Province, the Capricorn Orogen (including the Ashburton Basin and Glengarry basins), the southern margin of the Hamersley Basin, and the Sylvania Inlier and the Savory Sub-basin, in combination with university research in critical areas, have all helped to clarify the tectonic framework within Western Australia and bring closer a full metallogenic synthesis.

Force et al. (1991) have recently emphasised the importance of basin studies in exploration for all sediment-hosted commodities, and they are particularly important in relation to the clastic- and carbonate-hosted styles of base-metal mineralization. Semi-regional and detailed mapping within an established basin framework can target particular lithological and structural features that may be critical to a particular model; for example, evidence for growth faulting or shelf to deeper basin transitions.

Regional, semi-detailed and detailed mapping have also become important in relation to volcanic-associated mineralization. Regional studies in the east Yilgarn Craton, for example, are helping to define tectonic environments more favourable for VMS mineralization by defining more clearly the distribution of continental, back-arc and volcanic-arc settings. The distribution of felsic volcanic suites, which seem to be chemically more favourable for this type of mineralization, is also becoming clearer within the evolving framework of tectono-stratigraphic terranes and domains (e.g. Hallberg et al., 1993; Rattenbury, 1993; Witt, 1994). From the study of modern analogues and by detailed study of deposits such as Scuddles, Cas et al. (1993) have pointed out some of the developments that have taken place in the understanding of the detailed features of submarine volcanic environments. Geological environments with features indicating seafloor depths of greater than 1 km during submarine volcanism, for example, should be favourable for seafloor massive sulfides as sub-seafloor boiling of hydrothermal fluids would have been prevented. Typical features include the presence of coherent lavas, hyaloclastite, synvolcanic intrusive material and possibly resedimented volcaniclastic rocks from shallower water environments. These apply in general to the Scuddles sequence. Thus, they give at least a rough guide to prospectivity and can be mapped and applied in other situations in combination with geochemical factors and geophysical patterns. Clifford and Sheppy (1991), with reference to Scuddles, also point out the importance of recognizing evidence of growth faulting and associated depressions in the sequence that control the gravitational accumulation of the base metal-bearing exhalations. They highlight the importance of rapid thickness changes and stratigraphic 'stacking' of sulfide deposits over part of the succession which precedes proximal felsic volcanism and which most frequently shows cherts and finely bedded sedimentary rocks.

Geophysics

Dentith et al. (1994) have provided a useful review of the performance of exploration geophysics to date in Western Australia. They point out that most geophysical exploration in Western Australia is hindered by the general lack of outcrop and by the mantle of conductive and magnetic weathered rocks that covers much of the State. The weathered rocks necessitate an increase in the distance between the sensor and bedrock and also create geophysical noise. Although some of this noise may reflect variations in the underlying bedrock, discrimination and therefore interpretation are problematic.

Geophysical methods may provide useful information at both the regional and local levels. Regional and detailed magnetics, gravity and radiometrics make a major contribution to the elucidation of the lithological and

structural framework of prospective regions, as an extension of geological mapping. Aerial electromagnetic (EM) surveys are increasingly able to detect subtle changes in conductivity across geological contacts and are therefore being used as a complementary mapping tool. But these methods also have a more specific role in the detection of mineralized bodies themselves, or of their alteration envelope and other marginal, and possibly more extensive effects.

Most lead–zinc–silver and related deposits are in the form of sulfide bodies and therefore tend to be responsive to EM and IP methods, and to magnetics if magnetite or magnetic pyrrhotite are present. Bishop and Lewis (1992), in a review of geophysical exploration for Australian VMS mineralization, point out that deposits of this type tend to be good conductors and possibly magnetic, are chargeable and dense, and may be surrounded by a halo of disseminated sulfides. Electromagnetic surveying is the most important technique for this target type, at present and for the foreseeable future. In particular, downhole EM has been valuable in prospect exploration, and the most recent airborne high-penetration EM methods have been valuable in more regional to local assessments.

Individual prospects and deposits, however, show a variety of response. In the Pilbara Craton the Mons Cupri deposit is marked by a small aeromagnetic anomaly but shows little response to any EM geophysical techniques, possibly owing to the depth of the sulfide mineralization and the low sulfide content of the oxide ore near surface. The Salt Creek deposit showed a response only to IP surveys. In the Yilgarn Craton the Scuddles deposit gives clear ground EM and magnetic anomalies, only a subtle gravity response, and an IP anomaly caused only by shallow mineralization. Airborne EM surveys over the much shallower Gossan Hill deposit were inconclusive. Of three EM methods tried at Teutonic Bore, only SIROTEM gave a clear response whereas mise-a-la-masse surveys were less successful and magnetics of little use. At Nangaroo while VLF EM was undiagnostic, some response was obtained from IP and INPUT surveys. At Freddie Well various EM methods were successful, as was IP, but magnetic results were equivocal despite the presence of pyrrhotite. The Onedin prospect in the Koongie Park Formation of the Halls Creek Orogen shows a surface EM anomaly but questionable magnetic response.

Dentith et al. (1994) concluded that multiple methods are required to avoid missing VMS mineralization. The potential of areas that have been covered by aerial magnetic and EM surveys cannot be discounted. Induced polarization and EM should be tested at prospect scale, and downhole mise-a-la-masse used for detailing the extent of mineralization.

In the Bangemall Basin the blind deposit of clastic-hosted mineralization at Abra is expressed as a bullseye airborne-magnetic anomaly. The stratiform mineralization is iron rich with magnetite and hematite associated with the sulfides. A ground TEM response was also obtained but the airborne EM response was weak and did not clearly define the mineralization. Gravity shows a local anomaly at Abra.

Carbonate-hosted base-metal deposits present difficult geophysical targets. Dentith et al. (1994) concluded that direct detection of the ore is not usually possible. Geophysical exploration is used mainly as a regional mapping tool with seismic reflection data defining bedding and fault patterns. All the deposits in the Lennard Shelf show marcasite haloes, which can be detected by semi-regional IP surveys. Geophysical data are used in combination with geochemical and geological information to define prospective areas which are then grid drilled. In particular, gravity and magnetic data can be used to locate the mineralization-associated faults, basement highs and, in some cases, concealed reef carbonates. In the deeply buried Admiral Bay deposit, seismic profiles clearly show the basement offset and complexly faulted Broome Arch but not the related mineralization.

Geochemistry

Most lead–zinc–silver deposits and occurrences in Western Australia are sulfide concentrations. Owing to the deeply weathered nature of the terrain, most deposits that are exposed at the surface form oxidized gossans in which, depending on local conditions, many or all of the target elements and pathfinder elements may be leached or, in some cases, enriched. In **Chapter 3** these processes are reviewed from a number of studies of VMS deposits and prospects.

At Teutonic Bore (Nickel, 1984) intense weathering has extended to 40 m below the watertable. Although copper, zinc and silver are strongly depleted to below 16 m, lead is only partially depleted and, along with tin, arsenic and antimony, forms a strong chalcophile signature. Similar patterns are seen at Mason Hill and Tuff Hill (Bell, 1980) with lead, but not zinc, retained to some extent in the weathered rock. At Gossan Hill, Smith et al. (1980) found copper and zinc to be strongly leached in the gossan but still anomalous, with As, Sb, Bi, Mo, Ag, Sn, and Se retaining a strong signature. Taylor (1983) found a similar profile at Mugga Mugga, but at Freddie Well complex reactions with gabbro and other country rock restricted depletion.

In the Pilbara region, the landscape is more deeply dissected and the weathering profile partly stripped. At Whim Creek, Nickel (1982) described an immature gossan with an abundance of secondary ore minerals and a strong geochemical signature. At Mons Cupri, Smith (1980) indicated that some copper, lead and silver enrichment remains in the gossan.

The Sulphur Springs mineralization outcrops as spongy, cellular, siliceous and ferruginous gossan. The main gossan that underlies the Marker Chert at the top of the intermediate to felsic volcanic pile may be traced over 300 m of strike and is up to 100 m thick. Gossanous zones also occur within the Marker Chert and in the footwall felsic volcanic rocks.

The following generalizations are made from rock-chip geochemistry of gossan samples with respect to

mineralization in drillcore (P. Morant, Sipa Resources, 1995, pers. comm.).

> Gold (≤4.35 g/t), silver (≤255 ppm) and mercury (≤71 ppm) can be enriched in the gossans. Lead (≤1.35%), bismuth (≤263 ppm), arsenic (≤4260 ppm) and barium (≤9200 ppm) are not strongly enriched or depleted in gossan samples. Zinc (≤1.17% in secondary minerals, but typically <1000 ppm) and copper (≤8.9% in secondary minerals, but typically <1000 ppm) tend to be depleted by an order of magnitude in gossan samples compared with fresh mineralization. Tin (≤1050 ppm), antimony (≤940 ppm), selenium (≤740 ppm), tellurium (≤20 ppm) and molybdenum (≤302 ppm) are strongly anomalous in gossan samples, but there are insufficent data on drillcore samples for comparisons to be made. Tungsten (≤2 ppm) is not anomalous in the mineralization at Sulphur Springs.

Dispersion haloes associated with the weathering of lead–zinc–copper sulfides near the surface can form in the lower parts of the weathered zone, as at Teutonic Bore (Nickel, 1984), and in the laterite horizon, in duricrust, pisoliths and nodules or in ferruginous saprolite. In areas of patchy laterite, dispersion haloes may be found in calcareous soil, ferruginous granules and mottles in soils (Anand and Smith, 1993). Smith and Perdrix (1983) described dispersion haloes in Tertiary pisolitic laterite at Gossan Hill and Scuddles. Probably of most interest in relation to exploration for poorly exposed or 'blind' massive sulfides is the Scuddles situation, where the gossan pinches out 40 m below the surface in weathered bedrock. The pisolite anomaly shows anomalous bismuth, tin, arsenic, molybdenum and antimony but no lead, zinc or copper. Direct detection of the base-metal anomalism was possible only in RAB geochemistry.

In terms of practical exploration strategies the above features probably apply equally to volcanogenic and sediment-hosted massive sulfides. Where gossans are present they should be carefully mapped and sampled with particular emphasis on possible indicator elements. Where possible they should also be drilled to the lower saprolite to detect possible lead–zinc–copper enrichment at that level. Mapping of regolith-landform regimes is necessary for the correct choice and interpretation of sampling media. Laterite and related regolith forms are most favourable for base-metal and related-indicator dispersion. Anand and Smith (1993) have emphasized the importance of interfaces between regolith units in detailed, three-dimensional regolith models. Eroded areas may be strongly leached and lack lateritic components while in depositional areas gossans and/or laterite may be buried beneath barren material.

The resistant accessory minerals, such as cassiterite and platinum-group minerals, and chalcophile elements, are the most likely indicators for base-metal sulfides but Smith (1993) also pointed to the presence of gold as a minor commodity in many VMS deposits and to its effectiveness as a trace element. Butt et al. (1993) recommended multi-element analysis in early sampling with the suite Cu, Pb, Zn, Ag, As, Ba, Bi, Se, Hg and Sn.

Butt (1995) has emphasized the historical reliance on surface geochemical sampling related to gossans, or the weathering products of gossans, in soil, lag, and stream-sediment surveys. He argued, however, that such techniques, although appropriate for erosional terrains, are inappropriate for depositional areas. He also questioned the assumption that base-metal deposits always weather to gossans, given that gossans are rare in humid environments similar to those that previously existed in Australia. Noting the relative lack of exploration success for VMS deposits in the Yilgarn compared with, for example, the Canadian Shield, Butt (1995) questioned the effectiveness of the relatively simplistic geochemical exploration strategies adopted to date, and recommends an approach based on careful regolith-landform mapping as an essential first step. To detect dispersion haloes (other than those directly related to gossans) in saprolite and sediments, Butt (1995) suggested some promise lay in total analysis or, more experimentally, in a variety of partial extraction procedures, and in the use of hydrogeochemistry.

Another geochemical aspect of VMS mineralization that has exploration potential is lithogeochemistry. Canadian VMS deposits have been related to a 'fertile' lithogeochemistry of the primary host volcanics or to a lithogeochemistry related to hydrothermal alteration of the volcanic suite (Lescher et al., 1986; Whitford et al., 1992). The primary 'fertile' lithogeochemistry is considered to show relatively unfractionated REE patterns, usually associated with negative Eu anomalies and low Zr:Y ratios, reflecting high-level magmatic fractionation. A study of this aspect of the Scuddles deposit and its host rocks by Whitford et al. (1992), however, showed a complex picture of fertile and non-fertile signatures in various parts of the deposit, including some mixing of these features in a single unit. It was suggested that a clearer understanding of the relationship between primary and secondary (alteration-related) features was necessary before these criteria could be used as an unequivocal exploration guide.

Research

A new approach to the detection of buried mineralization has been suggested by Mann et al. (1993). The release of mobile metal ions from metal-containing orebodies appears to lead to them becoming weakly attached to surface soils. By using weak extractants and very low-level chemical pre-concentration and analysis techniques, these ions can be used to define enhanced and resolved anomaly patterns which can be interpreted for the detection of blind ore deposits.

Test case histories show weak to strong anomalies over subeconomic and economic base-metal mineralization buried by up to 300 m of overburden in Western Australia and in eastern Australia. Anomalies are sharp and coincident with the source and offer the possibility of very effective drill targeting. Applications to both volcanic-associated and sediment-hosted stratabound and stratiform base-metal deposit types may prove effective.

The independent UK consultant GeoScience has recently announced a new geochemical method for detecting VMS and other deposits, including Carlin-type epithermal gold, (Mining Journal, March 25, 1994). This method, PER Analysis, uses geochemical results from whole-rock analyses to determine mineralization style and thus allows further exploration to be focused on specific targets.

Conclusions

In the two and a half decades since the publication of GSWA Mineral Resources Bulletin No. 9, 'Lead, Zinc and Silver Deposits of Western Australia' (Blockley, 1971), many advances have been made in the understanding of the settings, features and genetic processes that combine to form the variety of types of these and related base-metal deposits. These changes, in combination with advances in technology, have led to an increase in the sophistication and effectiveness of exploration, and a corresponding increase in the number of mines, deposits and prospects that have been located.

The major discoveries have been predominantly in the Palaeozoic basins with the location of six major carbonate-hosted deposits; five in the Canning Basin (Cadjebut, Blendevale, Goongewa, Kapok and Admiral Bay) and one in the Bonaparte Basin (Sorby Hills). Only Cadjebut has reached the stage of production with Goongewa and Kapok close to commencement. Four major volcanogenic discoveries have been made in Archaean greenstones: the relatively small Teutonic Bore deposit in the East Yilgarn, which has now been mined out; the large, companion Gossan Hill and Scuddles deposits in the Murchison Province; and the promising Sulphur Springs mineralization (part of the Panorama Project) in the east Pilbara. Scuddles is now in production with potential to continue to produce for at least another 25 years, and Gossan Hill is expected to be in production in the near future. Only one major clastic-hosted lead–copper–barium–silver deposit has been located in Western Australia; the Abra deposit in the Bangemall Basin. This large-tonnage, low-grade body lies at too great a depth to be currently economic.

Of the 267 deposits, prospects and occurrences listed in this revised Bulletin only 97 are also described in the 1971 Bulletin. Of the 97 sites in the first Bulletin, 70 were vein hosted. In this Bulletin, 124 of the total 267 are vein hosted, 86 are volcanic hosted, 38 are clastic hosted and 19 are carbonate hosted.

The economics of lead, zinc and silver decree that, in the 1990s and the early part of the twenty-first century, any production must come from the large, moderate- to high-grade stratabound or stratiform deposits. The relatively low success rate in exploration for volcanic-associated and, particularly, clastic-hosted deposits in Western Australia is, as discussed above, probably due to a number of factors and not necessarily related to low potential in the appropriate tectonic settings that occur in the State. Some companies are still putting a substantial effort into base-metal exploration, basing their optimism on improved exploration techniques and, particularly, on improved metallogenic modelling. Present 'growth areas' such as the Pilbara and the various elements of the Capricorn and Paterson Orogens suggest that their confidence may well prove to be justified. The greenstone belts of the northwest and eastern Yilgarn Craton, however, are still proving somewhat enigmatic compared with similar Archaean terranes in Canada.

Carbonate-hosted deposits in Western Australia have been the most successfully sought targets in the last two decades or so but have received less attention in the early 1990s owing to the remoteness of their main prospective areas in the far northeast of the State and to the softening of lead–zinc prices. Despite developments at Cadjebut, Goongewa and Blendevale, the short-term development prospects for important discoveries like Sorby Hills and Admiral Bay are less encouraging.

In general, though, the mood for diversification in exploration, the increased sophistication of genetic modelling, the better understanding of the geological framework and the improvement in exploration techniques should see continuing expansion in the exploration for, and discovery of, lead, zinc and silver mineralization well into the next millenium.

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Appendix 1

Key to WAMEX open-file report group item numbers quoted in text

Item no.	*Wamex no.*	*Group title*	*Company*	*Start*	*End*	*Commodity*	*Tectonic unit*
8	1203	Barkers Cu exp.	International Ni Aust Ltd	1973	1973	Cu	HAMERS
34	44	Mount Angelo Cu exp.	Peko Mines NL	1961	1963	Cu	HALLCR
37	136	Bangemall Basin Cu–Pb–Zn exp.	Alcoa of Australia Ltd Anaconda Aust Inc	1966	1967	Cu Pb Zn	BANGE
44	1749/1	Christmas Gift Cu–Zn exp.	Aquitaine Aust Mins. P/L	1973	1976	Cu Zn	EGFS
69A	115/1	Twin Peaks Cu exp.	Kennecott Exp Aust P/L	1966	1966	Cu	MURCH/WGT
69B	115/2	Maroonah Cu–Pb–Zn exp.	Kennecott Exp Aust P/L	1966	1966	Cu Pb Zn	BANGE
102	1015	Widgiemooltha Ni–Cu exp.	Barrier Exp. NL	1972	1972	Cu Ni	EGFS
111	153	Mangaroon Pb/Cu exp.	Kennecott Exp Aust P/L	1966	1966	Cu Pb	GASC
131	1829	Gnows Nest Range Cu–Zn exp.	Mines Exp. P/L	1970	1972	Cu Zn	MURCH
144	1534	Mount Davis East Ni–Cu exp.	Asarco Australia Ltd	1972	1973	Cu Ni	EGFS
158	1252	Melita Cu–Zn exp.	CRA Exp. P/L	1973	1975	Cu Zn	EGFS
172	1094	Ti Tree Syncline Pb–Zn exp.	Union Miniere Ltd	1972	1972	Pb Zn	BANGE
206	1912	Melita Siding Cu–Zn exp.	Shell Mins. Exp Aust P/L	1975	1976	Cu Zn	EGFS
233	1958	Menangina U exp.	Western Mining Corp. Ltd	1971	1972	U	EGFS
245	1766	Mount Vernon Cu–Pb–Zn exp.	Amax Exp. Aust Inc	1974	1976	Cu Pb Zn	BANGE
251bh	67/34	Eastmans Cu–Hill Margaret R. exp.	Pickands Mather and Co Int	1964	1968	Cr Cu Pb Ni	HALLCR
251bz	67/51	Halls Ck and Golf Course Cu–Zn exp.	Pickands Mather and Co Int	1965	1970	Cu Zn	HALLCR
256	381	Ragged Hills Cu–Pb–Zn exp.	Associated Mins. P/L	1970	1971	Cu Pb Zn	HAMERS
263	1182	Halls Creek Cu–Pb–Zn exp.	Aust. Anglo American Ltd	1973	1975	Cu Pb Zn	HALLCR
276	234	'Wyloo' Cu–Pb–Zn exp.	Kennecott Exp Aust P/L	1968	1968	Cu Pb Zn	ASHB
288	173	Copper Gorge Cu exp.	Cominco Exp. P/L	1968	1968	Cu	NPGG
289	216	Wyloo Station Cu exp.	Placer Prospecting P/L	1968	1968	Cu	HAMERS
307	1154	Slate Bore Cu–Pb–Zn exp.	Jododex Australia P/L	1971	1975	Cu Pb Zn	ASHB
308	1477	Coondamar Creek Cu–Pb–Zn exp.	Carpentaria Exp Co P/L	1973	1976	Cu Pb Zn	NPGG
340	1768	Tuckabianna Cu–Zn exp.	Pennzoil of Australia Ltd	1975	1976	Cu Zn	MURCH
347	1993	Fields Find Cu–Zn exp.	Esso Australia Ltd	1975	1975	Cu Zn	MURCH
364	1713	Yangibana Cu–Pb–Zn exp.	Newmont P/L	1974	1975	Cu Pb Zn	GAS
365	1715	Beete Ni–Cu/Pb/Zn exp.	Aust. Selection P/L	1973	1975	Cu Pb Zn Ni	EGFS
369	1459	Mount Stuart Cu–Zn exp.	Great Boulder Mines Ltd	1973	1975	Cu Zn	ASHB
374	245	Diemals Find BM exp.	Ashton Mining NL Western Mining Corp. Ltd	1966	1971	DIAM BM	SCROSS
382	240	Dalgaranga Cu–Zn exp.	Broken Hill Pty Co Ltd	1969	1973	Cu Zn	MURCH
388	335	Nanutarra U/BM exp.	Leopold Mins. NL	1972	1972	BM U	GASC
391	513	'Yanrey' U/BM exp.	Leopold Mins. NL	1969	1970	BM U	CARNAR
456	1714	South Rundall Dome Cu exp.	Newmont P/L	1974	1975	Cu	PATER
464	1860	Osmond Range Pb–Zn exp.	Trend Exp. P/L	1973	1973	Pb Zn	HALLCR
466	1925	Mount Barloweerie Cu–Zn exp.	Western Mining Corp. Ltd	1974	1975	Cu Zn	MURCH
470	2137	Whelock Well Cu–Zn exp.	Electrolytic Zn Co	1976	1977	Cu Zn	MURCH
507	1945	Ningbing Range Pb–Zn exp.	Mimets Exp. P/L	1972	1973	Pb Zn	BONAP

Appendix 1 (continued)

Item no.	*Wamex no.*	*Group title*	*Company*	*Start*	*End*	*Commodity*	*Tectonic unit*
522	1722/1	Mugga Mugga Cu–Zn exp.	CRA Exp. P/L	1974	1975	Cu Zn	MURCH
530	1857	Chianti Cu–Zn exp.	Aust Consolidated Mins. Ltd	1971	1972	Cu Zn	KLEO
556/B	1641/2	Moogooree Cu–Pb–Zn exp.	Aquitaine Aust Mins. P/L	1972	1974	Pb Zn	CARNAR
564	1729	Montague Range Ni–Cu exp.	Cliffs International Inc Amax Exp. Aust Inc	1969	1972	Cu Ni	SCROSS
571	2257	Diamond Well Cu–Pb–Zn exp.	Noranda Australia Ltd	1977	1977	Cu Pb Zn	NABGLN
572	1039	Montague Range Ni–Cu/Cu–Zn exp.	International Ni Aust Ltd	1968	1975	Cu Ni Zn	SCROSS
575	1749/2	Christmas Gift Cu–Zn exp.	Aquitaine Aust Mins. P/L	1973	1976	Cu Zn	EGFS
617	–	–	–	–	–	–	–
640	1902	Yaloginda Ni–Cu exp.	Western Mining Corp. Ltd	1975	1976	Cu Ni	MURCH
642	1972	Killara Prospect Cu exp.	CSIRO	1976	1978	Cu	NABGLN
643	2112/2	Teano Range Cu–Pb–Zn exp.	International Ni Aust Ltd	1977	1978	Cu Pb Zn	BANGE
644	2211	Jurangie Hill Cu–Zn exp.	Newmont P/L	1977	1977	Cu Zn	EGFS
651	2332	Paynesville Cu–Zn exp.	Amax Iron Ore Corp.	1977	1978	Cu Zn	MURCH
656	1697	Bangemall Basin BM/U exp.	Endeavour Oil Co NL	1972	1972	BM U	GASC/BANGE/ASHB
664	2120	Nanutarra U exp.	Esso Australia Ltd	1977	1978	U	GASC
685	1818/2	Chulaar North Cu–Zn exp.	Electrolytic Zn Co	1973	1977	Cu Zn	MURCH
732	67/32	Emull Cu Pb Zn exp.	Pickands Mather and Co Int Shell Mins. Exp Aust P/L	1963	1978	Cu Pb Zn	HALLCR
734	446	Louisa Downs Cu–Zn/Pb exp.	Newmont P/L	1968	1971	Cu Pb Zn	HALLCR/KLEO
738	1250/1	Mount Amherst Cu/Cu–Pb–Zn exp.	Stratin Mins. P/L Dampier Mining Co Ltd	1971	1973	Cu Pb Zn	KIMB
740	1838	Halls Creek Nth Ni–Cu/ Cu–Zn exp.	Aust. Anglo American Ltd	1975	1976	Cu Ni Zn	HALLCR
741	1743	Louisa Downs Cu–Zn exp.	Kennco Exp Aust P/L	1969	1974	Cu Zn	HALLCR
778	307/2	Mount Ramsay Cu–Pb exp.	Serem Aust P/L	1968	1971	Cu Pb	HALLCR/KIMB/KLEO
780	1269	Richenda R. Cu–Pb–Zn–Ag–Au exp.	Not entered	1973	1974	Au Ag Cu Pb Zn	KLEO
786	1923	Chedda Cliffs Pb–Zn exp.	Mimets Exp. P/L	1972	1978	Pb Zn	CANLEN
851	2294	Jurangie Hill Cu–Zn exp.	Aquitaine Aust Mins. P/L	1974	1979	Cu Zn	EGFS
906	1520/1	Murphy Wells Ni–Cu/ Cu–Zn exp.	Esso Exp. Aust Inc	1972	1975	Cu Zn Ni	NPGG
910	1521/3	North Pole Cu–Zn exp.	Esso Australia Ltd Esso Exp. Aust Inc	1973	1975	Cu Zn	NPGG
911	2361	Mount Cotten Cu–Zn exp.	Newmont P/L	1978	1978	Cu Zn	PATER
936	2616	Meilga Cu and Thowagee Pb exp.	Academus Mins. NL	1970	1971	Cu Pb	ASHB
937	2103	Quinns Cu–Zn exp.	Newmont P/L	1976	1978	Cu Zn	MURCH
940	2186	Burnakura Cu–Zn exp.	Esso Australia Ltd	1977	1978	Cu Zn	MURCH
942	347	Coppin Gap Cu–molybdenum exp.	Aust. Anglo American Ltd	1969	1973	Cu Mo	NPGG
964	450	Coongan River Ni–Cu/ Cu–Zn exp.	Kennecott Exp Aust P/L	1968	1973	Cu Ni Zn	NPGG
966	459	Ragged Hills Cu/Pb exp.	Western Mining Corp. Ltd	1969	1972	Cu Pb	HAMERS
973	1704	Yandagooge River BM exp.	Otter Exp. NL	1971	1979	BM	BANGE/PATER
1001	1818/1	Chulaar South Cu–Zn exp.	Electrolytic Zn Co	1973	1977	Cu Zn	MURCH
1005	225	Warburton Range Cu exp.	Western Mining Corp. Ltd	1967	1971	Cu	MUSG

Appendix 1 (continued)

Item no.	Wamex no.	Group title	Company	Start	End	Commodity	Tectonic unit
1047	315	Capricorn Ranges Cu–Pb–Zn exp.	Carr Boyd Mins. Ltd	1969	1970	Cu Pb Zn	ASHB
1052	1573	Edmund Cu–Pb–Zn exp.	Union Oil Devel. Corp	1973	1973	Cu Pb Zn	BANGE
1053	1644	Cootamungie Well Cu–Pb–Zn exp.	Carpentaria Exp Co P/L	1973	1973	Cu Pb Zn	BANGE
1073	1244/1	Jurangie Hill Cu–Zn exp.	Amax Exp. Aust Inc	1971	1974	Cu Zn	EGFS
1108	1519	Mount Palgrave Cu exp.	Broken Hill Pty Co Ltd	1971	1974	Cu	BANGE
1111	2487	Mt Isabella/Genoa Bore Cu/Pb/Zn exp.	International Ni Aust Ltd	1977	1979	Cu Pb Zn	BANGE
1115	2651	Eva Well Cu–Pb–Zn/U exp.	Amax Iron Ore Corp.	1974	1980	Pb Zn U	PATER
1119	2578	Beasley River Ag–Pb–Zn exp.	Amax Iron Ore Corp.	1979	1979	Cu Pb Zn	HAMERS
1120	636	Turtle and Range Cu and Pb exp.	Australian Hanna Ltd	1969	1971	Cu Pb	GASC
			Homestake Iron Co Aust Ltd	1969	1971	Cu Pb	GASC
			Jododex Aust P/L				
			Union Oil Devel Corp				
1125	1799	Belfrey Cu–Zn exp.	Whim Creek Consol. NL	1974	1977	Cu Zn	HAMERS
1134/2	2693	Youangarra Ni–Cu exp.	Aust. Anglo American Ltd	1978	1980	Ni Cu	SCROSS
1174	630/1	Eulaminna Mine Cu–Zn exp.	Electrolytic Zn Co	1968	1973	Cu Zn	EGFS
1200	2716	Turtle Creek Cu–Pb–Zn/diamond exp.	Richenda Mins. P/L	1980	1981	Au Ag Cu Pb Zn DIAM	KLEO
1228	1775	Brandy Hill Cu–Zn exp.	Samin Ltd	1973	1979	Cu Zn	MURCH
1242	1971	Quandong Well Cu–Zn exp.	Dampier Mining Co Ltd	1973	1974	Cu Zn	MURCH
1244	2273/1	Mukinbudin Pb–Zn/Ag exp.	Not entered	1976	1979	Ag Pb Zn	SCROSS
1247	2533	Killara Homestead Cu–Pb–Zn exp.	Electrolytic Zn Co	1979	1980	Cu Pb Zn	NABGLN
1252	2586	Diamond Well U exp.	Chevron Exp. Corp	1978	1981	U	NABGLN
1282	1471/1	Bali Hi BM/Ag/U exp.	Russgar Mins. NL	1966	1978	Ag BM U	ASHB
			Esso Australia Ltd				
1284	2356/1	Uaroo Station BM/Au exp.	Aust. Anglo American Ltd	1978	1979	Au BM	GASC
1328	2790	Shay Gap BM exp.	Not entered	1981	1981	Cu Pb Zn Mo	NPGG
1348	2285	Narndee Cu–Zn exp.	Newmont P/L	1976	1978	Cu Zn	MURCH
1368	1868	Dalgaranga Ni–Cu/Cu–Zn exp.	Carpentaria Exp Co P/L	1973	1980	Cu Ni Zn	MURCH
1429	157	Fraser Range BM exp.	Newmont P/L	1965	1972	BM	ALBFRA/EGFS
1443	2531/2	Melita Cu–Zn exp.	Chevron Exp. Corp	1979	1981	Cu Zn	EGFS
1454	707	Mount Mulcahy Cu–Zn exp.	Western Mining Corp. Ltd	1969	1978	Cu Zn	MURCH
1456	1440	Tallering Peak Cu–Zn/Au exp.	Electrolytic Zn Co	1973	1980	Au Cu Zn	MURCH/WGT
1457	1513	Narndee Cu–Zn exp.	Westfield Mins. NL	1972	1977	Cu Zn	MURCH
			Whim Creek Consol. NL				
1469	2605/1	Irregully Creek Cu–Pb–Zn exp.	Alcoa of Australia Ltd	1979	1982	Cu Pb Zn	BANGE
1534	71	Little Tarraji River Cu exp.	Western Mining Corp. Ltd	1957	1960	Cu	KLEO
1542	3231/4	Blackfellow Creek Cu–Pb exp.	Kia Ora Au Corp NL	1970	1970	Cu Pb	KIMB
1615	1731	West River Cu–Zn exp.	Amax Exp. Aust Inc	1975	1977	Cu Zn	SCROSS
			CRA Exp. P/L				
1694	2415	Paterson Prov. U/Cu–Pb–Zn exp.	Occidental Mins. Corp	1978	1981	Cu Pb Zn U	PATER
1700	1394	Glen Florrie BM exp.	Great Boulder Mines Ltd	1972	1974	BM	ASHB
1701	1395	Yarraloola (Robe Hill) Cu–Pb–Zn exp.	Great Boulder Mines Ltd	1970	1982	Cu Pb Zn	ASHB
			Western Mining Corp. Ltd				

Appendix 1 (continued)

Item no.	*Wamex no.*	*Group title*	*Company*	*Start*	*End*	*Commodity*	*Tectonic unit*
1711	2965/1	South Mill Cu–Pb–Zn and U exp.	CRA Exp. P/L	1980	1981	Cu Pb Zn U	ASHB
1712	2965/2	Mount Stuart Cu–Pb–Zn exp.	CRA Exp. P/L	1981	1982	Cu Pb Zn	ASHB
1713	3298	Mount Stuart Cu–Pb–Zn exp.	Electrolytic Zn Co	1982	1983	Cu Pb Zn	ASHB
1721	1656	Gullewa Cu–Zn/Ni–Cu/Au exp.	North Flinders Mines Ltd Aztec Exp. Ltd Aust. Anglo American Ltd	1974	1980	Au Cu Ni Zn Sb	MURCH
1733	945	Wattagee Pool Cu–Zn /Ni–Cu exp.	Esso Exp. Aust Inc Eastmet Exp P/L Shell Mins. Exp Aust P/L	1971	1978	Cu Ni Zn	MURCH
1735	1478	Narndee/Boodanoo Cu–Zn exp.	Esso Australia Ltd Esso Exp. Aust Inc Freeport of Aust Inc. Westralian Ni Exp NL.	1973	1982	Cu Zn	MURCH
1740	2444	Mellenbye Cu–Zn exp.	Esso Australia Ltd Esso Exp. Aust Inc	1978	1981	Au Cu Zn	MURCH
1797	1803	Burnakura and Pluto Bore Cu–Zn exp.	Aust. Selection P/L	1974	1976	Cu Zn	MURCH
1813	457	Jimberlana Dyke (BM GK23) Pt and Ni–Cu exp.	Endeavour Mins. NL	1969	1972	Pt Cu Ni	SCROSS
1947	2246	Cu Hills/McPhee Creek Au/BM exp.	Dampier Mining Co Ltd	1977	1984	Au Cu Zn	HAMERS/NPGG
1964	2038	Middle Creek Cu–Zn exp.	Aquitaine Aust Mins. P/L	1976	1977	Cu Zn	NPGG
1969	2703	Bellary Dome Au and BM exp.	Hamersley Exp P/L	1980	1983	Au Cu Ni Zn	HAMERS/ASHB
1974	3931	Abydos Cu–Zn exp.	Mt Newman Mining Co P/L	1978	1982	Cu Zn	NPGG
1977	2705	Osmond Range BM/diamond exp.	Carpentaria Exp Co P/L	1980	1984	Cu Pb Zn DIAM	BIRRIN
1980	574	Sabina Vale mineral sands exp.	Vulcan Investments P/L	1969	1973	HMS	SSWAN
2017	2129	Killara BM exp.	Pacminex P/L	1977	1978	Cu Pb Zn	NABGLN
2020	2772	Lake Gregory Cu–Pb–Zn exp.	Esso Exp. Aust Inc	1981	1982	Cu Pb Zn	NABGLN/NABEAR
2030	2492/2	Steeple Hill BM exp.	Broken Hill Pty Co Ltd	1977	1979	Cu Pb Zn	EGFS
2038	2276	Glenayle Cu–Pb–Zn exp.	CSR Ltd Pacminex P/L	1977	1979	Cu Pb Zn	NABGLN/BANGE
2039	2356/2	Lyndon Station/Coria Springs BM Au & U exp.	Aust. Anglo American Ltd	1978	1982	Au Ni W U Cu Sn Ta Mo Zn Pb BM	BANGE/GASC
2051	3127	Ilgarari Pb–Zn exp.	Alcoa of Australia Ltd	1982	1983	Ag Pb	SAVORY
2062	1590	Ti–Tree Well Cu–Pb–Zn exp.	Australasian Mins. Inc	1972	1973	Cu Pb Zn	GASC
2064	2800	Moogooree Pb–Zn exp.	International Ni Aust Ltd	1980	1980	Pb Zn	CARNAR/GASC
2079	2915	Barbwire Pb–Zn exp.	Shell Company Aust. Ltd	1981	1983	Pb Zn	CANCEN/CANFTZ
2097	303	Sherlock Bay Ni–Cu exp.	Aust. Inland Exp Co Inc Texasgulf Australia Ltd	1967	1982	Cu Ni	NPGG
2099	1615	Poison Hill Cu–Pb–Zn exp.	Dresser Products Aust P/L	1973	1975	Cu Pb Zn	NHAMP
2102	1473	Pincher Well Cu–Zn exp.	Western Mining Corp. Ltd	1971	1973	Cu Zn	SCROSS
2136	438	Uaroo Cu–Pb–Zn exp.	Mr Ibbotson G	1968	1970	Cu Pb Zn	GASC
2138	3191	Tallering Peak/Carlinga Well Au/ Cu–Zn exp.	Preussag Australia P/L	1981	1985	Au Cu Zn	MURCH/WGT
2180	309	Prairie Downs Cu–Pb–Zn exp.	Aust Ores & Mins. P/L	1969	1971	Cu Pb Zn	SYLAN/BANGE

Appendix 1 (continued)

Item no.	*Wamex no.*	*Group title*	*Company*	*Start*	*End*	*Commodity*	*Tectonic unit*
2181	2264	Sweetwaters Well Pb–Zn exp.	Broken Hill Pty Co Ltd Dampier Mining Co Ltd	1977	1980	Pb Zn	NABEAR
2186	1013	Speewah Valley fluorite exp.	Great Boulder Mines Ltd	1972	1984	CaF2	KIMB
2242	2339	Mount Phillips/Gillie Well U exp.	Nord Resources Pacific P/L	1979	1983	U	BANGE/GASC
2257	3052/1	Ti Tree Well Cu–molybdenum exp.	Amax Exp. Aust Inc	1979	1983	Cu Mo	BANGE/GASC
2258	3052/2	Ti Tree Well Cu–Pb–Zn exp.	Alcoa of Australia Ltd	1979	1983	Cu Pb Zn	BANGE/GASC
2276	1336	Twin Peaks Cu exp.	Aust. Anglo American Ltd	1973	1974	Cu Zn	MURCH/WGT
2278	2260	Syftkog Cu–Pb–Zn exp.	Noranda Australia Ltd	1977	1984	Cu Pb Zn	GASC
2285	3072	Cooliboo Bore Cu–Zn exp.	Esso Australia Ltd	1982	1984	Cu Zn	SCROSS
2286	3095	Smith Well Cu–Zn exp.	Esso Exp. Aust Inc Jones Mining Ltd	1981	1984	Cu Zn	SCROSS
2331	1587	Baramine Cu–Zn exp.	Australasian Mins. Inc	1972	1974	Cu Zn	HAMERS
2332	1719	Galena Pb exp.	Aust Consol. Mins. Ltd	1973	1976	Pb	NHAMP
2333	1778	Eelya Hill Cu–Zn exploartion	Aquitaine Aust Mins. P/L Electrolytic Zn Co Esso Australia Ltd	1971	1983	Cu Zn	MURCH
2348	3316/1	Dakota (Smith Well) Au–Cu–Zn exp.	Esso Exp. Aust Inc Black Hill Mins. Ltd	1981	1986	Au Cu Zn	SCROSS
2354	3454/1	Stella Range Au exp.	Jones Mining NL	1983	1984	Au	EGFS
2364	990	Mundong Well U exp.	Katanning Holdings Ltd Newmex Exp. Ltd Esso Exp. Aust Inc Esso Australia Ltd	1972	1983	Ag Cu Pb Zn U	GASC
2366	434	Mount Constantine BM and U exp.	Bell Brothers P/L	1969	1972	BM U Cu Pb Zn	HAMERS/NPGG
2379	1180	Mount Angelo Cu–Zn exp.	Asarco Australia Ltd	1972	1973	Cu Zn	HALLCR
2389	1678	Carlton Hill Pb–Zn exp.	Alcoa of Australia Ltd	1972	1981	Pb Zn	BONAP
2431	311	Copper Gorge Cu–Zn exp.	Aust Ores & Mins. P/L	1969	1983	Cu Zn	NPGG
2454	324	Copper Range/Copper Knob Cu exp.	Endeavour Oil Co NL Mr Shaw FW	1968	1975	Cu	SYLVAN
2456	2218	Nambi Cu–Zn exp.	Esso Exp. Aust Inc	1977	1982	Cu Zn	EGFS
2457	2825	Muccan/Yukerakine Cu–Mo/W exp.	Duval Mining Australia Ltd	1981	1982	Au Mo Cu Ni W	NPGG
2489	2494	Eastman Yard Cu–Zn/Pb–Zn exp.	BHP Mins. P/L Broken Hill Pty Co Ltd	1977	1985	Cu Pb Zn BM	HAMERS/KLEO
2490	2632/3	Noonyereena Hill Cu–Pb–Zn /U exp.	Chevron Exp. Corp	1980	1982	U Cu Pb Zn BM	NABGLN
2491	2877	Ragged Hills Cu–Pb–Zn exp.	Esso Exp. Aust Inc	1980	1982	Cu Pb Zn	HAMERS
2515	3082	Carlinga Well Au/Cu–Zn exp.	Western Mining Corp. Ltd South West Exp P/L	1981	1985	Au Cu Zn	MURCH/WGT
2524	1526/2	Two Peaks U/Cu exp.	Uranerz Australia P/L	1973	1980	U Cu	BANGE/GASC
2541	2358	Salmon Gums U/BM exp.	Central Norseman Au Corp Ltd	1979	1981	U Au BM LIGN	ALBFRA
2543	2927	Ashburton Dwns. U–Cu–Pb–Zn exp.	Uranerz Australia P/L	1981	1982	U Cu Pb Zn	ASHB
2553	2356/3	High Range BM/Au/U exp.	Aust. Anglo American Ltd	1978	1982	W U BM Au Cu Pb Zn Sn	BANGE/GASC
2555	1831	Yerecoin Cu–Zn exp.	Otter Exp. NL	1976	1976	Cu Zn	WGT

Appendix 1 (continued)

Item no.	*Wamex no.*	*Group title*	*Company*	*Start*	*End*	*Commodity*	*Tectonic unit*
2565	2258	Mount Stuart Cu–Pb–Zn exp.	Noranda Australia Ltd	1976	1982	Cu Pb Zn	ASHB
2569	2829	Mount Boggola Pb–Zn exp.	CRA Exp. P/L	1981	1982	Pb Zn	ASHB/BANGE
2602	156	Copper Hills Cu exp.	Hawkstone Mins. Ltd Mr Stubbs SH Newmont P/L	1965	1986	Cu	NPGG
2603	322	Wyloo Cu–Pb–Zn exp.	Electrolytic Zn Co	1968	1970	Cu Pb Zn	ASHB
2612	3923	Lofty Range Cu–Pb–Zn exp.	BP Mins. Aust P/L	1984	1985	Cu Pb Zn	BANGE
2647	848	Doyle Well Ni–Cu exp.	Mines Administration P/L	1969	1973	Cu Ni	EGFS
2653	1147/4	Barker Gorge Pb–Zn exp.	Shell Mins. Exp Aust P/L	1972	1983	Pb Zn	CANLEN/KLEO
2654	2291	Brooking Gorge Pb–Zn exp.	BHP Mins. P/L Dampier Mining Co Ltd	1977	1985	Pb Zn	CANFTZ/CANLEN/KLEO
2683	2659	Halls Creek Cu–Zn exp.	Broken Hill Pty Co Ltd BHP Mins. P/L	1979	1980	Cu Zn	HALLCR
2685	2273/2	Bonnie Rock Pb/Zn/Ag exp.	West Coast Holdings Ltd	1981	1983	Ag Pb Zn	SCROSS
2686	2273/3	Bonnie Rock Zn exp.	Asarco Australia Ltd	1970	1972	Mo Zn	SCROSS
2704	2820	Capricorn Range Au/Cu–Zn exp.	West Coast Holdings Ltd	1981	1983	Au Cu Pb Zn	ASHB
2718	3047	Murdaburia Hill Au/Cu–Zn exp.	Amax Australia Ltd	1980	1985	Au Cu Zn	MURCH
2722	3884	Yalanga Bore Cu–Pb–Zn exp.	Duval Mining Australia Ltd	1983	1984	Cu Pb Zn	MURCH
2723	4222	Barbwire Range Pb–Zn exp.	BHP Mins. P/L	1985	1986	Pb Zn	CANCEN/CANFTZ
2760	2335	North Pole Cu–Pb–Zn exp.	Newmont P/L	1978	1980	Ba Cu Pb Zn	NPGG
2764	3469	Colour Dam Cu–Zn exp.	Esso Exp. Aust Inc	1981	1983	Au Cu Zn	EGFS
2775	427	Kooline Cu–Pb–Zn exp.	Carr Boyd Mins. Ltd	1969	1971	Cu Pb Zn	ASHB
2776	3482/3	Lennard Shelf Pb–Zn exp.	Great Aust Resources NL	1981	1985	Pb Zn	CANLEN
2814	1346	Jubricoo Creek Pb–Zn exp.	Carpentaria Exp Co P/L	1973	1973	Pb Zn	GASC
2871	3063	Mount Mulcahy Cu–Zn exp.	Seltrust Mining Corp P/L Pegmin Ltd	1981	1986	Cu Zn	MURCH
2872	1626/1	Ningbing Pb–Zn exp.	Aquitaine Aust Mins P/L St Joe Bonaparte P/L	1972	1983	Pb Zn	BONAP
2907	1851	Lambshaft Well Cu–Zn exp.	Union Miniere Dev & Mining Corp Ltd	1975	1975	Cu Zn	MURCH
2915	3840	Avoca Downs Cu–Zn/Au exp.	Chevron Exp. Corp	1984	1985	Au Cu Zn	EGFS
2917	2593	Ajana Cu–Pb–Zn exp.	Esso Exp. Aust Inc	1980	1982	Cu Pb Zn	NHAMP
3004	2165	Twelve Mile Pool Cu–Pb–Zn exp.	Samantha Mines NL	1976	1979	Cu Pb Zn	NABGLN
3050	3452	Yarraloola Cu–Zn exp.	Noranda Australia Ltd	1983	1984	Cu Zn	ASHB
3054	1348	Northampton Pb exp.	Allied Mins. NL	1972	1974	Pb	NHAMP
3092	1385/2	Kanowna Ni–Cu/Cu–Zn/Au exp.	Great Boulder Mines Ltd Noranda Australia Ltd	1968	1975	Au Ni Cu Zn	EGFS
3099	2728	Cheela/Wanangarra Well Pb–Zn exp.	Broken Hill Pty Co Ltd	1980	1983	Pb Zn	ASHB
3101	3145/2	Paroo Au/Cu–Pb–Zn exp.	Jarrahmond Holdings P/L Aust Consol. Mins. Ltd	1982	1986	Cu Pb Zn Au	NABGLN
3102	3348	Karalundi Cu–Pb–Zn exp.	CRA Exp. P/L	1982	1983	Cu Pb Zn	NABGLN
3103	3336	Diamond Well Pb–Zn/Ag exp.	Duval Mining Australia Ltd	1982	1984	Ag Pb Zn	NABGLN
3110	2039	Anti Dam Cu–Zn exp.	Aquitaine Aust Mins. P/L	1976	1979	Cu Zn	EGFS

Appendix 1 (continued)

Item no.	*Wamex no.*	*Group title*	*Company*	*Start*	*End*	*Commodity*	*Tectonic unit*
3167	1795	Ningbing/Weaber Plains Pb–Zn exp.	CRA Exp. P/L Tenneco Oil & Mins. Aust Seltrust Mining Corp P/L Aust. Selection P/L Amax Exp. Aust Inc	1972	1985	Pb Zn	BONAP
3192	2881	Evanston Cu–Zn/Au exp.	Nord Resources Pacific P/L	1981	1984	Au Cu Zn	SCROSS
3193	3319	Quartz Circle Cu–Zn exp.	Alcoa of Australia Ltd	1976	1980	Cu Zn	NPGG
3196	3149	Troy Creek Cu–Pb–Zn exp.	Amax Australia Ltd	1982	1983	Cu Pb Zn	NABEAR
3216	3810	Deadman Hill Au/BM exp.	Indian Ocean Res. Ltd	1984	1985	Au BM	HAMERS/SYLVAN
3219	2390	Brookton Cu–Zn exp.	Otter Exp. NL	1976	1983	Cu Zn	SW
3224	2979	Ragged Hills Pb exp.	Hancock & Wright Prosp. P/L	1974	1982	Pb	NPGG
3227	62	Ashburton–Bangemall BM/ asbestos/manganese /Au exp.	Westfield Mins. NL Ashburton Exp P/L	1961	1967	Au Cu Pb Zn Mn Mo BM ASB	ASHB/BANGE/GASC /HAMERS/MURCH/ NABGLN/NPGG
3231	2037	Evelyn Cu–Pb–Zn exp.	Aquitaine Aust Mins. P/L	1976	1978	Ag Cu Pb Zn	NPGG
3232	3679	Killara Cu–Pb–Zn exp.	Carpentaria Exp Co P/L	1983	1985	Cu Pb Zn	NABGLN
3238	4116	Scorpion Cu–Pb–Zn/Au exp.	CRA Exp. P/L	1984	1986	Au Cu Pb Zn	NABEAR
3273	1817/1	Wendys Bore Cu–Zn/Au exp.	Esso Exp. Aust Inc Walgardy P/L Chevron Exp. Corp BP Mins. Aust P/L Aquitaine Aust Mins. P/L	1976	1987	Au Cu Zn	EGFS
3286	4209	Ponton Creek carbonatite exp.	Union Oil Devel. Corp	1984	1987	REE	ALBFRA/EGFS
3316	283	Kununurra Mine Cu–Pb–Zn/Ag/ Au exp.	Acmin Exp.s P/L Alliance Mins. Aust NL Acmex Holdings Ltd	1968	1971	Au Ag Cu Pb Zn	KIMB
3317	1638/1	Murphy Well Cu–Zn exp.	Esso Exp. Aust Inc	1974	1975	Cu Zn	NPGG
3325	1675	Knob Peak Pb–Zn exp.	Placer Prospecting P/L	1973	1983	Pb Zn	BONAP
3406	1295/2	Freddie Well Cu–Zn exp.	Conwest Australia NL CRA Exp. P/L Newmont P/L	1971	1988	Cu Zn	SCROSS
3419	3500/3	Rudall River BM/U/diamond exp.	CRA Exp. P/L	1983	1987	U Cu Pb Zn BM DIAM	PATER
3438	1065	Mary Springs Pb exp.	Samin Ltd	1972	1988	Pb	NHAMP
3536	2945/3	Edjudina South Au exp.	Picon Exp.s P/L	1984	1988	Au	EGFS
3541	4142	Miralga Creek Au exp.	Noranda Australia Ltd	1984	1988	Au	NPGG
3576	2473	Twin Peaks Cu–Zn/Au exp.	Cyprus Mins. Australia Co Amoco Mins. Aust Co	1978	1988	Au Cu Zn	MURCH/WGT
3601	4179	Yilgarn Block Cu–Zn/Ni–Cu exp.	North Flinders Mines Ltd	1976	1980	Ni Cu Zn	MURCH/SCROSS/ WGT/EGFS/SW
3608	3195/1	Gidgie Well Cu–Zn/Au exp.	Aztec Exp. Ltd Chevron Exp. Corp	1981	1988	Au Cu Zn	MURCH
3614	5746	King Leopold Au/BM exp.	Century Metals & Mining NL	1987	1988	Au BM	KLEO

Appendix 1 (continued)

Item no.	Wamex no.	Group title	Company	Start	End	Commodity	Tectonic unit
3671	4704	Mount Alexander Cu–Pb–Zn/Au exp.	Cyprus Mins. Australia Co	1985	1988	Au Cu Pb Zn	ASHB
3701	4237	Abydos BM/Au exp.	Mr MacDonald SA	1984	1988	BM Au	NPGG
3706	4361	Victoria Cu Mine BM exp.	MC Mining NL	1984	1988	BM	GASC
3743	5487	Braeside Au/platinum exp.	Newmont Australia Ltd	1988	1988	Au Pt BM	HAMERS
3746	5383	Kooline Au/BM exp.	Auen Deeps Ltd	1987	1988	Au BM	ASHB
3800	5140/2	Finlayson Range Cu–Zn exp.	Mitchell Exp. Co	1986	1988	Cu Zn	NABGLN/EGFS
3804	3601/6	Marboo Well/Paddy Well/Kunda Ck Au/BM exp.	Billiton Australia	1987	1989	BM Au	ASHB
3808	4066	Ivanhoe Au/BM exp.	Mr Moder EM	1984	1988	BM Au	BONAP
3810	4120	Gidgie Well North Au/BM exp.	Chevron Exp. Corp	1985	1989	BM Au	MURCH
3835	4515	Uaroo U exp.	CRA Exp. P/L	1985	1988	Au Pt U	GASC
3891	1295/3	Freddie Well/Shirley Bore BM/Au exp.	CRA Exp. P/L	1982	1987	BM Au	SCROSS
3896	5070	Ag King/Uaroo Ag/Au exp.	Mr Ibbotson G	1986	1989	Au Ag Cu	ASHB
3922	3531/6	Dalgaranga/Gum Well/Outcamp Well BM exp.	CRA Exp. P/L	1984	1989	Au BM Cu Zn	MURCH
4029	1807/1	Teutonic Bore (Agnew–JV) Cu–Zn/Au exp.	BP Mins. Aust P/L Aust. Selection P/L Carpentaria Exp Co P/L Chevron Exp. Corp Seltrust Mining Corp P/L	1974	1989	Pt Au Cu Zn	EGFS
4106	6177	Carnarvon Basin Pb–Zn exp.	Electrolytic Zn Co	1988	1989	Pb Zn BM	CARNAR
4140	6638	Moogooree Pb–Zn exp.	Aberfoyle Resources Ltd	1988	1989	Pb Zn	CARNAR/GASC
4143	6711	Koongie Park Au/Ag exp.	Asarco Australia Ltd	1984	1986	Ag Au	HALLCR
4156	3601/1	Hardey Junction Pb–Zn/Au exp.	Austamax Resources Ltd BP Mins. Aust P/L ACM Au Ltd Billiton Australia Mins. Aust P/L	1983	1989	Au Pb Zn	ASHB
4244	4371	Paynes Find Au/BM exp.	UCABS P/L Sovereign Res. Aust NL	1985	1989	BM Ag Au	MURCH
4365	6669	Cane River Au/Cu–Pb exp.	Aberfoyle Resources Ltd	1989	1990	Au	ASHB
4378	2085/2	Copper Range Cu–Zn exp.	Aquitaine Aust Mins. P/L	1977	1986	Cu Zn	SYLVAN
4380	2904/3	Quinns Au/Cu–Zn–Pb exp.	CRA Exp. P/L	1985	1990	Au Cu Pb Zn	MURCH
4385	3197	Emu Creek Cu–Pb–Zn exp.	K'goorlie S'thern Au Mines NL Mitchell Exp. Co	1982	1990	Cu Pb Zn	NPGG
4401	3805/1	Koorabooka BM exp.	BHP Mins. P/L	1984	1986	Cu Pb Zn	BANGE
4415	4599	Dicks Reward Au/BM exp.	ACM Au Ltd Aurex P/L	1986	1990	Au BM	SCROSS
4471	3071	Gifford Creek Au/Mn/BM exp.	Cliffs International Inc	1981	1984	BM Mn Au U	ASHB
4475	3582	Steeple Hill Cu–Zn/Au exp.	CSR Ltd Placer Exp. Ltd	1983	1990	Au Cu Zn	EGFS
4550	1790	Edamurta Cu–Zn/Au exp.	Samantha Mines NL Union Min. Dev & M'g Cp. Ltd	1973	1987	Au Cu Zn	MURCH
4579	5140/1	Mount Bartle Cu–Zn/Au exp.	Mitchell Exp. Co	1986	1989	Au Cu Zn	NABGLN
4641	1609/2	Jillawarra BM/Au exp.	Amoco Mins. Aust Co G'peko	1974	1987	BM Au Zn Pb Ba	BANGE

Appendix 1 (continued)

Item no.	Wamex no.	Group title	Company	Start	End	Commodity	Tectonic unit
4642	1609/3	Teano Range (Jillawarra.) BM. exp.	Geopeko	1982	1983	BaSO4 Cu Pb Zn	BANGE
4644	1609/5	Manganese Range(Jillawarra Area) Au/BM exp.	Cyprus Au Australia Corp.	1987	1990	Au BM Mn	BANGE
4645	2357	Mount Alexander W/U/Au exp.	Amax Iron Ore Corp. Amax Australia Ltd Amoco Mins. Aust Co	1980	1986	Au U W BM	BANGE/ASHB/GASC
4654	5650	Barbwire East/Crossland Pb–Zn exp.	CRA Exp. P/L	1987	1990	Cu Pb Zn	CANFTZ/CANCEN
4682	3534/4	Mount Townsend Au/Cu–Zn exp.	CRA Exp. P/L	1982	1990	Au Cu Zn	SCROSS
4734	6083	Eldridge diamond/Au/BM exp.	Moonstone Mines NL Troy Resources NL	1987	1990	BM DIAM Au	HALLCR
4739	6162/2	Barbwire Range Pb–Zn exp.	BHP Mins. P/L	1988	1991	Pb Zn	CANFTZ/CANCEN
4835	5523	Gascoyne/Mangaroon Au/Pt exp.	Regional Resources NL	1987	1989	BM Au Pt	GASC
4879	6965	Henry River BM exp.	Herald Resources Ltd	1990	1991	Cu Pb Zn	BANGE
4907	4227	Ninghan Cu–Zn exp.	CRA Exp. P/L	1984	1989	Cu Zn	MURCH
4977	6230	Capricorn BM exp.	Maritana Au NL	1988	1991	Au BM	HAMERS/SYLVAN
5028	3350	Melita Cu–Zn exp.	Dechow & Co P/L	1982	1985	Cu Zn	EGFS
5038	3601/2	Wyloo (Mt McGrath JV) Au/BM. exp.	Billiton Australia Aust. Ores & Mins. Ltd	1985	1990	BM Au	ASHB
5163	189/1	Balla Balla titanium/vanadium and Salt Ck Cu–Pb–Zn exp.	Texasgulf Australia Ltd Elf Aquitaine Aust P/L Agnew Clough Ltd Garrick Agnew P/L	1967	1990	Ag Ti Fe V Cu Pb Zn	NPGG
5172	2467/2	Fieldings Gully Cu–Zn/Au exp.	Alcoa of Australia Ltd	1978	1986	Au Cu Zn	NPGG
5185	3277	Range/Turtle Cu/Pb exp.	Jays Exp. P/L	1981	1984	Cu Pb	ASHB
5199	3557	Scorpion Au/BM/U exp.	Geopeko	1983	1984	Au BM U	NABGLN/NABEAR/ BANGE
5222	3889	Sanford Au/BM exp.	Mt Martin Au Mines NL	1983	1988	Au BM	MURCH
5240	4511/2	Moolyella Au exp.	Mr Griffiths PJ	1986	1991	Au	NPGG
5271	5479	Yangibana Bore REE exp.	Hurlston P/L	1985	1991	REE	GASC
5335	6635	Mount Vernon BM exp.	Western Mining Corp. Ltd	1989	1991	Au BM	BANGE
5357	4879	Kooline Pb–Ag exp.	Nero Exp. P/L	1986	1990	Ag Pb	ASHB
5414	1822	Wongan Hills Au/Cu–Zn exp.	Aquitaine Aust Mins. P/L Ltd BHP Mins. P/L Billiton Australia Shell Company Australia Otter Exp. NL	1975	1991	Au Cu Zn BM	MURCH
5453	5258	Mount Broome Au exp.	Cygnet Resources P/L	1987	1989	BM Au	KLEO
5573	1215	Duketon/Fisher Well Cu–Zn/Au exp.	Golconda Exp Ltd Duketon Exp. Ltd Esso Australia Ltd Carpentaria Exp Co P/L Homestake Australia Ltd Esso Exp. Aust Inc	1973	1988	Au Ag Ni Cu Pb Zn	EGFS

Appendix 1 (continued)

Item no.	Wamex no.	Group title	Company	Start	End	Commodity	Tectonic unit
5594	3023	Halls Creek Au/Zn/Sn/W exp.	West Coast Holdings Ltd	1981	1991	Ag Au W Cu Pb Zn Sn	HALLCR
5607	1696/2	Walgardy Cu–Zn/Au exp.	Dalrymple Resources NL Aztec Exp. Ltd Walgardy P/L	1986	1991	Au Cu Zn	MURCH
5657	6717	Wattagee Hill Au/BM exp.	Outokumpu Exp Aust P/L	1989	1991	Au Cu Pb Zn	MURCH
5751	5395/1	Jimblebar Au/platinum/BM exp.	Billiton Australia Geopeko	1986	1989	Au Pt BM	SYLVAN
5759	6229/1	Devil Creek Pb–Zn–Au exp.	Cyprus Au Australia Corp. Arimco NL	1988	1990	Au Ag Pb Zn Cu	HAMERS/NPGG
5792	1474	North Pole BM/barite exp.	Kitchener Mining NL Carpentaria Exp Co P/L Leopold Mins. NL	1973	1985	Ba BM	NPGG
5832	1817/2	Wendys Bore Cu–Pb–Zn exp.	Esso Exp. Aust Inc BP Mins. Aust P/L Carpentaria Exp Co P/L Chevron Exp. Corp MIM Exp. P/L Seltrust Mining Corp P/L	1975	1992	Cu Pb Zn	EGFS
5834	4831	Mount Mulcahy Au/Cu–Zn exp.	Southwest Au Mines NL BHP Mins. P/L West Aust. Metals NL	1986	1991	Au Cu Zn	MURCH
5861	2950/2	Eastmans Bore Au/BM exp.	Geopeko	1986	1990	Au Pt Cu Pb	HALLCR
5865	7180	Koorabooka Au/BM/REE exp.	Newcrest Mining Ltd	1990	1991	REE BM Au	BANGE
5944	1471/3	Capricorn U/Au/BM exp.	Uranerz Australia P/L Barrack Exp. P/L	1966	1989	Au U BM Cu	ASHB
5965	7232	Mount Vernon BM exp.	Western Mining Corp. Ltd	1990	1991	BM	BANGE
5983	2049/3	Tuckabianna BM/Au exp.	Pacminex P/L CSR Ltd	1976	1986	Au Cu Zn	MURCH
5997	818/2	Karratha Au/BM and precious metal exp.	Agip Australia P/L	1967	1991	Pd Pt Ni Au Ag Cu	NPGG
5998	251/4	Murrin Murrin BM/Au exp.	Samson Exp. NL Weighton P/L Aust. Selection P/L BP Australia Ltd Seltrust Mining Corp P/L BP Mins. Aust P/L Northern Selcast P/L	1964	1987	Au Ni Cu Pb Zn ASB	EGFS
6027	2540	Grants Patch Au/Ag/BM exp.	Aust. Mineral Ventures	1979	1980	Au Ag BM	HALLCR
6086	1696/4	Walgardy Well Au/BM exp.	Dalrymple Resources NL	1989	1991	BM Au	MURCH
6150	7344/2	Ajana BM exp.	CRA Exp. P/L	1991	1992	Cu Pb Zn	NHAMP/NPERTH
6157	1168/8	Koongie Park Cu–Pb–Zn exp.	Kennecott Exp Aust P/L	1972	1976	Cu Pb Zn	HALLCR
6182	1626/5	Sorby Hills/Jeremiah Hills Pb–Zn exp.	Aquitaine Aust Mins. P/L	1971	1981	Pb Zn	BONAP
6230	263/1	Lennons Find Au/BM exp.	Westfield Mins. NL Centenary Int Mining Ltd Project Mining Corp Ltd	1964	1988	Ag Au Cu Pb Zn	NPGG

Appendix 1 (continued)

Item no.	*Wamex no.*	*Group title*	*Company*	*Start*	*End*	*Commodity*	*Tectonic unit*
			Cominco Exp. P/L Serem Aust P/L Research Exp & Management				
6401	6069/2	Fraser Range mineral exp.	Growth Resources NL	1987	1992	Au Ni LIGN DIAM Pd Ti Cr Pt V U	ALBFRA
6420	6942	West River Au/BM exp.	Pancontinental Mining Ltd	1990	1992	Au BM	SCROSS
6434	1508/1	Mount Clement Au/Cu–Pb–Zn exp.	Dampier Mining Co Ltd	1974	1992	Au Ag CuPb Zn	ASHB
6438	6783/1	Gifford Creek Au/BM/REE/Diam. exp.	Newcrest Mining Ltd Newmont Australia Ltd	1989	1992	DIAM Au REE BM	BANGE/GASC
6473	7606	North Gascoyne BM exp.	BHP Mins. P/L	1991	1992	Ag Cu Pb Zn	GASC
6534	6854	Copper Ridge BM/Au exp.	West Aust. Metals NL	1989	1990	Au Ag Cu Pb	CARNAR/GASC
6563	7779	Sawback Range BM exp.	RGC Exp. P/L	1991	1992	BM	BANGE
6564	7780	Yarraloola Cu–Zn exp.	RGC Exp. P/L	1991	1991	Cu Zn	CARNAR
6654	7786	East Kimberley Cu exp.	CRA Exp. P/L	1991	1992	Cu	KIMB
6759	6936/2	Twin Peaks BM exp.	Poseidon Exp. Ltd	1988	1992	BM	MURCH
6808	6769/2	Northampton BM/Au exp.	West Aust. Metals NL	1986	1992	Au Cu Pb Zn	NHAMP
6819	3784/3	Helens Find Au exp.	Endeavour Resources Ltd Metals Exp. Ltd	1983	1989	Au	EGFS
6869	7921/2	Barbwire BM exp.	Pasminco Exp.	1992	1993	Pb Zn	CANFTZ/CANCEN
6882	2150/2	Nifty Cu–Pb–Zn exp.	WMC Resources Ltd Western Mining Corp. Ltd	1979	1992	Cu Zn	PATER
6927	1295/4	Freddie Well/Shirley Bore Cu–Zn/Au exp.	CRA Exp. P/L	1971	1993	Au Cu Zn	SCROSS
7056	2904/4	Quinns Au/BM exp.	Freeport of Australia Inc CRA Exp. P/L	1983	1992	Au Cu Zn	MURCH
7144	7734	Mount Amherst Au/Ag/BM exp.	Roebuck Resources NL	1990	1993	Au Ag BM	HALLCR
7158	7038	Mount Sandiman Pb–Zn exp.	Dominion Mining Ltd	1990	1993	Zn Pb	CARNAR
7486	4525/1	Narndee Cu–Zn/Au exp.	Anglo Aust. Resources NL Billiton Australia Poseidon Exp. Ltd	1986	1994	Au Cu Zn	MURCH
7521	7174	Double Jay BM exp.	MIM Exp. P/L	1989	1993	BM	MURCH
8613	8945	Kite Au exp.	North Mining Ltd	1993	1995	Au	EGFS

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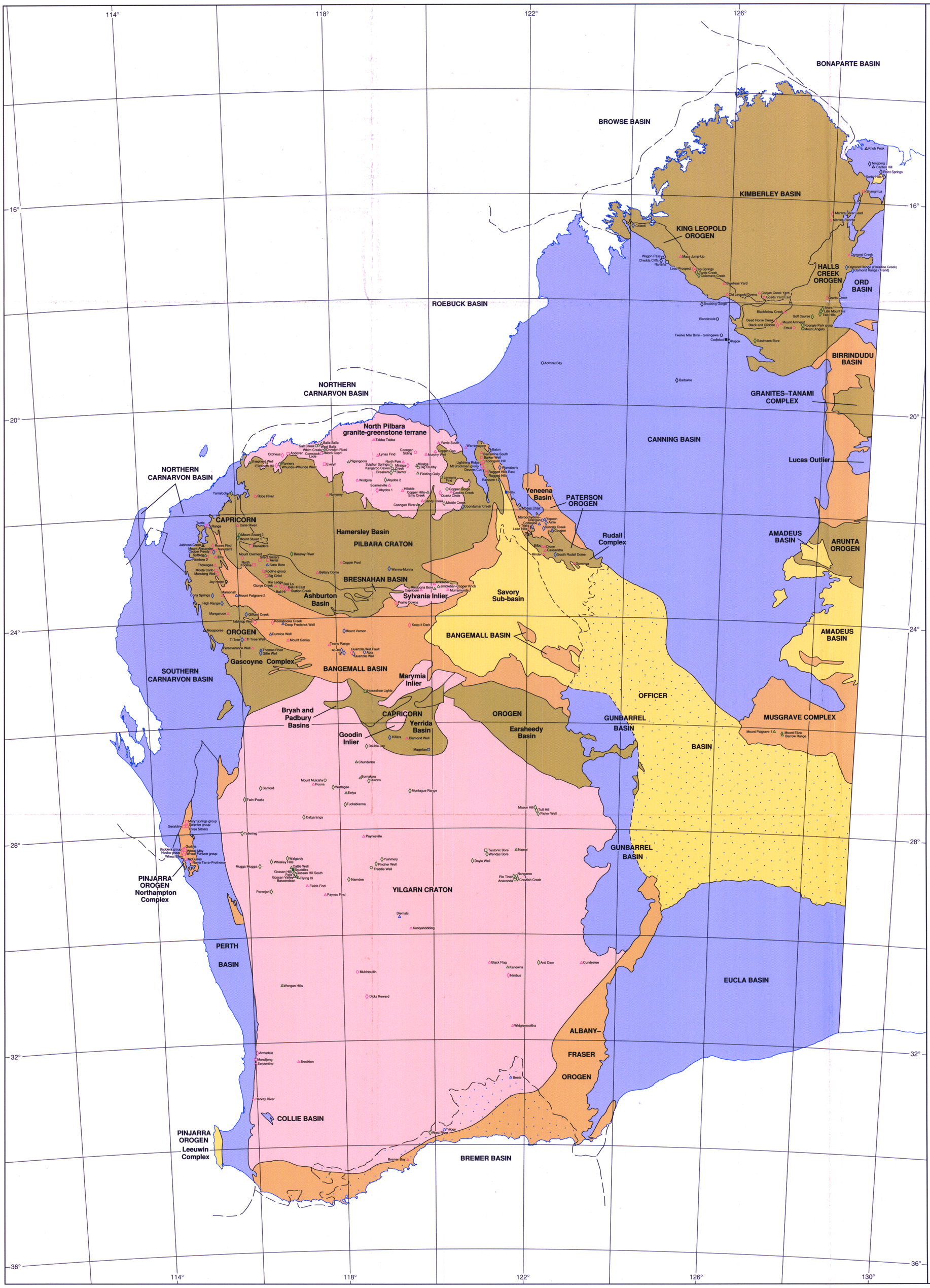

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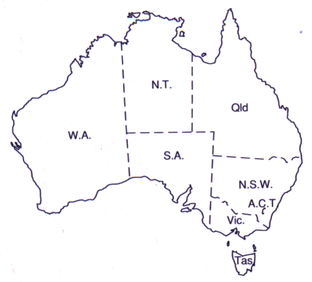
- Phanerozoic basins
- Neoproterozoic basins
- Mesoproterozoic rocks
- Palaeoproterozoic rocks
- Archaean rocks

MINERALIZATION CLASSIFICATION

	VMS	Clastic-hosted	Carbonate-hosted	Hydrothermal vein-type
Mine, operating	■	■	■	■
Mine, abandoned or shut down	□	□	□	□
Deposit	○	○	○	○
Prospect	◊	◊	◊	◊
Major occurrence	△	△	△	△



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SCALE 1: 5 000 000

0 50 100 150 200
Kilometres

ALBERS EQUAL AREA PROJECTION

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
MINERAL RESOURCES BULLETIN 15 PLATE 1

LEAD–ZINC–SILVER

MINES, DEPOSITS, PROSPECTS, AND MAJOR OCCURRENCES OF WESTERN AUSTRALIA

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