GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

REPORT 24

STUDIES OF SELECTED CARBONATE-HOSTED LEAD-ZINC DEPOSITS IN THE KIMBERLEY REGION

by
C. R. RINGROSE

DEPARTMENT OF MINES
WESTERN AUSTRALIA

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

REPORT 24

STUDIES OF SELECTED CARBONATE-HOSTED LEAD-ZINC DEPOSITS IN THE KIMBERLEY REGION

by
C. R. RINGROSE

State Printing Division
Perth 1989

A61482-1

MINISTER FOR MINES
THE HONOURABLE JEFF CARR M.L.A.

DIRECTOR GENERAL OF MINES
D. R. KELLY

DIRECTOR, GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
PHILLIP E. PLAYFORD

National Library of Australia
Cataloguing-in-publication entry

Ringrose C. R. (Christopher Robert), 1955-

Studies of selected carbonate-hosted lead-zinc deposits in the Kimberley region.

Bibliography
ISBN 0 7309 0875 5.

1. Lead ores—Western Australia—Kimberley. 2. Zinc ores—Western Australia—Kimberley. I. Geological Survey of Western Australia. II. Title. (Series : Report (Geological Survey of Western Australia); 24).

553.44099414

ISSN 0508-4741

Copies available from:

The Director
Geological Survey of Western Australia
100 Plain Street
East Perth, Western Australia 6004
Telephone (09) 222 3168

FOREWORD

This report was compiled as part of the Geological Survey program to assist exploration for minerals and petroleum in carbonates associated with Devonian reef complexes in the Kimberley region. The Lennard Shelf area in the West Kimberley is now regarded as a major zinc-lead province containing Mississippi Valley-type deposits. The report was compiled prior to the announcement of the Cadjebut discovery. This zinc-lead deposit commenced production in June 1987 and it represents a new phase of major zinc and lead production within the State.

Phillip E. Playford,
Director.

CONTENTS

PLATES

FIGURES

TABLES

STUDIES OF SELECTED CARBONATE-HOSTED LEAD-ZINC DEPOSITS IN THE KIMBERLEY REGION

ABSTRACT

The Pb-Zn prospects at Blendevale, Wagon Pass, Narlarla, and Sorby Hills are important examples of Mississippi Valley-type mineralization which characterize the margins of the Canning and Bonaparte Basins in northwestern Australia.

These epigenetic orebodies have simple sulphide assemblages of galena-sphalerite-pyrite and marcasite, with accessory chalcopyrite and/or tennantite-tetrahedrite. Sulphides occur as open-space fillings in secondary-rock porosities, fractures, solution cavities, and bedding-plane partings. All sulphide zones, except those of Blendevale, are spatially and genetically associated with zones of pervasive dolomitization and/or chloritization of the host carbonates.

At each deposit the paragenetic sequence of mineralization is similar, involving dolomitization, sulphide precipitation, and late-stage calcite formation. Early diagenetic iron sulphide formation and calcite cementation were followed by main-stage sulphide mineralization of the host carbonates, in a deep-burial environment. Coarse-grained calcite infilling was precipitated later.

For all deposits it is postulated that sulphide precipitation occurred when metalliferous, basin-derived brines mixed with H_2S-bearing pore fluids in suitably dilatant trap sites along the basin margin. Differences in Pb/Zn ratio and orebody shape, amongst the prospects, reflect the following: evolution of the metalliferous fluid in time and space; petrology of the ore-fluid aquifer; stratigraphic setting and "level" of the host strata; and porosity and permeability of the host-rock at the ore site. Several pulses of sulphide-forming fluids were involved, each following fault movements. The waning stages of brine incursion coincided with the downward percolation and mixing of meteoric fluids at some ore sites.

Other, undiscovered, sulphide orebodies are probably located near faults where two kinds of structure influenced deposition of mineralization: faults that parallel the basin margin and faults which are high-angle cross structures.

INTRODUCTION

The Canning and Bonaparte Basins of the Kimberley Region in Western Australia have received much attention over the past fifteen years or so, as geological provinces with potential for the occurrence of world-class lead-zinc resources in sedimentary rocks. Prior to this, the Narlarla deposits were discovered in 1901, and other galena occurrences were known in Devonian reef limestones of the Lennard Shelf (Blockley, 1971). The small Narlarla deposit was worked out between 1948 and 1966. In 1939, Finucane and Jones had suggested that this occurrence of lead and zinc had similarities to the Mississippi Valley lead deposits, but athough the reefal nature of the Devonian sediments was known, it was not until the publication of Geological Survey of Western Australia Bulletin 118 "Devonian reef complexes of the Canning Basin, Western Australia" (Playford and Lowry, 1966) that it became generally apparent that the geological environment of the Lennard Shelf had similarities to geology in the region of the major Mississippi Valley lead-zinc deposits of North America.

As a result of exploration to date, several deposits of carbonate-hosted, lead-zinc sulphides have been discovered in the Kimberley region, including the Cadjebut deposit presently being mined by BHP and Billiton Australia.

SCOPE OF THE PRESENT STUDY

The present study describes the geology of a few carbonate-hosted, lead-zinc prospects in the Kimberley region, *i.e.* Wagon Pass, Blendevale (also known as Pillara), and Sorby Hills; and includes a reappraisal of the geology of the main Narlarla orebody (the No. 2) based on investigations following dewatering of the mine.

The study includes an introductory description of the geology of the Kimberley region and a review and discussion of current thinking on the genesis of carbonate-hosted, lead-zinc deposits.

For each deposit, the structural and stratigraphic setting, host lithologies, ore mineralogy, ore textures and ore paragenesis are described. Characteristics of the prospects are compared and contrasted, and recommendations for future exploration programs are outlined.

AIMS OF THE PRESENT STUDY

The present investigation was undertaken in conjunction with three other research projects concerning: the diagenetic history of the Devonian reef complexes; fluid inclusion and stable isotope studies of sulphide mineralization in the Canning and Bonaparte Basins; and stratigraphic studies of these same basins based on palynology. These projects were carried out by Dr C. Kerans (a WAMPRI senior research fellow), Dr I. Lambert and co-workers (at the Baas Becking Laboratory in Canberra), and Miss K. Grey (GSWA), respectively.

The integrated objective of this research is to shed light upon geological processes, which relate to the formation of lead-zinc ore deposits and accumulation of petroleum in the Canning and Bonaparte Basins.

The principal objective of the present study is to integrate all available geological data for each of the lead-zinc prospects under review, with the author's petrological and mineralogical studies to compare and contrast the ore-forming process at each.

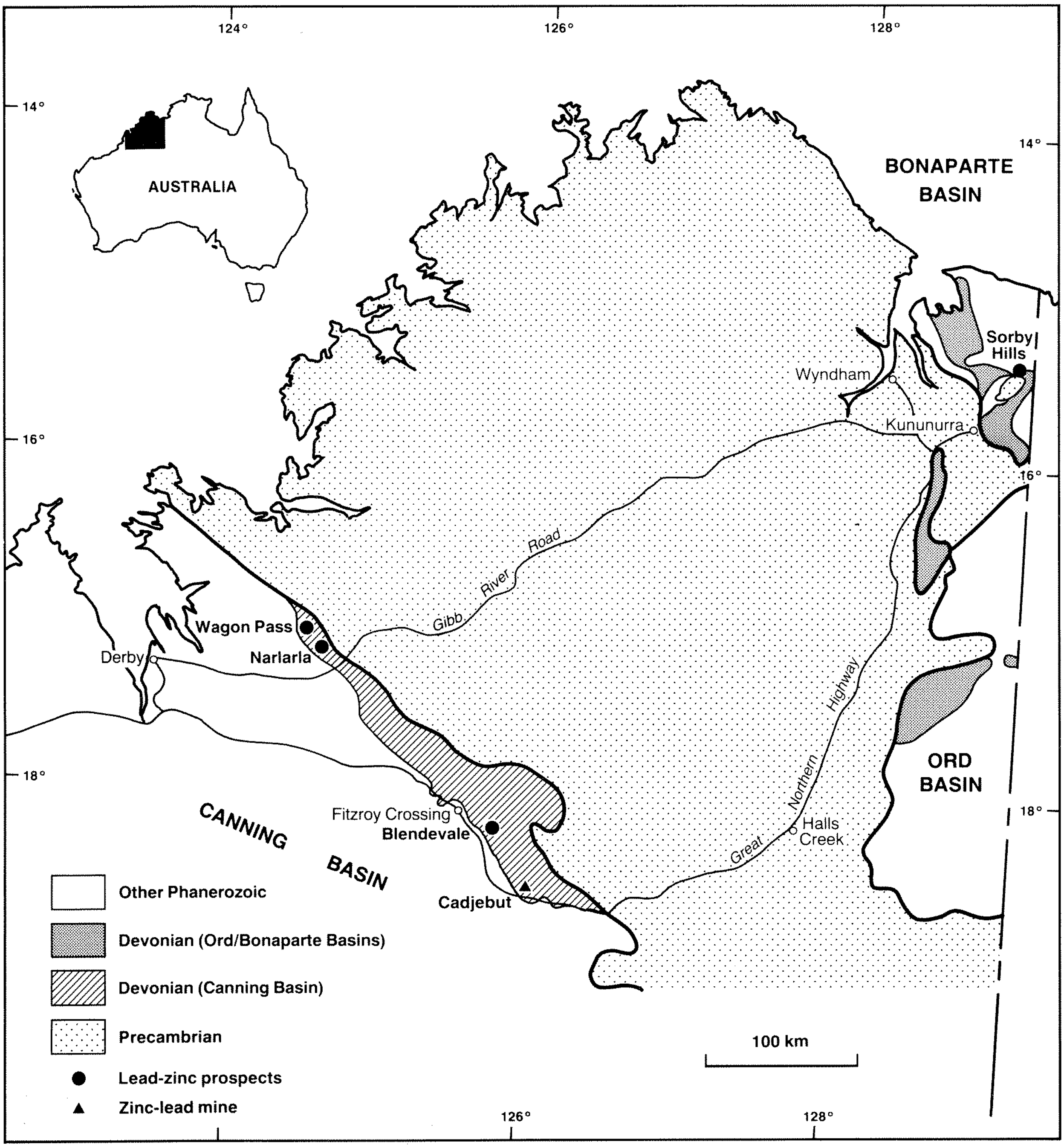


Figure 1. Location of the principal carbonate-hosted, lead-zinc prospects in the Kimberley region.

LOCATION OF THE PROSPECTS CONCERNED

Wagon Pass, Narlarla and Blendevale are located on the northern margin of the Canning Basin; the former two near Derby, the latter close to Fitzroy Crossing; whereas Sorby Hills lies just northeast of Kununurra in the Bonaparte Basin (Fig. 1). Wagon Pass and Narlarla are accessible from Derby, via 140 km of the Gibb River Road then a station track from Napier Downs heading northwest along the limestone ranges. Blendevale lies in the Limestone Billy Hills, approximately 11 km by track from an exit on the Great Northern Highway, itself 43 km south of Fitzroy Crossing. Sorby Hills may be reached from Kununurra via 45 km of bitumen and dirt road.

METHODS USED AND SOURCES OF INFORMATION

Each of the principal prospects was visited during the 1982 and 1983 field seasons, and representative sample suites of the mineralization at each were collected for petrological studies. During 1983 the Narlarla pit, marking the all but mined-out Narlarla No. 2 orebody, was dewatered and a thorough sampling and mapping program was completed.

An extensive mineralogical and petrological examination of sulphide and host-rock samples was carried out on approximately 500 polished thin sections. Emphasis was placed upon ore mineralogy and ore-gangue textural relationships to determine mineral paragenesis.

The geological information pertaining to the principal prospects concerned has been compiled essentially from unpublished company reports held by GSWA. Discussion of their genesis incorporates research results of WAMPRI, Baas Becking workers, and the GSWA, which are duly referenced.

GEOLOGICAL SETTING

The Bonaparte and Canning Basins of northwestern Australia are intracratonic basins which are separated by the Proterozoic Kimberley Block (Fig. 2). They are believed to have originated as failed arms oriented northwest-southeast during the intracratonic rifting, which gave rise to the Tethys (Veevers, 1976). The basins were initiated in Late Proterozoic to Early Cambrian times, and contain sediments of Middle Cambrian to Cretaceous age. A further period of major rifting was associated with the break-up of Gondwana in the Mesozoic. The descriptions given are taken mainly from Playford and others (1975), Purcell (1984), Playford (1980, 1984), and Mory and Beere (1988).

CANNING BASIN AND ITS SUBDIVISIONS

The onshore Canning Basin covers an area of 430 000 km^2. It contains sediments of Ordovician to Cretaceous age (Yeates and others, 1984) which comprise a maximum aggregate thickness of about 10 000 m, resting unconformably on Precambrian basement. A thin cover of Tertiary rocks is also present.

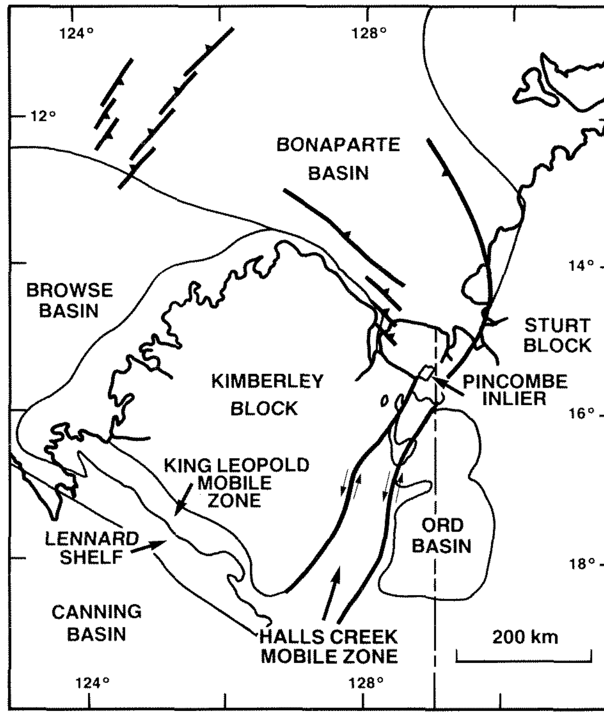


Figure 2. Regional tectonic setting of the Bonaparte Basin (from Laws, 1981).

The principal tectonic subdivisions of the onshore Canning Basin are: the Lennard Shelf; Fitzroy Trough; Broome Platform; Kidson Subbasin and Anketell Shelf (Fig. 3); with the first two units being the main areas of concern in this report. The Lennard Shelf (Fig. 4) is an area of relatively shallow basement, lying along the northern margin of the basin and containing up to 3 000 m of sediments which thicken basinward. It contains the thick, well preserved Devonian reef complexes, which host the lead-zinc deposits at Wagon Pass, Narlarla, and Blendevale prospects. The adjacent Fitzroy Trough (Fig. 4) is a deep fault-bounded depression filled with over 10 000 m of Palaeozoic Mesozoic sediments. The northern trough margin is formed by the Pinnacle Fault and the southern boundary by the Fenton Fault.

STRATIGRAPHIC-TECTONIC HISTORY OF THE NORTHERN CANNING BASIN

The Canning Basin contains a complex stratigraphic succession which may be related to three major phases of tectonic history (Brown and others, 1984): development of an intracratonic depression in the Early to Middle Ordovician; rifting along a northwesterly axis in the Silurian to Early Carboniferous; and rifting in post-Early Carboniferous related to the break-up of Gondwana.

During the initial phase of basin development approximately 1 000 m of Ordovician sediments, including siltstone, shale, carbonates (dolomitized in parts), arkosic sandstone and conglomerate, accumulated within an extensive, epeiric sea established over a broad intracratonic depression.

In Silurian to Middle Devonian times a broad elongate arch emerged, possibly due to thermal upwarp. A thick evaporitic sequence (the

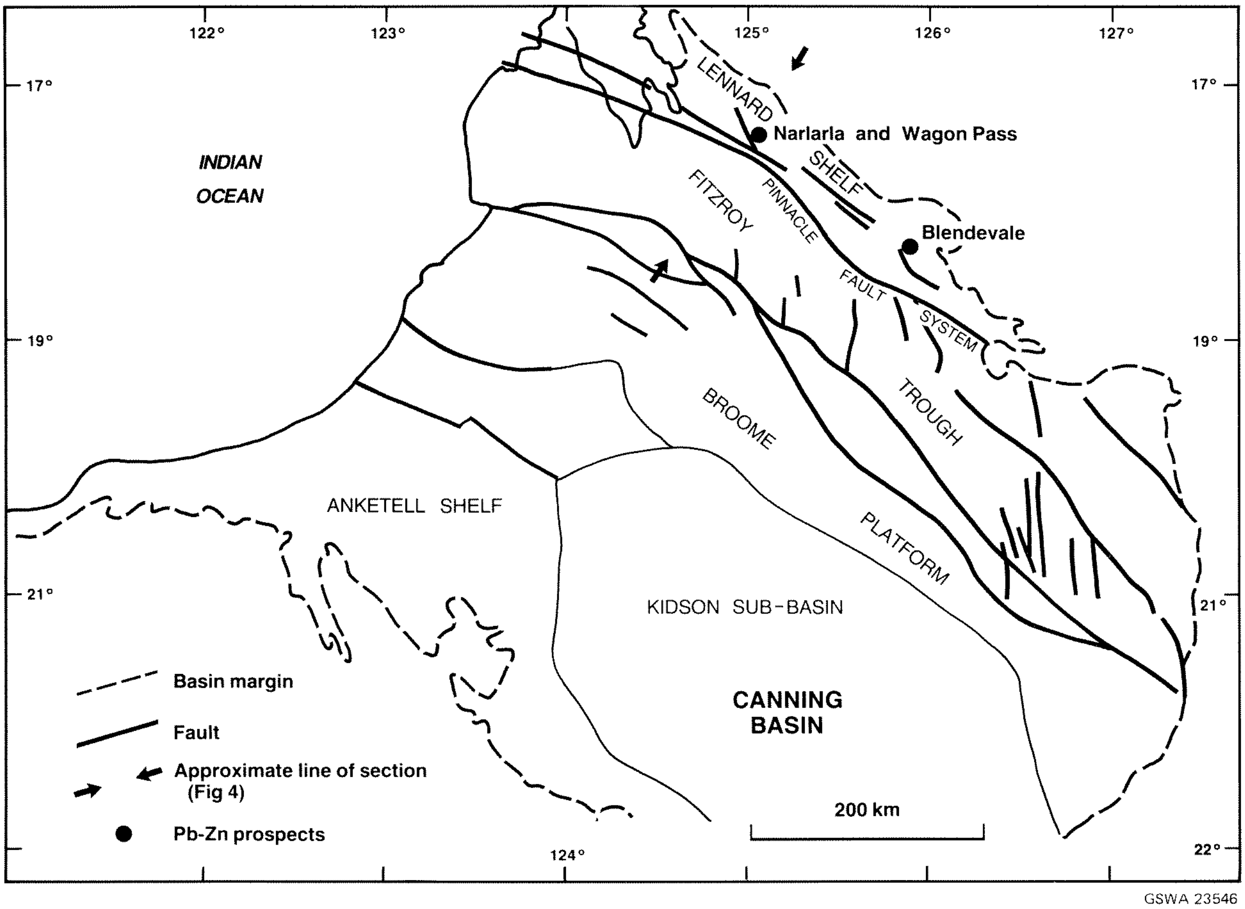


Figure 3. Tectonic elements of the Canning Basin (modified from Yeates and others, 1984).

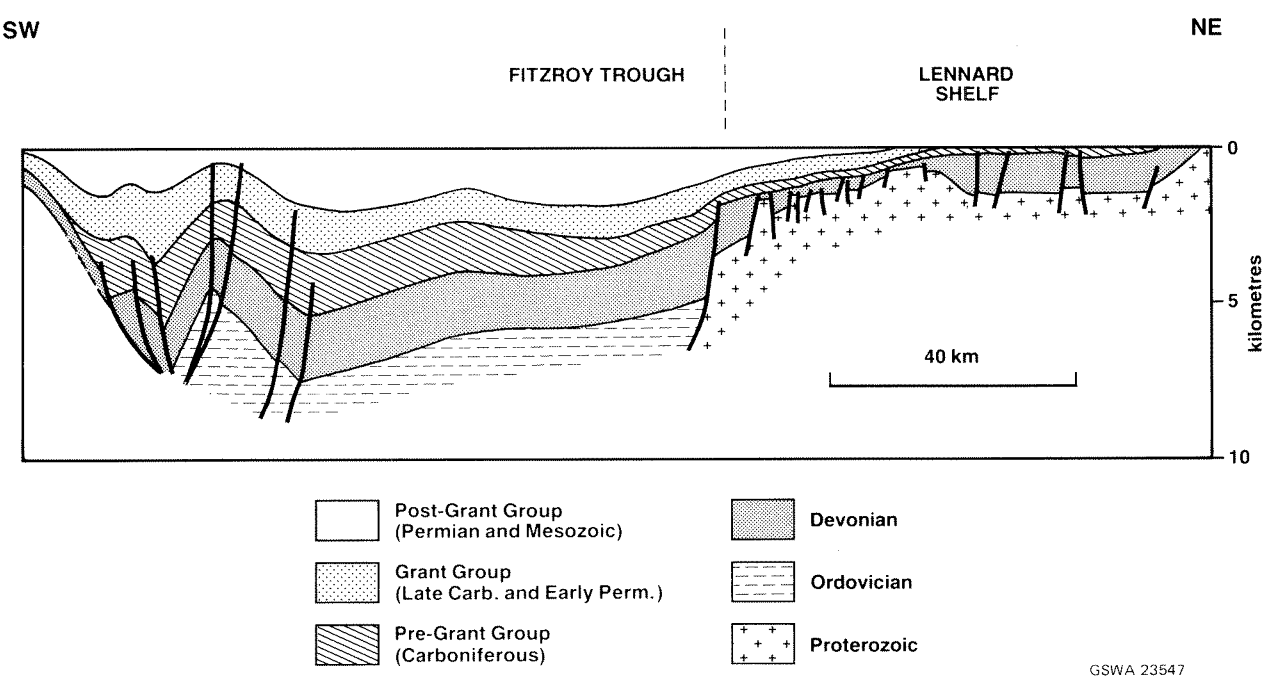


Figure 4. Generalized cross section of the northern part of the Canning Basin (modified from Brown and others, 1984).

Caribuddy Group) developed within a crestal graben structure which was a precursor to the Fitzroy Trough.

Between the early Givetian and Tournaisian the Fitzroy Trough formed as a result of approximately 50 km of crustal extension. A deep-marine trough resulted, which filled a symmetrical rift bounded by shallow-marine shelves. On the northern shelf, the Devonian reef complexes were developed during the Frasnian and Famennian.

By the latest Famennian, shallow-marine conditions were established and limestone, shale and clastic sediments of the Fairfield Group were laid down, unconformably, over the Devonian reefs. The Fitzroy Trough was infilled by 2 500 m of sediments, during a period of rapid subsidence with limited crustal extension (<5 km) in the Tournaisian to Namurian.

It has been suggested (Brown and others, 1984) that the latest Devonian to mid-Carboniferous period of rift development was accompanied by the emplacement of basic intrusives along the rift axes, which formed anticlinal structures in the sedimentary succession.

The subsequent history of the Canning Basin is dominated by the evolution of Australia's northwest passive margin during the break-up of Gondwana. Initially a period of uplift and erosion occurred in Westphalian to Stephanian times, which was followed by deposition of the Grant Group (Upper Carboniferous to Lower Permian), a glacigene unit consisting largely of sandstone deposited on a mildly faulted and tilted, low-relief unconformity surface which, over the Devonian reefs, was karstic. A suite of mafic intrusives occurring along the northwestern margin of the Canning Basin (along an east-west trending zone) is apparently Permian in age and genetically related to the subsequent break-up of Gondwana (Reeckeman and Mebberson, 1984).

From Early Permian to Late Triassic, shales and sands, up to 2 500 m thick and of regional extent, were deposited in the Fitzroy Trough. Between Late Triassic and Early Jurassic times, a regional, erosional unconformity marked the onset of compressional tectonism. During gradual subsidence (concurrent with continental break-up in the offshore Canning Basin area in post-mid to Late Jurassic) a thick cover of Jurassic and younger sediments was deposited.

STRATIGRAPHY AND LITHOLOGY OF THE DEVONIAN REEF COMPLEXES

The Wagon Pass, Narlarla and Blendevale lead-zinc sulphide prospects are hosted by the Devonian reef complexes of the Lennard Shelf. The growth of these reefs, in the Middle to Late Devonian, followed a period of block faulting of the Lennard Shelf related to the onset of tensional tectonism that formed the Fitzroy Trough. This faulting generated a rugged topography with local relief of several hundreds of metres along the mainland shore of the Proterozoic Kimberley hinterland. Reefs grew around the shoreline and colonized islands of Proterozoic and Ordovician rocks (Playford, 1980).

The Devonian reef complexes developed as flat-topped, reef-rimmed limestone platforms, flanked by marginal slopes which descended to the surrounding basin floors in water depths of tens to hundreds of metres (Playford, 1980). These three, broad, physical subdivisions constitute the major lithofacies of the Devonian reef complexes. The stratigraphic nomenclature of the complexes together with a diagrammatic illustration of their development through time are shown in Figure 5.

Platforms existed both as extensive bodies covering hundreds of square kilometres, and as small platform atolls and pinnacle reefs. During the Givetian and Frasnian, stromatoporoids, cyanobacteria, and corals acted as the main platform-building organisms. In the Famennian, cyanobacteria alone were dominant. The platforms were largely stromatoporoid and coral biostromes in the Givetian and Frasnian, and fenestral (microbial) limestone in the Famennian.

Marginal-slope deposits accumulated on depositional slopes in front of the platforms and consisted mainly of platform-derived debris. Depositional dips were high, up to 35 – 40° and greater where sediments were microbial-bound.

Sediments of the basin facies were deposited horizontally. They consisted largely of shale and siltstone, or sandstone and conglomerate, interbedded with thin beds of pelagic limestone. Some Frasnian basinal shale units are dark and rich in organic matter, but those of late Frasnian to middle Famennian are red and lack a significant organic component.

Thick sections of conglomerate and sandstone interfinger with the Devonian reef complexes in some areas, adjoining the rocks of the Halls Creek Province. These are believed to be torrential deposits shed from active fault scarps. They are intercalated with all facies of the complex and range in age from Frasnian to Famennian.

Conditions favourable for reef growth ended in the late Famennian and the reefs were covered by interbedded shale, sandstone, and shelf limestone of the Fairfield Group.

BONAPARTE BASIN AND ITS SUBDIVISIONS

The Bonaparte Basin is a northwest-trending basin of Phanerozoic sediments, covering parts of Western Australia, the Northern Territory, and the adjacent offshore areas. The basin has an area of approximately 270 000 km^2, of which 8 000 km^2 lies onshore in Western Australia (Fig. 6), and contains a total stratigraphic thickness of about 20 000 m. The sedimentary sequence includes Phanerozioc rocks of all ages except the Silurian; it is entirely Palaeozoic onshore (Fig. 7) with Mesozoic and Cainozoic rocks in the offshore part of the basin.

The southern part of the basin is bounded by two Precambrian basement highs: the Sturt Block to the east; and the Kimberley Block to the west (Fig. 6). The eastern margin is a continuation of the northeasterly trending Halls Creek Mobile Zone (Fig. 6). Periodic rejuvenation of faults along

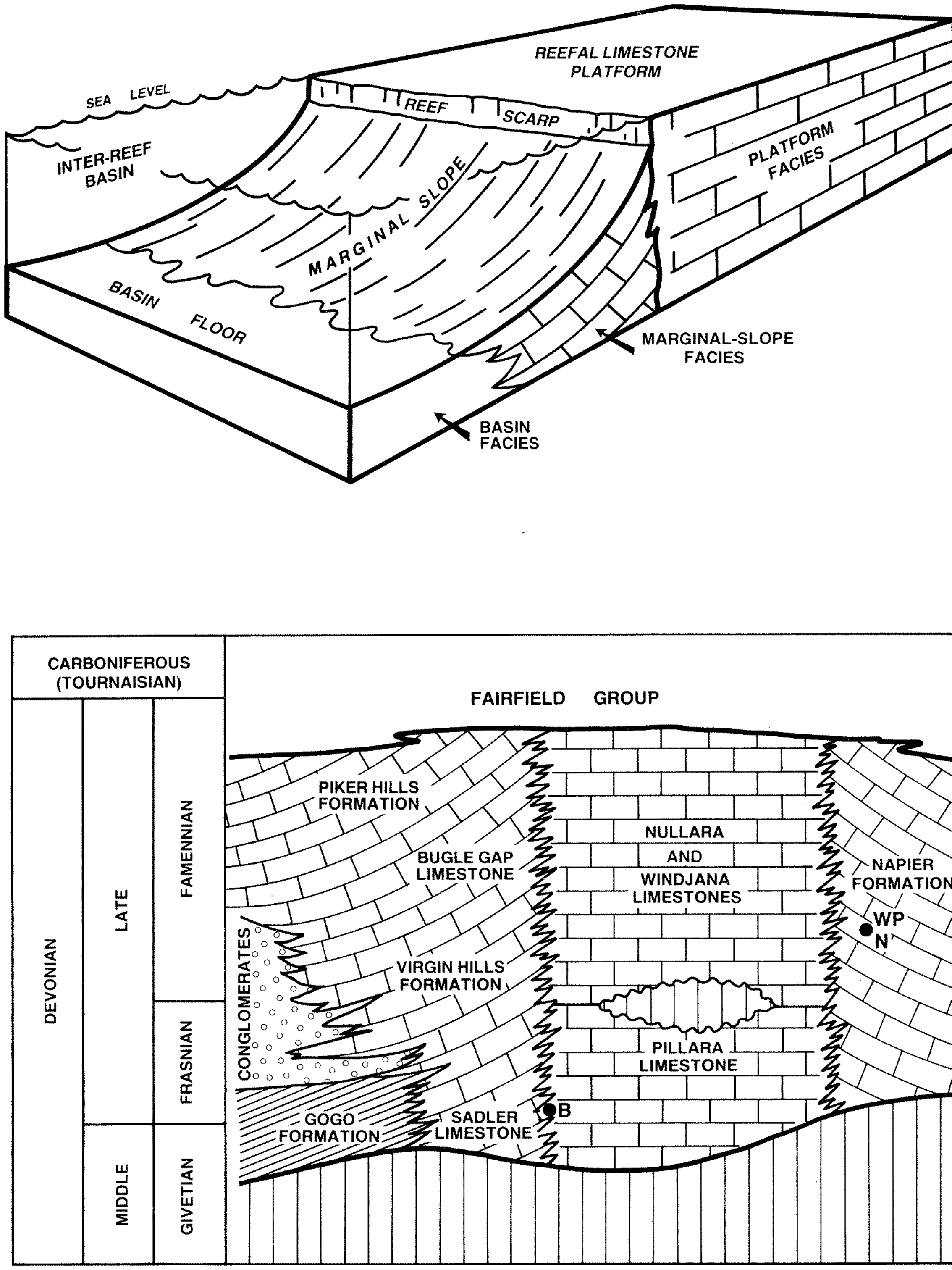


Figure 5. General morphology and major facies of the Devonian reef complexes through time showing the stratigraphic location of Wagon Pass (WP), Narlarla (N) and Blendevale (B), (modified from Playford, 1980).

this trend played an important role in controlling deposition in Palaeozoic times (Laws and Brown, 1976).

In the south, the basin is divided by the Pincombe Ridge (a major, northeast-plunging palaeo-high exposed at the surface in the Pincombe Inlier, Figs 6 and 7) into the Carlton Shelf, to the west and the Burt Range Shelf to the east (Mory and Beere, 1988). These shelves are areas of relatively shallow basement containing up to 3 000 m of sediment, which thickens basinwards into the Petrel Sub-basin (Fig. 6).

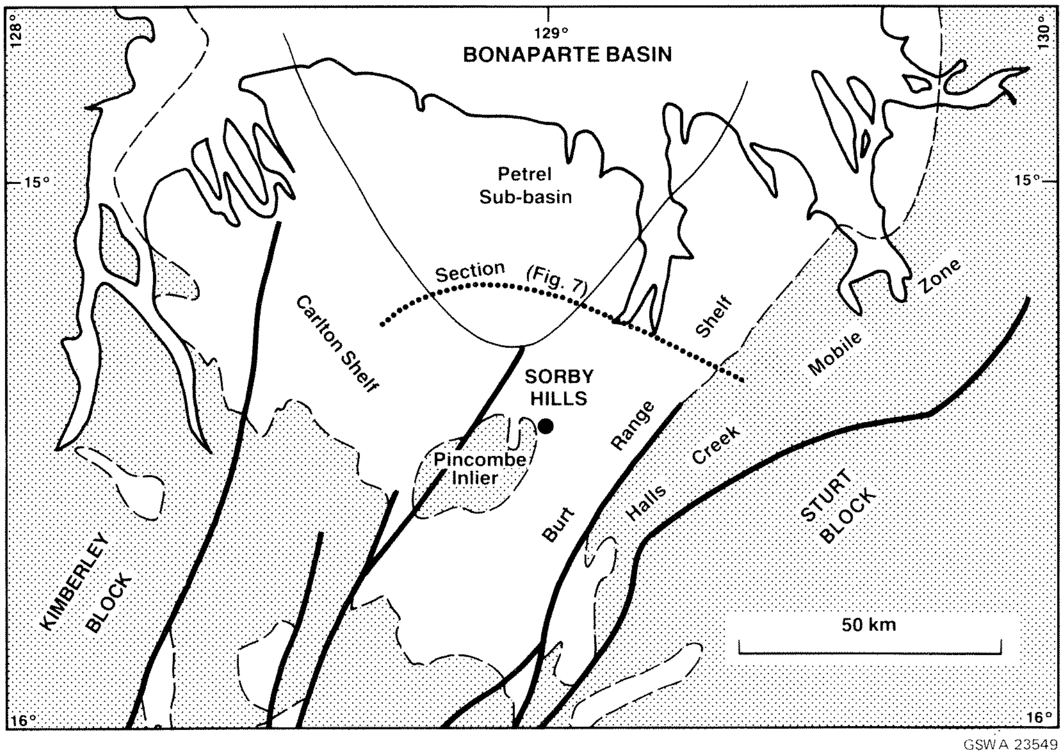


Figure 6. Tectonic subdivisions of the onshore Bonaparte Basin.

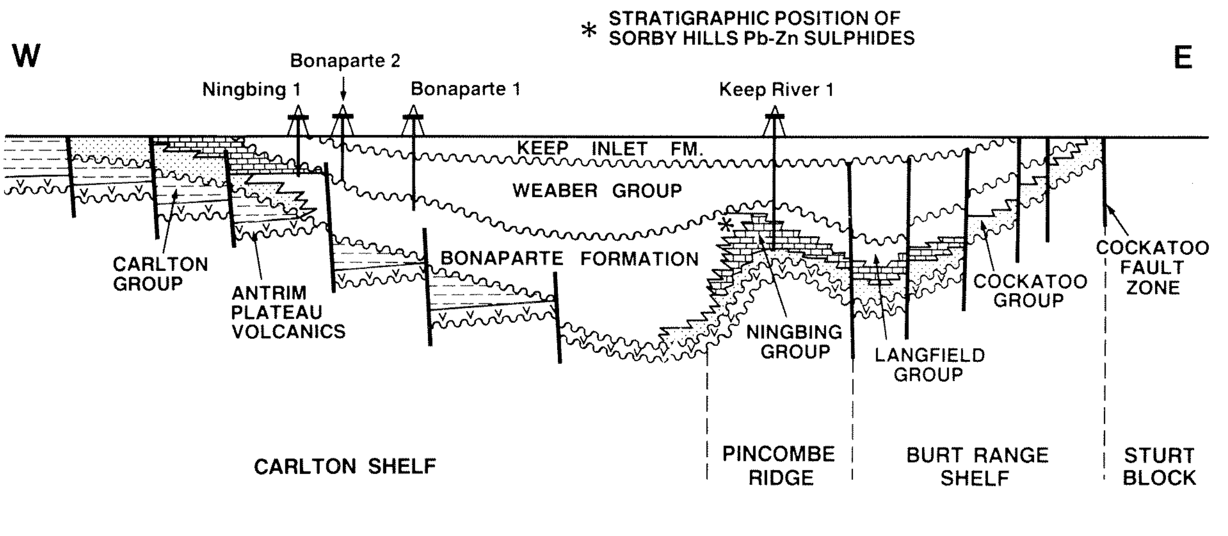


Figure 7. Generalized cross section of the onshore Bonaparte Basin (from Laws, 1981).

STRATIGRAPHIC-TECTONIC HISTORY OF THE ONSHORE BONAPARTE BASIN.

In the Bonaparte Basin the initiation of extensional tectonism and basin subsidence is marked by the extrusion of continental, tholeiitic basalts (the Antrim Plateau Volcanics) in the Early Cambrian.

The earliest sediments of the onshore portion of the basin are shallow and marginal-marine clastics and minor carbonates of Middle Cambrian to Early Ordovician age (Carlton Group) which reach a maximum thickness of 1 300 m. From Middle Ordovician to Middle Devonian times, a break in sedimentation occurred on the marginal shelves (Veevers and Roberts, 1968). Towards the end of this hiatus, a thick evaporite sequence of Late Silurian to Early Devonian age formed in the central graben of the Bonaparte Basin (Petrel Sub-basin). In the Devonian this graben may have been a crestal downfaulted zone of the upwarped crust (*cf.* the Caribuddy Group of the Canning Basin).

The major period of crustal extension during the Frasnian to Tournaisian, produced a deep marine trough bounded by the Carlton and Burt Range

Shelves. In the Frasnian, sedimentation recommenced on the marginal shelves, with deposition of sandstone and conglomerate of the Cockatoo Group derived from active fault scarps. In the Famennian, reefal carbonates of the Ningbing Group developed on the shelf areas. During the Tournaisian, sediments of the Langfield Group were laid down prior to a period of faulting and folding. These sediments graded into finer grained clastics and minor sands of the Bonaparte Formation, deposited in deeper water.

In the Visean a thick sequence of siltstone and mudstone (2 000 m) with minor sandstone interbeds (Milligans Formation) was deposited over most of the onshore Bonaparte Basin. The palaeoshoreline at this time was situated some distance to the east and south of the present basin limits and major deepening of the basin and transgression occurred (Laws and Brown, 1976). This sedimentation was followed by basinal infill by prograding deltas (Weaber Group).

Following deposition of the Weaber Group a period of broad-scale folding led to widespread erosion prior to deposition of the glacial, continental and shallow-marine facies of the Permian Keep Inlet Formation.

During the Triassic to mid-Jurassic, crustal upwarping resulted in tensional stress, major block-faulting, and the erosion of older sediments. Tensional stress was finally relieved in the mid-Jurassic by the onset of continental break-up, with the development of regional subsidence and open-marine conditions during the Cretaceous.

FAMENNIAN AND TOURNAISIAN SEDIMENTARY ROCKS OF THE CARLTON AND BURT RANGE SHELVES

The Famennian sediments of the onshore Bonaparte Basin are similar to the Devonian reef complexes of the Canning Basin, and contain indications of lead-zinc sulphide mineralization. The Tournaisian sedimentary sequence of the Burt Range Shelf is host to the Sorby Hills lead-zinc prospect and is therefore of particular interest.

Sedimentary rocks of Famennian age are mostly restricted to the Carlton Shelf, where a Famennian reef complex (Ningbing Group) crops out extensively along the basin margin. Although this complex is slightly younger than the Frasnian to Famennian carbonate complexes of the Canning Basin, it may be part of a semi-continuous belt on the northern and western margins of the Kimberley Block (Veevers and Roberts, 1968).

Back-reef sediments, which consist of peloidal, oolitic and oncolitic calcarenites, form the bulk of Famennian outcrops on the Carlton Shelf. The platform-margin subfacies comprises a thin reef of algal boundstone, dominated by *Girvanella* and *Sphaerocodium*, and the marginal-slope outcrops consist of pebbles and boulders of back-reef and reefal limestone (Mory and Beere, 1988). Sandy, back-reef subfacies of the Buttons Formation is well developed in the southwestern and southeastern portions of the basin. The reef complex also extends along the Pincombe Ridge (Fig. 7) as evidenced by the Keep River 1 and Weaber 1 wells (Laws, 1981).

Sediments of Tournaisian age (the Langfield Group) rest on the Ningbing Group, conformably on the Burt Range Shelf and disconformably on the Carlton Shelf (Mory and Beere, 1988). The section includes alternating sandstone and limestone of the Burt Range Formation, Enga Sandstone, Septimus Limestone, and the Zimmermann Sandstone, which (except for the Burt Range Formation) are present only on the Burt Range Shelf.

The Burt Range Formation comprises limestone, sandy limestone, and minor sandstone, deposited mainly in a subtidal to intertidal environment. These sediments are cyclic in depositional style.

GEOLOGY OF MISSISSIPPI VALLEY-TYPE (MVT) DEPOSITS

This section describes the characteristics, geological setting and genesis of Mississippi Valley-type (MVT) deposits, with which the Kimberley prospects appear to have the greatest affinity. However, given the lack of any previous formal classification, this section also describes other carbonate-hosted, lead-zinc deposits to which the Kimberley prospects may be compared.

Mississippi Valley-type stratabound, discordant, sulphide deposits belong to the broad class of sediment-hosted, stratabound orebodies of copper, lead, and zinc that are distinguished from volcanogenic base-metal sulphide ores by a lack of associated volcanism (Gustafson and Williams, 1981). In addition to those of the MVT, the sediment-hosted base-metal deposits include the following: deposits of stratiform copper; stratiform, shale-hosted, lead-zinc; stratabound, sandstone-hosted lead-zinc; and discordant, carbonate-hosted, lead-zinc (copper) that are spatially and possibly genetically related to shale-hosted, lead-zinc orebodies (Table 1).

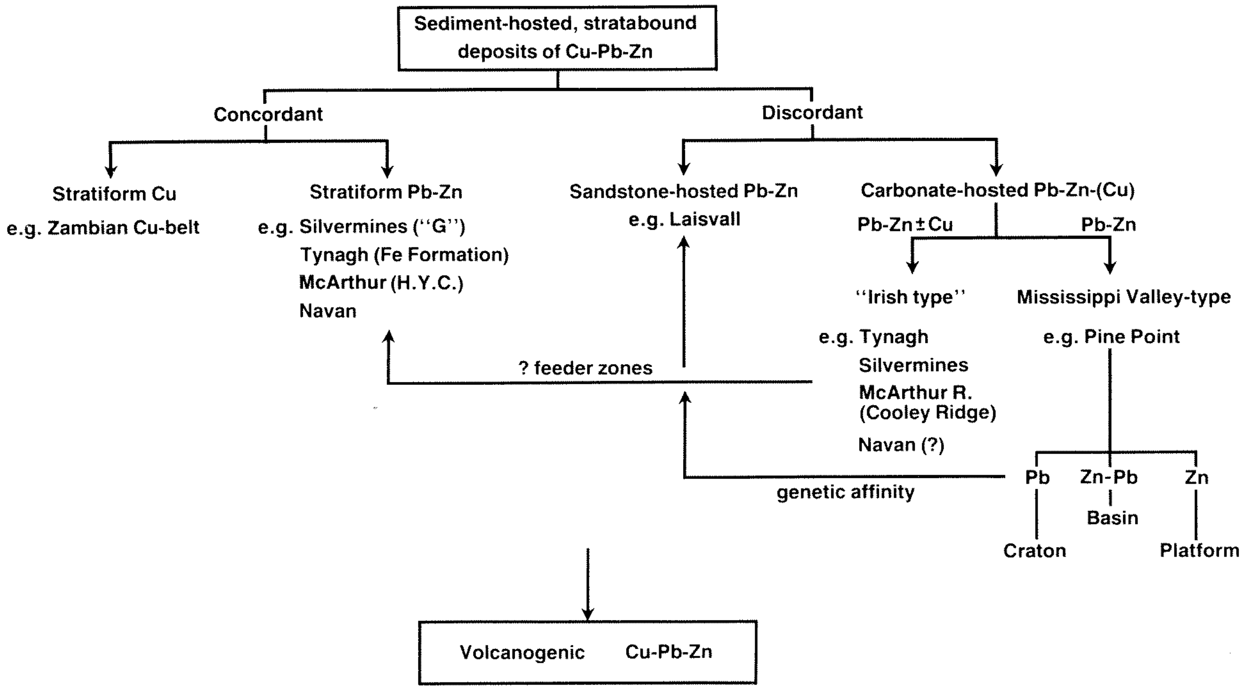
Mississippi Valley-type deposits have many similarities to the last mentioned group of ores and it seems likely that the two groups are gradational in character and possibly formed by similar processes (Gustafson and Williams, 1981; Badham, 1981).

SIZE, DISTRIBUTION AND PREVIOUS STUDIES

Mississippi Valley-type deposits have provided much of the lead and a large part of the zinc mined in the world. Individual mines are usually of a low tonnage (1 x 10^6 Mt to 10 x 10^6 Mt of 10% lead plus zinc). However, districts commonly comprising several mines are comparable in tonnage to sediment-hosted stratiform orebodies of lead and zinc such as McArthur River, H.Y.C. (Fig. 8).

Research on these deposits has been continuous for over 130 years and a voluminous literature exists throughout the world on aspects of the geology of MVT deposits. Significant summary articles include: Anderson (1978); Anderson and MacQueen (1982); Heyl and others (1974); Ohle (1959, 1980); Brown (1967); Cathles (1981); White (1974); and Wolf (1976, 1981).

TABLE 1. SUBDIVISIONS OF SEDIMENT-HOSTED, STRATABOUND DEPOSITS OF Cu-Pb-Zn (AFTER GUSTAFSON AND WILLIAMS, 1981) AND A SCHEME FOR THE SUBDIVISION OF MISSISSIPPI VALLEY-TYPE DEPOSITS (PROPOSED BY SANGSTER, 1983)



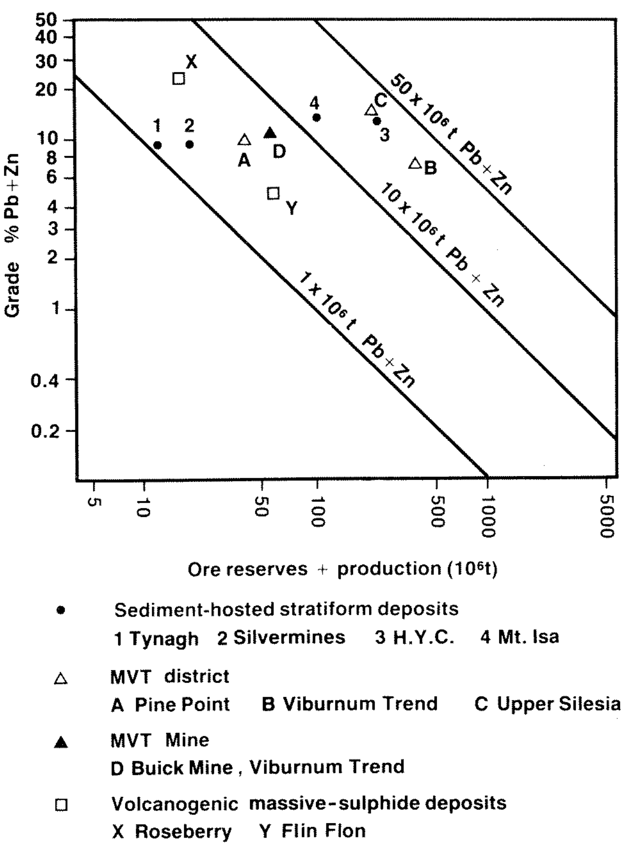


Figure 8. Size and grade of sediment-hosted, lead-zinc deposits compared with some MVT districts and mines and two examples of volcanogenic massive sulphide deposits (modified from Gustafson and Williams, 1981).

Important early studies of American examples established that the orebodies were: clearly epigenetic (Winslow, 1894); deposited from brines (Newhouse, 1932); deposited at temperatures near 100°C (Newhouse, 1933); and isotopically incompatible with a magmatic source (Ecklemann and Kulp, 1959).

However, it was not until the mid-1960s that these facts were unified into the 'sedimentary-diagenetic' or 'basin evolution' genetic model, proposed for the Pine Point orebodies of Canada (Beales and Jackson, 1966; Jackson and Beales, 1967). The generalized model suggests that solutions, squeezed out of a sedimentary basin, migrate along a basal aquifer and precipitate their metals near the surface, due to cooling or mixing with other solutions (Fig. 9).

Most current discussions on the genesis of MVT orebodies accept the general approach of this model, but have also considered in more detail the

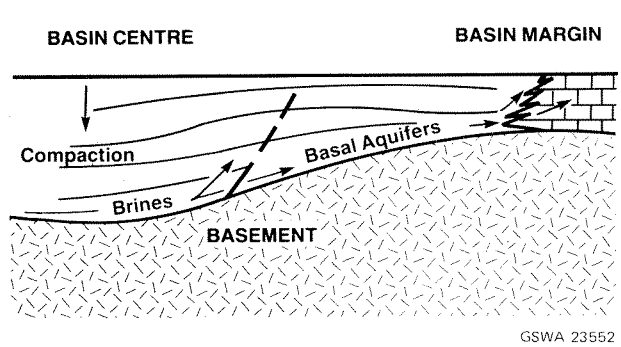


Figure 9. Diagrammatic illustration of the formation of MVT deposits.

A61482-2

following aspects: the flow patterns of ore fluids; the timing of ore deposition; and the mechanism of sulphide precipitation. Some recent significant research data are presented in the following publications: Cathles and Smith (1983); Sverjensky (1981, 1984); Wu and Beales (1981); Olson (1984); Rhodes and others (1984); Akande and Fertilli (1984); Walker and others (1983); and the proceedings of an international conference on MVT deposits held in Rolla, Missouri (1983).

GEOLOGICAL SETTING AND CHARACTERISTICS

(a) Mississippi Valley-type deposits occur in carbonate rocks (generally dolomites) along basin margins, or around basement highs within basins, also in unmetamorphosed and generally tectonically undisturbed rocks.

(b) Ore deposits of a similar character tend to occur in clusters which may be distributed over hundreds of kilometres (Ohle, 1967).

(c) The stratigraphic evidence in undisturbed platformal areas suggests shallow depths of formation (a few 100's to about 1 000 metres).

(d) Within platform sequences, deposits are often localized along unconformity or facies boundaries.

(e) Ores have a relatively simple mineralogy; usually galena and/or sphalerite, with minor iron sulphides (marcasite and/or pyrite). Chalcopyrite is not uncommon but is usually minor. Gangue minerals usually include barite and/or fluorite.

(f) The predominant trace elements in the ores are Co, Ni, Cd, In, Ge, Ga, and Ag (Ohle, 1967) although galena is a low-silver variety and sphalerite is low in iron.

(g) The ores are clearly epigenetic, commonly filling pre-existing pore spaces developed in breccias of various types and occupying other post-lithification features such as fractures. The development of pre-existing pore space is apparently a prerequisite for the formation of an economic deposit (Callahan, 1967).

NATURE OF ORE FLUIDS

Studies of fluid inclusions (Roedder, 1968a, 1976, and 1979) have established that in MVT deposits the ore fluids had temperatures generally in the range of 80 – 150°C (with a maximum near 200°C) and were highly concentrated Na-Ca-Cl brines with associated organic materials (kerogen or bitumen).

Isotopic studies show that sulphur, although of wide-ranging values, is generally heavy. This establishes a crustal (ultimately sea water) origin, involving later sulphate reduction (Ohmoto and Rye, 1979; Sverjensky and others, 1979).

GENESIS OF MISSISSIPPI VALLEY-TYPE (MVT) DEPOSITS

The generally held concept of Mississippi Valley-type ore formation is the 'basin-brine model' which proposes that hot saline solutions (similar to oil-field brines) migrate out of sedimentary basins along aquifers, and eventually form ore deposits in porous, marginal, carbonate rocks (Fig. 9). Fluids are driven by sediment compaction and derive their metals through leaching of the host sediments by brines. Within this working hypothesis there are many areas of controversy concerning the details of the following: time of ore formation; source of metals and sulphur; flow paths and the duration of flow; and mechanism of sulphide precipitation.

Of these questions, Anderson and MacQueen (1982), consider timing is perhaps the most crucial. For most deposits the age of ore formation can only be given as post-depositional and although some recent studies (Wu and Beales, 1981; York and others, 1980) have indicated the possibility of applying palaeomagnetic and K-Ar dating methods to MVT ores, these new research directions are in their infancy. The exact role of evaporites, as suggested by high fluid-inclusion salinities and the contribution of organic matter as a potential supplier of H_2S in carbonate rocks, poses further important unresolved questions. In recent publications, the ore-fluid flow paths and chemical evolution of the ore fluid have been described by Sverjensky (1984), while the genesis and duration of ore-forming flow have been discussed by Cathles and Smith (1983).

The mechanism of sulphide precipitation has also been the subject of controversy. In one hypothesis (a "mixing" model), a basin-derived brine transported base metals and precipitated sulphides when it intersected a second fluid, which was a source of reduced sulphur (Beales and Jackson, 1966). A second scheme (a "reduced sulphur" model), proposes that reduced sulphur (as H_2S) and base metals were transported together in the same solution, at low concentrations, and that the cause of precipitation could be neutralization, cooling, or dilution (Sverjensky, 1981).

RELATIONSHIP TO 'IRISH-TYPE' SEDIMENTARY EXHALITE DEPOSITS

A second group of carbonate-hosted, lead-zinc deposits shows a number of similarities to MVT deposits, such as portions of the deposits at Tynagh and Silvermines in Ireland (Taylor and Andrew, 1978; Russell, 1975) and the Cooley and Ridge orebodies of the McArthur River area (Williams, 1978). The Irish deposits and those at Cooley and Ridge are distinguished from MVT deposits by the following: the presence of a syngenetic component of the mineralization; a clear spatial and genetic relationship to growth faults and syntectonic debris flows; and a period of formation very early in the diagenetic history of the host sediments.

The ores in both MVT and Irish-type deposits are dominated by sphalerite and galena. However, Irish-type deposits have a greater proportion of pyrite and higher contents of Sb, Cu, Ag and Cd, resulting in the presence of minerals such as tennantite and tetrahedrite.

It has been postulated that the ore fluids which formed the discordant portions of the Irish-type and McArthur River deposits were expelled from basins during sediment compaction, in a manner similar to that proposed for MVT deposits (Walker and others, 1983; Badham, 1981). In the case of the Irish-type deposits it is envisaged that the 'normal' formational waters escaped on to the sea-floor, in regions characterized by high heat flow, growth faults, and local rapid subsidence and sedimentation (Badham, 1981), to generate a syngenetic ore deposit.

However, recent fluid-inclusion data (Samson and Russell, 1983) indicate that at Silvermines the ore fluids were at a relatively high temperature (150-220°C) and could not have originated from compacted basinal sediments, even assuming an anomalously high geothermal gradient.

Gustafson and Williams (1981) suggest that MVT deposits and other sediment-hosted, base-metal deposits (such as the 'Irish-type' mentioned above) may be formed by similar genetic processes. In the case of MVT deposits the fluids were derived from basins at lower temperatures, and carried less iron and barium, than those that formed the McArthur River, Mt Isa (Pb-Zn) and Irish deposits. Heating of fluids may be enhanced by magmatic intrusion in basins being actively deformed, with fluid flow aided by large faults.

THE WAGON PASS PROSPECT

LOCATION AND HISTORY OF EXPLORATION

The Wagon Pass lead-zinc prospect lies towards the northwestern limit of the exposed Devonian reef belt and approximately 12 km northwest (along strike) of the Narlarla orebodies (Fig. 10).

Discovery of the Wagon Pass sulphide mineralization occurred during an exploration program carried out within the Napier Range Joint Venture area. The partners—The Shell Company of Australia Ltd (Metals Division)* and BHP Minerals—recognized the potential in this area for deposits similar to those at Narlarla. Exploration began in 1978 with aerial photography, geological mapping, rock-chip geochemistry, and limited drilling, which (collectively) outlined several areas with surface and subsurface indications of mineralization.

Following the delineation of these target areas, a low-level, airborne magnetic survey was flown in 1979 to delineate basement structure. Several

* Now Billiton Australia.

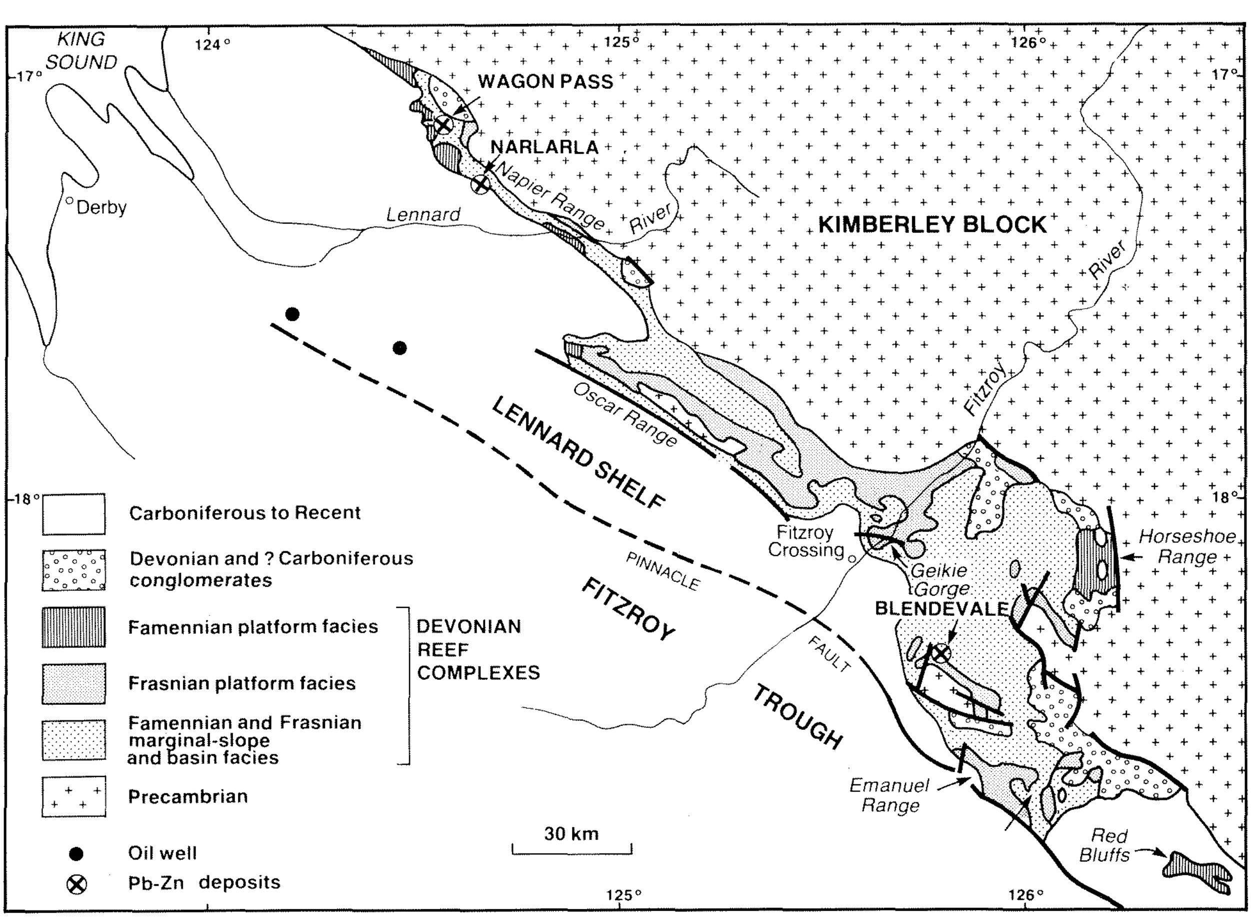


Figure 10. Generalized map of the Devonian reef belt of the northern Canning Basin (from Playford, 1984).

drill-holes were also completed as part of the follow-up program. Initial results were generally discouraging, but work continued and in 1980 a significant lead-zinc intersection was outlined in NRD 23, with 0.21% Cu, 6.1% Pb, 7.5% Zn and 31.5 g/t Ag at a depth of 200 – 240 m. Since then much detailed work has been carried out around this intersection, but to date the known tonnage of ore remains subeconomic.

GENERAL GEOLOGY

The Napier Range is a narrow strip (up to 15 km wide, averaging 7 km wide) of carbonate rocks that crop out from the Dingo Gap in the southeast to Limestone Spring in the northwest (Fig. 10). In the Wagon Pass area, the rocks form a rugged, flat-topped plateau rising to approximately 150 m above the level of the surrounding plains. The main lithologies that crop out in the vicinity in-

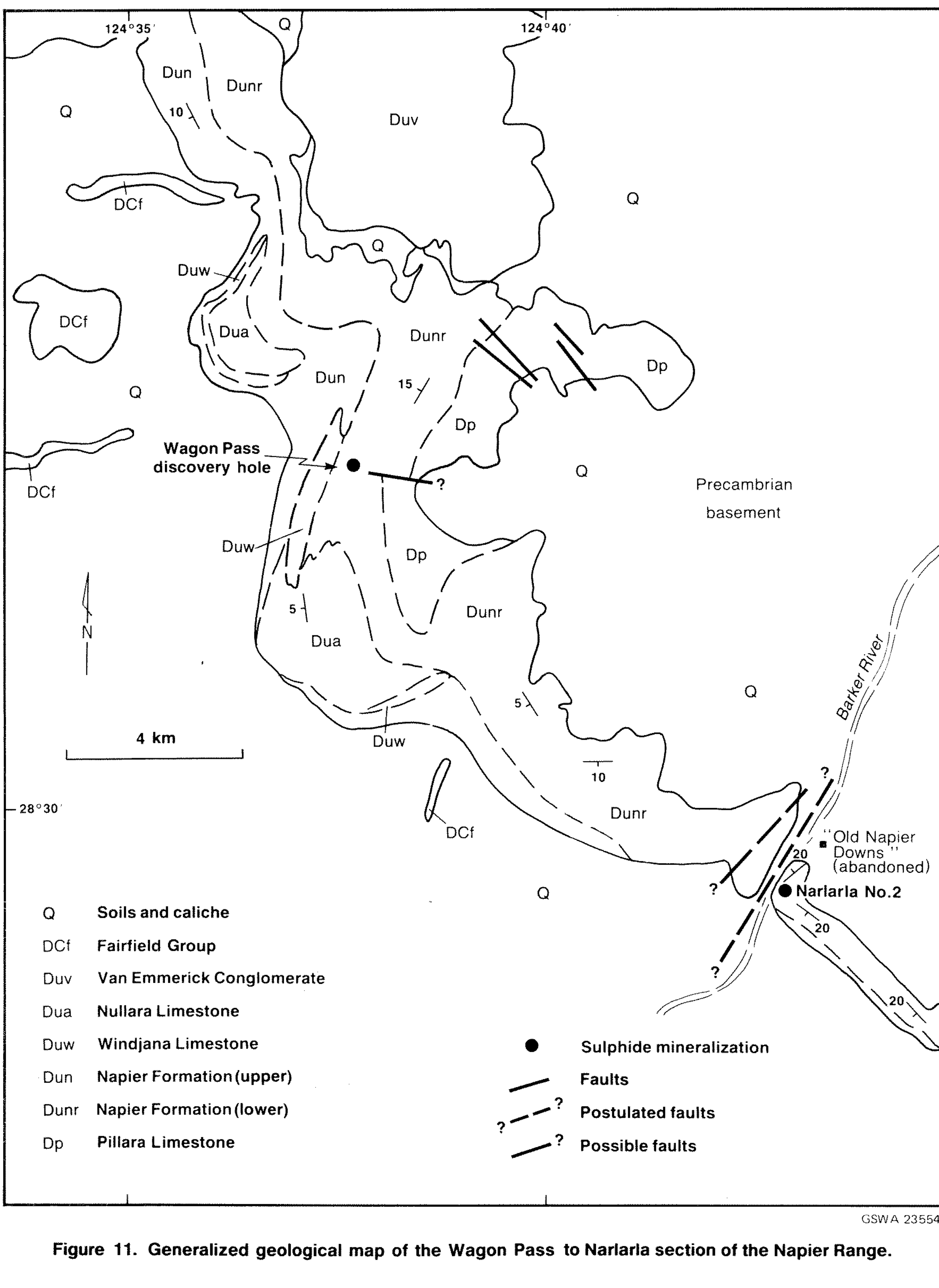


Figure 11. Generalized geological map of the Wagon Pass to Narlarla section of the Napier Range.

clude: the Pillara Limestone (Frasnian platform facies); the Napier Formation (Frasnian-Famennian marginal-slope facies); the Windjana Limestone (Famennian reef sub-facies); the Nullara Limestone (Famennian back-reef) and intercalated Devonian conglomerates units (Figs 5 and 11). Together these units form a northerly trending outcrop, approximately 8 km in width, in the vicinity of Wagon Pass. Wagon Pass itself is a topographic low, cutting the plateau, and has possibly developed along an east-west fault (Fig. 11).

To the west of the carbonate plateau, Carboniferous sediments of the Fairfield Group form the plains. To the east, in general, there is a rugged topography developed on Precambrian basement, with an area of rounded hills of the Devonian Van Emmerick Conglomerate lying to the north of Wagon Pass (Fig. 11). The conglomerate contains rounded pebbles of Proterozoic metasediment, granite, and volcanics, together with large carbonate clasts, in a matrix of arkosic sandstone.

The Pillara Limestone, forming the eastern margin of the carbonate outcrop in the Wagon Pass area, is a white to cream, relatively pure limestone. This includes several lithological subfacies of stromatoporoid, oncolite, birdseye, and *Amphipora* limestone. The latter is the predominant variety. The Pillara Limestone interdigitates with clastic horizons of conglomerate and arkosic sandstone towards its base.

The Napier Formation is informally subdivided (in this report) into a lower and an upper section. The lower or 'Virgin Hills Type' portion is dominantly a sequence of stylobedded packstone and grainstone, of a characteristic red-brown colour, containing 5-10% of siliciclastic (biotite, quartz, or feldspar) detritus. The sequence is a distal fore-reef facies, which has intercalated horizons of polymictic debris flows, detritus, intraclastic breccia, stromatolitic boundstone, calcareous siltstone and lime mudstone. Debris flows consist of coarse, reef-derived detritus which originated through the collapse of sections of platform margin and incorporated marginal-slope mud and sand during its passage towards the basin.

Although a few green mudstone and green calcareous siltstone units occur as part of the original sedimentary sequence within the Napier Forma-

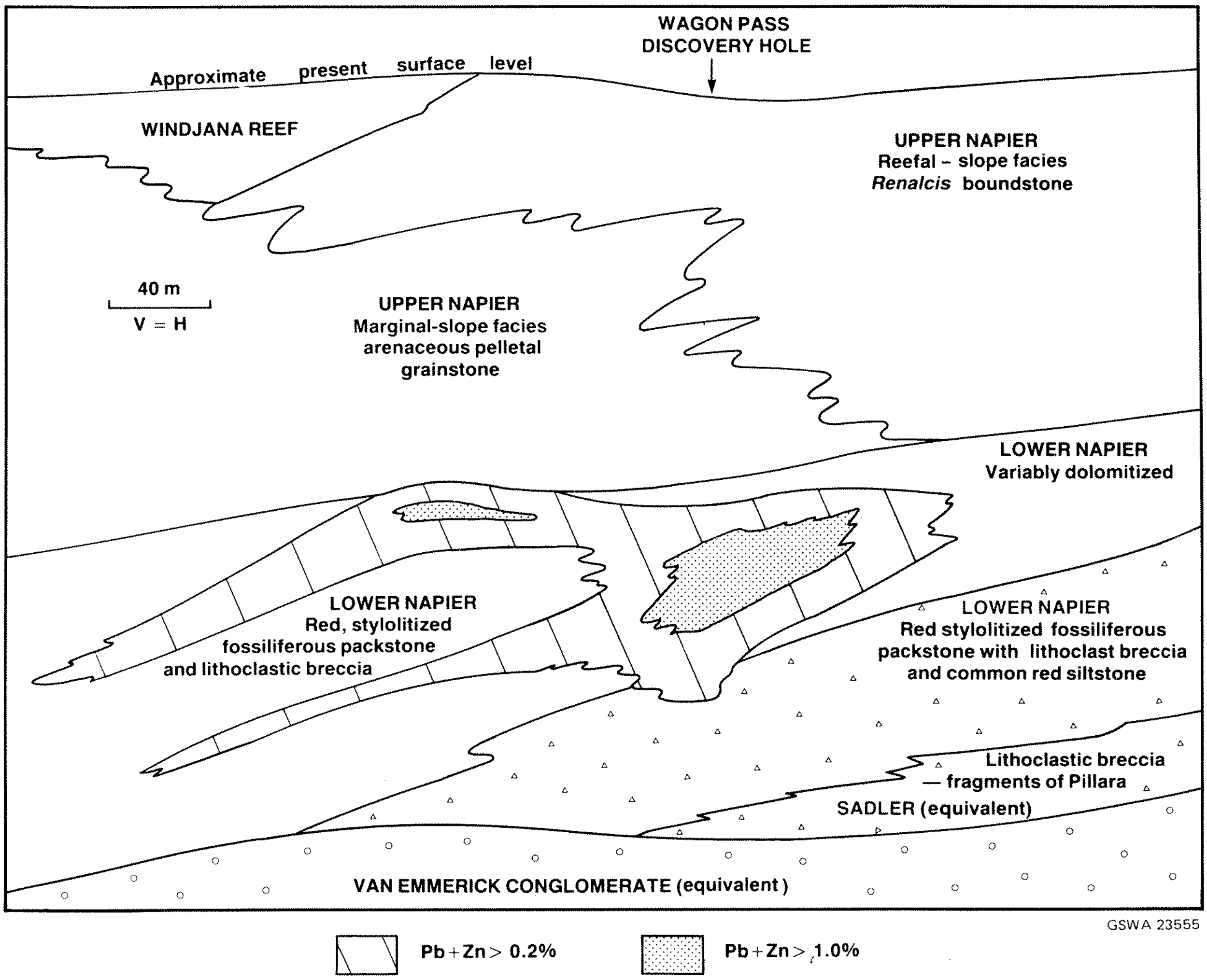


Figure 12. Generalized geological cross-section of the Wagon Pass sulphide ore lens (data courtesy of Shell Co. of Australia Ltd, Metals Division).

tion, the loss of the red-brown colour is due in general to dolomitization, which affects the Napier Formation in places throughout the Napier Range, and mineralizing-fluid activity.

The upper Napier Formation is parallel to, and locally interfingers with, the reef margin marked by the Windjana Limestone. In comparison to the lower Napier, the upper section is white, light-grey to cream in colour and contains abundant bioclastic and fossil detritus. The dominant lithologies are lime grainstone to packstone with minor fine sandstone and argillaceous components.

The Windjana Limestone is the reef facies of the Nullara cycle (Playford, 1980). In the Wagon Pass area, the Windjana Limestone is a crudely bedded body of clastic, carbonate detritus cemented and supported by clusters of cyanobacteria. Bioclastic debris is of skeletal sand, ooids, pellets and micritic intraclasts. Neptunian dykes filled with clastic and carbonate debris are ubiquitous in this reef.

The Nullara Limestone is a medium-bedded, cream to light-grey, dominantly oolitic limestone which is generally free of dolomitization. This unit is the back-reef equivalent of the Windjana Limestone.

Evidence from drill-hole intersections in the Wagon Pass area suggests that the Napier Formation is underlain by coarse, arkosic sandstone with interbedded breccia containing abundant Pillara Limestone clasts. These sands are equivalent to the Van Emmerick Conglomerate, and they appear to pinch out against the Pillara Limestone. Further, a fore-reef subfacies of this limestone, equivalent to the Sadler Limestone (Fig. 12), overlies the above-mentioned arkosic sandstone and interdigitates with the lower portions of the Napier Formation (Fig. 12).

PETROLOGY OF THE MINERALIZED CARBONATES

The Wagon Pass sulphide mineralization lies within the lower Napier Formation, just below the contact of its upper and lower portions. The host rocks (which consisted originally of red-brown, stylobedded packstone and grainstone with units of intraformational breccia as previously described) have been pervasively dolomitized and locally chloritized with resultant replacement, recrystallization, discolouration, and fracturing. These altered lithologies include dolomite, chloritic dolomite, dolomitized and/or chloritized intraformational breccias, chloritized mudstone, and fractured forms of these.

Dolomite ranges in colour from light-tan to pinkish-brown and consists of interlocking aggregates of subhedral to euhedral, rhombic grains enclosing scattered grains of biotite, K-feldspar and quartz as inclusions. Grain sizes of dolomite range through fine, medium and coarse (0.02 to 1.2 mm overall, Plate 1). In most samples examined, grain-size variation merely reflects the original texture of the replaced limestone and there is no clear evidence of cross-cutting relationships of fine, medium, and coarse-grained dolomite types.

Chloritic dolomite is a dolomitized limestone (as described above) in which chlorite occurs as a thin selvage to individual rhombs and as an infill of intergranular porosity in dolomite (Plate 1).

Dolomitized and chloritized intraformational breccias consist of angular to subrounded fragments of dolomite (after limestone), about 2 – 20 mm in size, set in a chlorite-rich matrix charged with minute dolomite rhombs and formed by replacement of the original argillaceous breccia matrix. Breccias were formed on the marginal slopes by debris flows of marginal-slope and reefal detritus.

Chlorite has formed essentially as an alteration product of the argillaceous sedimentary component. However, some small proportion of chlorite was precipitated as suggested by: the intergrowth of microlaminae of chlorite with dolomite growth zones; and the rims of chlorite seams on coarse dolomite filling open spaces. The precipitated chlorite generally shows a corrosive contact with the underlying, 'host' carbonate.

Where the zone of argillaceous matrix was particularly thick, or layers of mudstone were intercalated with limestone, a chlorite-rich rock has been formed. This chloritized mudstone locally contains bands of calcitized laths, which are possibly pseudomorphs after gypsum. The laths are elongate to spindle-shaped averaging 2 mm in length and 0.3 mm in breadth (Plate 1) and locally include minute sphalerite granules. These bands are brecciated in places with sulphide-bearing, chloritic matrix 'squeezed' between the fragments. These textures suggest that during sulphide mineralization, which mainly post-dated lath growth, the chloritic matrix became fluid-saturated and may have been plastic.

Calcite is of several generations, occurring as irregularly-shaped vugh linings, fracture fillings, veins, and replacement of ?gypsum laths (as described above). The calcite varies texturally and it includes a fibrous, radiaxial type and a clear, coarsed-grained (to 1 cm), blocky, 'spar' type.

SHAPE, EXTENT, STYLES, AND ZONATION OF MINERALIZATION

The Wagon Pass sulphide mineralization (defined in this report by an area in which lead plus zinc exceeds 0.2%) is a shallow-dipping zone with elongate down-dip extensions and a relatively sharp up-dip face (Figs 12 and 13). This zone of weak mineralization contains a lens of generally higher grade mineralization (lead plus zinc > 1%) which is approximately 30 – 80 m wide and 3 – 36 m thick. The zone of weak mineralization extends sporadically for some 300 m along strike to the north-northwest and contains pods of higher grade ore.

The sulphide mineralization, in dolomitized and chloritized host rocks, is dominated by galena and sphalerite in approximately equal proportions, lesser amounts of iron sulphide (to 20% of sulphide assemblage) and minor copper sulphides (to 1% of sulphide assemblage). Sulphide mineralization is of four styles (Plate 2): pervasive, low-density disseminations; semi-massive 'beds' of

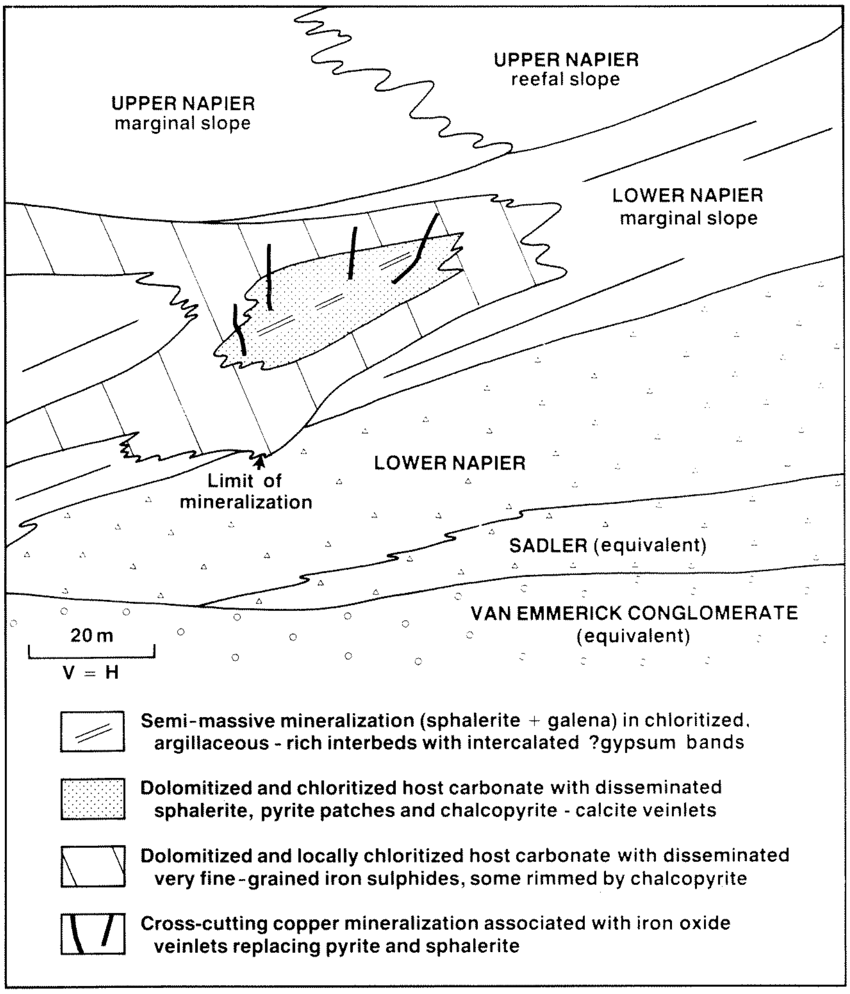


Figure 13. Idealized zonation pattern of sulphide minerals and textures, Wagon Pass ore lens.

coalescing grains in chloritized mudstone; disseminations within breccia matrices; and veins and fracture linings. Of these styles the last-mentioned is quantitatively the least important.

Disseminated sphalerite is the most widespread and the most common form of mineralization. Low-density disseminations occur in dolomite, and concentrations of coalescing grains occur in chloritized mudstone. Galena, by contrast, has a more restricted distribution within dolomite, but is common in chloritized mudstone and the matrices of dolomitic, chloritic, intraformational breccia. Vein-filling mineralization is distinctive in mineralogy and paragenesis. Most commonly it comprises copper-rich mineralization (chalcopyrite with minor bornite) in calcite, with or without sphalerite and pyrite.

The spatial relationships of these ore styles within the principal ore lens, (where lead plus zinc > 1%) is drawn in generalized form in Figure 13. The most intense mineralization (consisting of semi-massive galena and sphalerite in chloritized, argillaceous-rich interbeds and breccia matrices) is surrounded by an aureole of sphalerite-bearing chloritized dolomite. This zinc zone grades outwards into pyrite-bearing, chloritized dolomite and dolomite at the fringes of the mineralization (Fig. 13). Iron sulphide mineralization also overprints the galena-sphalerite zones in places. Copper mineralization is cross-cutting and generally lies stratigraphically above the lead-zinc sulphides.

SULPHIDE MINERALOGY AND TEXTURES

Sulphide mineralogy and texture of the Wagon Pass mineralization is summarized in Table 2.

The most common form of sphalerite occurs as disseminated grains forming concentrated laminae locally interbedded with ?gypsum laminae in heavily mineralized, semi-massive 'beds'. In these 'beds' sphalerite occurs as coalescing subhedra, 0.05 to 0.4 mm in diameter, of rounded, cuboid or hexagonal outline (Plate 3). Grains are typically zoned (as observed in transmitted light) with, in turn, growth bands of watery-yellow, purple, and red-brown, around a zone of diffuse opaque material or a rounded, opaque nucleus (Plate 3). The nucleus may be composed of a diffuse, rounded mass, possibly of carbonaceous material, or of a minute granule, possibly very iron-rich sphalerite.

TABLE 2. SULPHIDE MINERALOGY, PARAGENESIS, AND TEXTURES, WAGON PASS PROSPECT

Sulphide	*Grain size (mm)*	*Grain form*	*Texture*	*Paragenetically associated sulphide(s)*	*Host (rock or mineral)*	*Distribution*	*Paragenesis*	*Comment*
Sphalerite (1)	0.1–0.4	Rounded, cuboid hexagonal	Disseminated grains, locally coalescing in laminae	Galena	Chloritized, shaly beds, dolomite	Central, heavily mineralized portions of ore zone	Main Stage	Most common in chloritic mudstone interbeds and breccia matrices.
Sphalerite (2)	0.05–0.4	Angular, subhedral to euhedral	Disseminated grains	—	Dolomite	Margins of 'central zone' and outwards	Main Stage	Interstitial to dolomite grains, locally with cross-cutting contacts
Sphalerite (3)	x 0.05–1 (laminae width)	Elongate, grains of parallel-orientation forming concentric laminae	'Colloform'	—	Dolomite	Localized; occurs as rims to dolomite clasts which include sphalerite (2) grains	Main Stage	The concentration of angular sphalerite grains in dolomite increases towards a vugh or open fracture where the grains coalesce and may be capped by 'colloform' growth
Sphalerite (4)	0.2–1 (microveinlets)	Euhedral, hexagonal to lath-like	Fissure filling	—	Dolomite and sulphide-rich zones	Irregular	Late Stage	?Low iron content, watery yellow in transmitted light
Galena (1)	0.5–4	Octahedral, cubic	Disseminated grains	Sphalerite (1)	Chloritized shaly beds, dolomite	'Central'	Main Stage	—
Galena (2)	0.04–4 (spheroids)	Spheroids and botryoids	'Colloform' to 'spongy'	Covellite, digenite, sphalerite (4)	Galena (1)	Central	Late Stage	May represent remobilization and local reprecipitation of galena (?supergene)
Pyrite (1)	0.1–1	Granular euhedra (cubic) to rounded subhedra	Irregularly shaped patches (up to 2 cm across) of coalesced grains	?Sphalerite (3), (4)	Dolomite and earlier formed sulphides	Irregular	End Main Stage	Clearly cross-cuts and corrodes dolomite

Pyrite (2)	0.5–4	Cubic, hexagonal	Disseminated	?Sphalerite (3)	Dolomite and earlier formed sulphides	Irregular	End Main Stage	Encloses sphalerite (2) and is susceptible to replacement by covellite and digenite with iron
Pyrite (3) (bravoitic)	0.005–0.02	Cubic, hexagonal	Disseminated	?Pyrite (1), (2)	Enclosed in dolomite grains or interstitial to them	Peripheral to main sulphide zone	?pre Main Stage	Nickeliferous pyrite distinguished by coloured growth zones
Marcasite	0.2–1	Granular, rectangular	Crusts	Pyrite (1)	Forms rims to pyrite (1) patches	Irregular	?End Main Stage or early Late Stage	Also forms pseudomorphically after pyrite where the latter is cut by iron oxide veining
Chalcopyrite (1)	3–8	Rounded blebs	Disseminated in veins	?Sphalerite (3) pyrite (2)	Calcite cutting dolomite in veinlets	Peripheral	?Main Stage	Locally post-dates colloform sphalerite and intergrown with bornite
Chalcopyrite (2)	0.1–0.3	Granular; anhedral, rhombic, and rectangular	Coalescing grains as fissure coatings	?Sphalerite (3)	Calcite cutting dolomite in veinlets	Peripheral	?Main Stage	
Chalcopyrite (3)	0.1–0.3	Anhedral blebs	Disseminated	?Sphalerite (3)	Coatings to disseminated pyrite (3), interstitial to dolomite	Peripheral	Late Stage	Replaces pyrite in network veining
Digenite/covellite	0.01–0.1	Anhedral to lath-like grains; or 'amorphous' patches	In microveinlets to 0.2 mm in width; grains—0.05 mm	—	Iron oxide veinlets in pyrite (1)	Peripheral	Late Stage	Replaces pyrite in network veining

Sphalerite also occurs as low-density, disseminated, subhedra and triangular to rounded grains (0.05 to 0.4 mm) interstitial to dolomite grains (Plate 3). Here, sphalerite growth has exploited secondary, intergranular, rock porosity (after dolomitization). It fills the voids generally with no evidence of dissolution or replacement of the carbonate. However, some cross-cutting contacts of sphalerite with respect to dolomite do occur. Locally, interstitial grains of sphalerite coalesce towards an open space or fracture and are overgrown by banded, botryoidal sphalerite growing into the void (Plate 3).

A third form of sphalerite, in microveinlets, occurs at Wagon Pass. This type is very pale grey to clear (in transmitted light), in comparison to the more usual red-brown and yellow sphalerite. These veinlets (to 1 mm in width) cross-cut laminae of sphalerite euhedra in heavily mineralized, chloritized, mudstone interbeds (Plate 3).

Galena occurs most commonly as disseminated cubic or octahedral euhedra to rounded subhedra, 0.5 to 4 mm in size, within heavily mineralized, chloritized, argillaceous interbeds (Plate 4). Galena of a similar form also occurs in the chloritized, dolomitized matrices of breccias (Plate 4). These crystals are generally free of inclusions of carbonate but may include grains of sphalerite.

A 'colloform' type of galena is locally associated with disseminated, galena euhedra (Plate 4). In these occurrences, botryoidal to spherical growths of galena, ranging in size from 0.04 to 4 mm, occur as partial replacements of galena cubes. They are spatially associated with microveinlets which consist mainly of iron oxides and contain fine-grained digenite, covellite, and bornite. This last fact suggests that 'colloform' galena may have formed by mobilization and local reprecipitation of galena by oxidizing fluids which also transported copper.

Pyrite is the dominant iron sulphide in the Wagon Pass mineralization. It occurs most commonly in patches, 0.5 to 2 cm in size, comprising numerous coalescing cubic to hexagonal subhedra, 0.1 to 1.0 mm in size. Individual pyrite euhedra have interstitial to cross-cutting contacts with dolomite grains. These pyrite patches include siliciclastic detrital grains and earlier formed sphalerite and dolomite grains. Pyrite patches occur throughout the mineralized section but are slightly more common outside the zones of most intense sphalerite-galena mineralization.

Coarse-grained euhedra of pyrite also occur locally within beds of 'semi-massive' sphalerite-galena mineralization. Cubes and subrounded euhedra of pyrite, 0.5 to 4 mm in size, are locally replaced by iron oxide along growth zones (Plate 5).

Very fine-grained disseminated euhedra of pyrite and of nickeliferous pyrite (bravoite), 0.006 to 0.02 mm in size, also occur within dolomite throughout the zone of mineralization. This form of iron sulphide is often included within, and interstitial to, dolomite grains. It may be a peripheral facies of the sphalerite-galena mineralization or have formed prior to dolomitization, possibly in an early diagenetic environment.

Marcasite has a restricted occurrence. It forms rims (about 1 mm in width) to the pyrite patches, described above, and is intergrown with pyrite in zones where veinlets of iron oxide and copper-bearing mineralization cut pyrite patches (Plate 5). Grains of marcasite are rectangular to bladed, 0.2 to 1 mm in size. In both of these occurrences marcasite is formed later than pyrite, possibly due to the local replacement of pyrite (and local reprecipitation) by a later, ?acidic fluid. Marcasite has cross-cutting contacts with dolomite.

Copper mineralization at Wagon Pass includes (in approximate order of abundance) chalcopyrite, bornite, covellite, digenite, and chalcocite. Chalcopyrite occurs in three principal forms: as coarse-grained, rounded blebs (3 to 8 mm in size) within vein calcite and as fracture-wall rims (0.2 to 1 mm in width); as anhedral coatings to very fine-grained pyrite grains (0.005 to 0.2 mm in size) disseminated within dolomite; and in association with bornite, digenite, and covellite. Bornite-bearing mineralization cross-cuts and replaces patches of iron sulphide, enclosing galena and sphalerite in an intricate network of microveinlets of iron oxide (Plate 5).

IMPLICATIONS OF THE SULPHIDE MINERALOGY AND TEXTURES

The sulphide assemblage in general is very simple and clearly dominated by galena and sphalerite, in the relative proportions of 60 to 40% of sulphide. Chalcopyrite is a minor component.

The sulphides are fine to coarse grained with sphalerite generally the finer grained phase. This grain-size variation may imply a differing rate of crystallization, from relatively fast (fine grain) to slow (coarse grain), concomitant with decreasing saturation of the ore fluids with respect to sulphide. Textural forms also reflect differences in the porosity and competence of their host rock. In chloritized argillaceous interbeds, euhedra of sphalerite were able to grow unhindered in a 'plastic', fluid-saturated medium, and did not include host-rock mineral components. In dolomites intergranular porosity was exploited and irregular sphalerite shapes resulted.

The lessening of saturation may reflect, in turn, a decrease in the concentration of metals or a reduced sulphur supply with time at the site of mineralization.

PARAGENETIC SEQUENCE OF MINERALIZATION

The paragenesis of mineralization at Wagon Pass is illustrated in Figure 14.

The Lower Napier Formation comprises carbonate, siliciclastic and clay components that were cemented by the precipitation of equant spar during their early diagenesis.

At some later time, these sediments were dolomitized and chloritized penecontemporaneously, with chlorite formation persisting after dolomite formation.

Textural evidence from a few samples indicates that there were at least two stages of dolomitization and chloritization (with an intervening stage of calcite precipitation) at least on

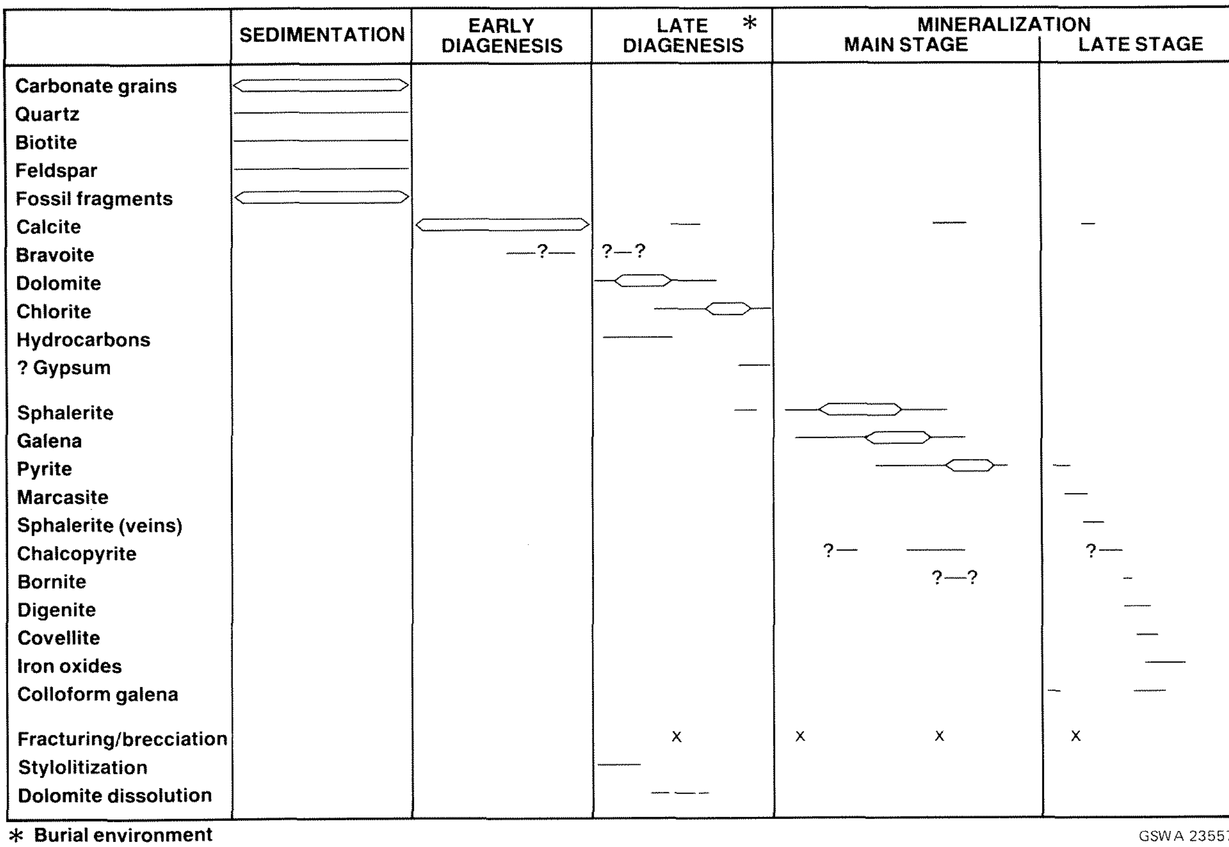


Figure 14. Paragenetic sequence of mineralization, Wagon Pass.

a local scale. There is no evidence of widespread overprinting, and it is more probable that dolomitization and chloritization were interrelated, dynamic processes. These acted with differing intensity at different positions within the ore zone. Dolomitization and chloritization processes were controlled by host-rock permeability and chemistry, within the zone of mineralization.

There is a lack of direct evidence that sulphide precipitation preceded dolomitization and chloritization, in general; *i.e.* overgrowths of dolomite on sulphides do not occur. However, the small amount of disseminated, very fine-grained pyrite and bravoite included within dolomite rhombs may be earlier than, or contemporaneous with, dolomitization.

Evidence that sulphide precipitation post-dated dolomitization and chloritization is suggested by sulphide infillings of intergranular dolomite pores and local replacement of dolomite by sulphides, mainly pyrite.

In general terms, the main stages of sulphide mineralization began with deposition of sphalerite, followed by the coprecipitation of sphalerite and galena, and ended with the formation of chalcopyrite and pyrite. Further chloritization after dolomitization, around and within sulphide-rich interbeds, may also have occurred.

The major part of copper mineralization at Wagon Pass, in veinlets with calcite, appears to have formed just following main-stage sphalerite-galena mineralization. Locally, however, chalcopyrite occurs in veinlets of calcite which itself has been corroded by an assemblage of chlorite with minor dolomite. This suggests that some chalcopyrite formed relatively early in the paragenesis prior to, and/or contemporaneously with, sphalerite-galena precipitation.

A later phase of cross-cutting copper mineralization also occurs, characterized by chalcopyrite with digenite, covellite, iron oxide, and microveinlets of sphalerite. This latter phase is considered to mark the downward percolation of oxidizing meteoric fluids, which may have derived their copper from the 'red-bed' country rocks.

Fracturing of dolomite was observed in a number of samples examined. This disruption has resulted from a combination of three processes in interaction: the dissolution of carbonate during dolomitization leading to local solution fragmentation; mechanical deformation of brittle dolomite along and adjacent to faults; and hydraulic fracturing adjacent to and along faults, concomitant with the influx of sulphide-forming fluids. Incursion of mineralizing fluids, fault activity, and brecciation are temporally and genetically related.

DISCUSSION

The dolomitization of the lower Napier Formation has occurred on a regional scale in the Napier Range and pervasively affects the underlying, basal arkosic sandstone. Chloritization, by contrast, is more localized within the Napier Range and appears to have occurred during the waning phases of dolomitizing fluid activity. These alteration processes are contemporaneous with, and post-dated in part by, compaction stylolitization within the Napier Range in general, which suggests that alteration occurred during relatively deep burial of the host rocks.

Pervasive dolomitization in the Napier Range is considered to have formed from basin-derived fluids that migrated through permeable, arkosic sands and the lower Napier Formation during their late diagenesis while buried. The formation of dolomite from basin-derived, Mg-bearing fluids has been described by Mattes and Mountjoy (1980) and is advocated, on the basis of petrological and isotopic considerations, by Kerans (1985). This idea is supported by fluid-inclusion data (Etminan and others, 1984) which indicates that the dolomite-forming fluids were warm (90°C), hydrocarbon-bearing, and saline.

Chloritization has resulted mainly from the alteration of sedimentary clay minerals, although textural evidence clearly indicates precipitation of chlorite locally. Alteration of clay components within the host rock (kaolinite and montmorillonite for example) to chlorite is considered to have resulted from the activity of Mg-bearing fluids in the presence of reduced iron as follows:

$$Fe^{2+} + Mg^{2+} + \text{clay minerals} \longrightarrow \text{'chlorite'} + H_2O + 8H^{+}(aq)$$

Reduced iron may have been produced by the reaction of iron oxides within the "red-bed" carbonates, utilizing hydrocarbon as a reducing agent such that:

$$\underset{\text{(red iron oxide)}}{8Fe(OH)_2} + \underset{\text{(hydrocarbons)}}{CH_4} \longrightarrow \underset{\text{(incorporated in chlorite)}}{8Fe^{2+}} + 8OH^{-} + 6H_2 + CO_2$$

Precipitation of chlorite may have been from aluminosiliceous gels in the presence of reduced iron.

The formation of chlorite involves the production of acidic solutions (supported by textural evidence), which may have dissolved carbonate locally and reprecipitated calcite outwards from areas of concentrated chloritization.

The presence of possible gypsum, intercalated in chloritized sulphide-bearing mudstone beds, suggests that the oxidation state of sulphur (in solutions flowing through the ore zone) was variable and that sulphate ions were present locally and periodically. This sulphate, probably introduced together with chloritizing fluids, may also have been the source of reduced sulphur. Sulphate may have been reduced thermochemically, in the presence of hydrocarbons, or by the activity of bacteria introduced by meteoric water. An alternative source of sulphur is that of a precursor sulphide occurring as disseminated, fine-grained pyrite, which may have been mobilized by warm, basin-derived fluids. However, the volume of sulphide for such a source appears inadequate.

The metal-bearing brines are considered to have been further pulses of basin-derived compaction fluids. Metal-bearing brines were probably warmer and acted only locally within the dolomitized, chloritized, host rock. They precipitated their metals as sulphide where they intersected a source of reduced sulphur. The sulphide textures are epigenetic: laminar textures were controlled by the permeability of the host rock; and sulphide breccias were also formed *in situ*.

THE NARLARLA DEPOSITS

LOCATION AND HISTORY OF DEVELOPMENT

The Narlarla deposits lie in the Napier Range approximately 150 km east of Derby and 12 km southeast of the Wagon Pass prospect. These deposits were first pegged in 1901 and again in 1906 but apparently, because of their remoteness, were not worked until taken up by Devonian Pty Ltd in 1948.

There are two deposits at the locality — the No. 1 and the No. 2. The smaller No. 1 deposit was quickly worked out but a significant production was achieved from the No. 2 deposit. From 1948 until work ceased in 1966, 2115 t of lead, 2867 t of zinc, and 162 kg of silver were recorded from 11 033 t or ore: a representative sample of sulphide ore assayed 23.2% lead, 30.9% zinc, 0.48% cadmium, 0.10% antimony and 162 g/t silver (Blockley, 1971).

PREVIOUS STUDIES

Several previous studies of the deposits have been made including those of Woodward (1907), Finucane and Jones (1939), Hutton (1965), and Halligan (1965). Prider (1941) and Gellatly (1970) have investigated mineralogical and petrological aspects of the ores, respectively. A detailed summary of previous work was given by Blockley (1971).

Between 1978 and 1982, detailed mapping and exploration drilling, for extensions to the known ore, were carried out by Shell as part of their Napier Range program. No encouraging results were recorded and Shell's interest in the deposits has now been relinquished.

In 1983 the Geological Survey of Western Australia dewatered the Narlara No. 2 pit and a detailed mapping and sampling program was carried out. The results of this examination have been reported by Ringrose (1984), and mineralogical aspects of the secondary ore zone were expanded upon in a later paper (Ringrose, 1985).

ORIGIN OF THE DEPOSITS

Several models of ore genesis have previously been proposed for the Narlarla mineralization. Finucane and Jones (1939) recognized the similarities of the Narlarla ores to those of the Missouri district and suggested (without qualification) that the "ores were formed by deposition from water of meteoric origin." Prider (1941) suggested a possible connection between Narlarla mineralization and the igneous activity which produced the small volcanic necks and plugs at Mount North, Mount Percy, and further south in the northern part of the Canning Basin (Mount North lies 28 km to the south-southeast of Narlarla and is the closest occurrence of post-Devonian igneous activity). Halligan (1965) postulated that the Narlarla ore was formed from migrating ground waters that remobilized lead from veins in the underlying Lamboo Complex.

Most recently Gellatly (1970) has proposed that the ores were formed syngenetically and emplaced through gravitational sliding, slumping, or mudflow intrusion into their present position on the depositional slope.

GENERAL GEOLOGY

The Narlarla deposits occur within marginal-slope facies sediments of the Fammenian reef development cycle — the Napier formation (Fig. 5). At the Narlarla locality the exhumed carbonate reefs form a steep-sided, narrow plateau (0.6 km in width) of rugged topography rising up to 130 m above the level of the surrounding plain. Mapping and drill-hole data indicate that the Devonian sediments rest directly upon Precambrian basement or upon sediments equivalent to the Van Emmerick Conglomerate. The latter unit overlies the Pillara Formation and represents torrential fan deposits, shed from faulted Precambrian scarps. The Proterozoic Lamboo Complex crops out immediately to the northeast of the carbonates and the unconformity deepens basinwards, to the

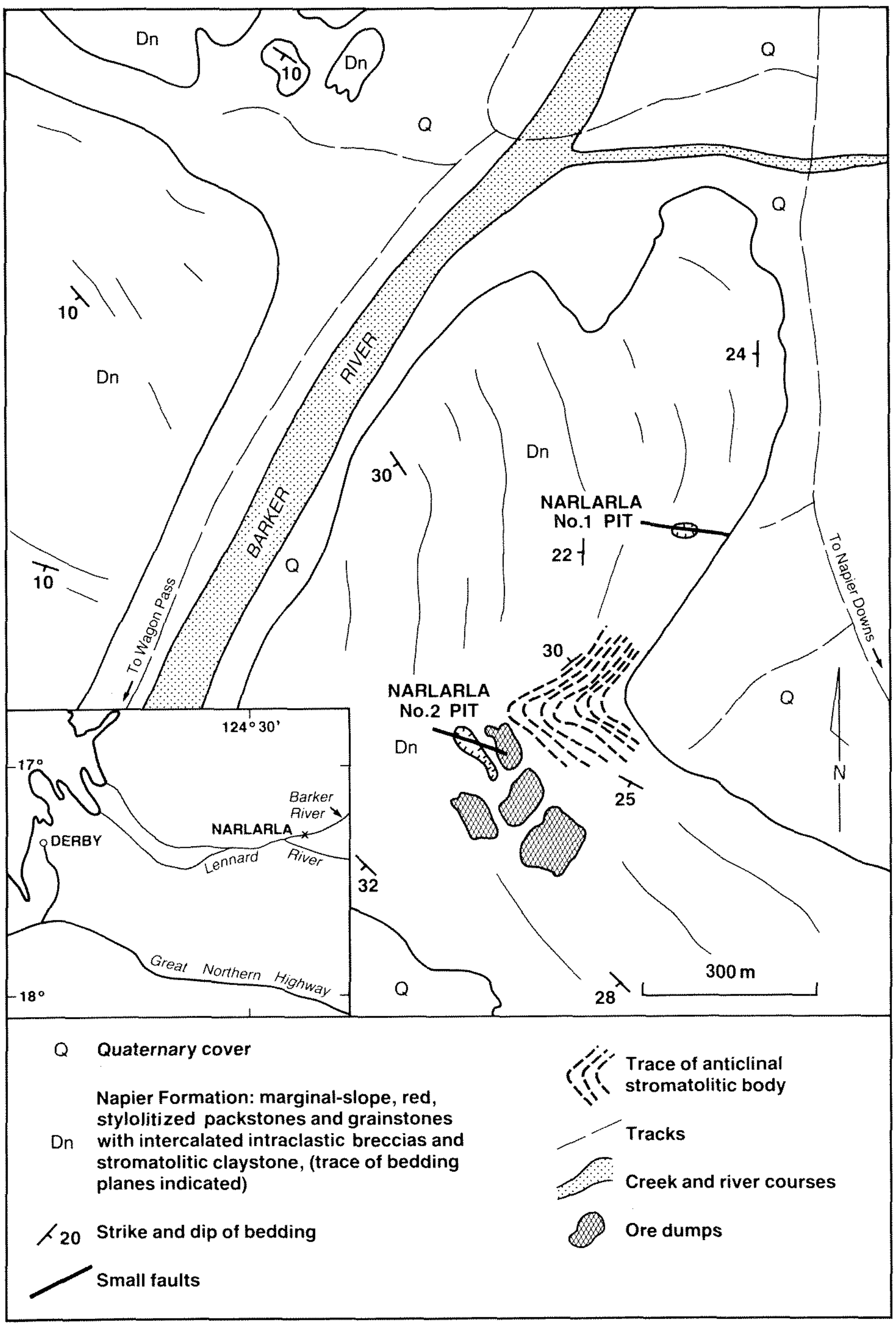
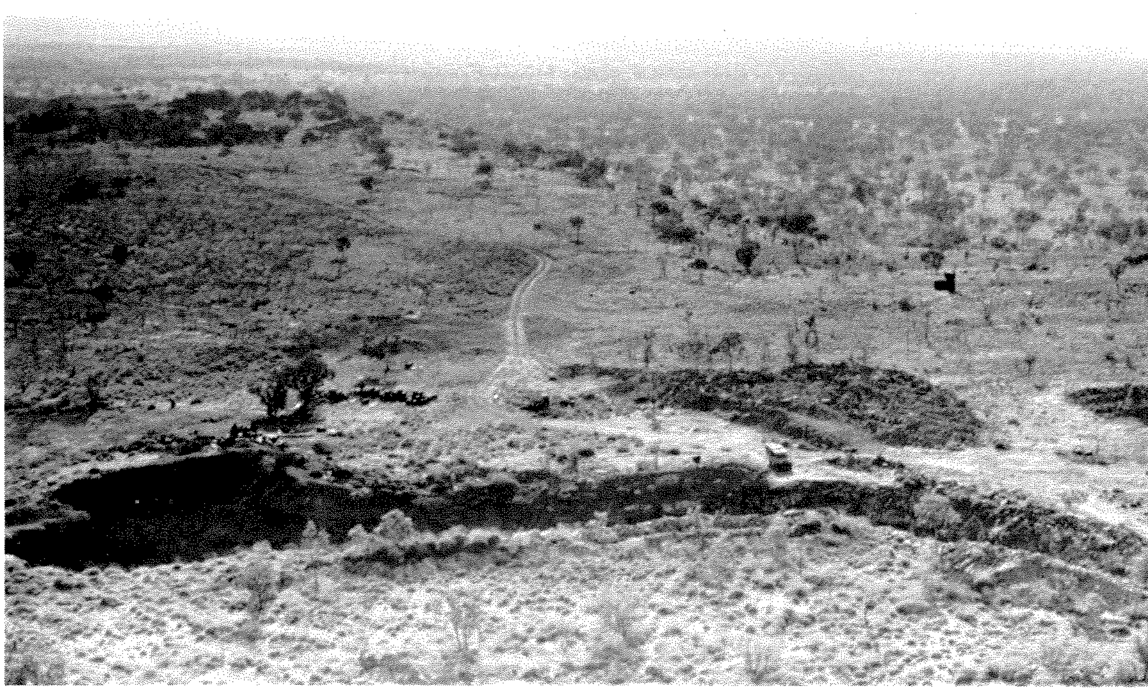


Figure 15. General geology of the Narlarla deposits.



GSWA 23559

Figure 16. General view of the Narlarla locality to the northeast, with the No. 2 pit in the foreground and the No.1 deposit in the background. The plateau is of marginal-slope facies Napier Formation carbonates.

southwest. The dip of the Napier Formation in this area is largely depositional, generally ranging between 20° to 30° to the southwest.

East of the Narlarla deposits, the Napier Range is cut by the Barker River gorge which approximately coincides with the axis of a palaeoembayment upon the marginal slope. This palaeoembayment is indicated by a localized change in the strike of the outcropping carbonates which form a tight, re-entrant arc about the Barker River (Fig. 15). Each shoulder of this re-entrant is marked by the occurrence of a 'depositional anticlinal stromatolitic ridge'. The stromatolitic ridge of the southern shoulder lies close to the No. 2 deposit (Figs 15 and 16).

The site of the Narlarla No. 2 deposit is marked by an elongate (northwest-southeast) open cut (measuring about 120 m in length, 30 m in width, and 16 m in depth) and a large remnant of the original gossan (measuring 35 m × 5 m). Before mining, the gossan was over 5 m in height.

The No. 1 deposit is a low hill of gossan, partially worked-out, measuring about 30 m in length, 15 m in width and 3 m in height. The present erosion level is approximately coincident with the base of the Late Carboniferous pre-Grant Formation, the No. 1 deposit being more deeply eroded than No. 2.

Ore-mineral assemblages in both deposits consist mainly of galena and sphalerite, with minor iron sulphides and important secondary-ore zones of cerussite, smithsonite, and hydrozincite.

The No. 1 ore zone is enclosed by green to reddish-brown, fissile, slickensided chlorite rock and feldspathic and siliceous dolomite. These rocks, together with minor remnants of secondary ore, form a low hill of gossan on the fine-grained, pink, dolomitized Napier Formation sediments of the surrounding plateau. Old workings consisted of a shallow trench, with a pit at the western end, trending 105° across the gossan. The trench is coincident with a fault (Fig. 17).

Structures within the gossanous, chloritic zone include planar features (?relic bedding) and slickensided surfaces. Planar structures are generally horizontal or dip to the south, but are locally vertical along the length of the principal fault (Fig. 17). The orientation of these planar structures contrasts sharply with the bedding of dolomitized Napier Formation sediments, which are peripheral to the gossan.

Slickensides lie on imbricated planes which strike parallel to the ?relic bedding planes of the chlorite rock, but generally dip at a slightly higher angle to the south. Lineations upon slickensided surfaces are mainly oriented at right angles to the fault line (Fig. 17).

Wall rock enclosing the No. 2 ore consists of typical Napier Formation packstones and grainstones: yellow-brown to red, thinly bedded, partially dolomitized and fossiliferous, with a notable proportion of argillaceous to rudaceous siliciclastic and carbonate detritus. Bedding planes are accentuated by subparallel stylolites. Also present are subsidiary lenses and beds of intraclastic breccia, together with thicker, finely laminated, silty, stromatolitic boundstone. Immediately surrounding the ore, these wall rocks are strongly chloritized.

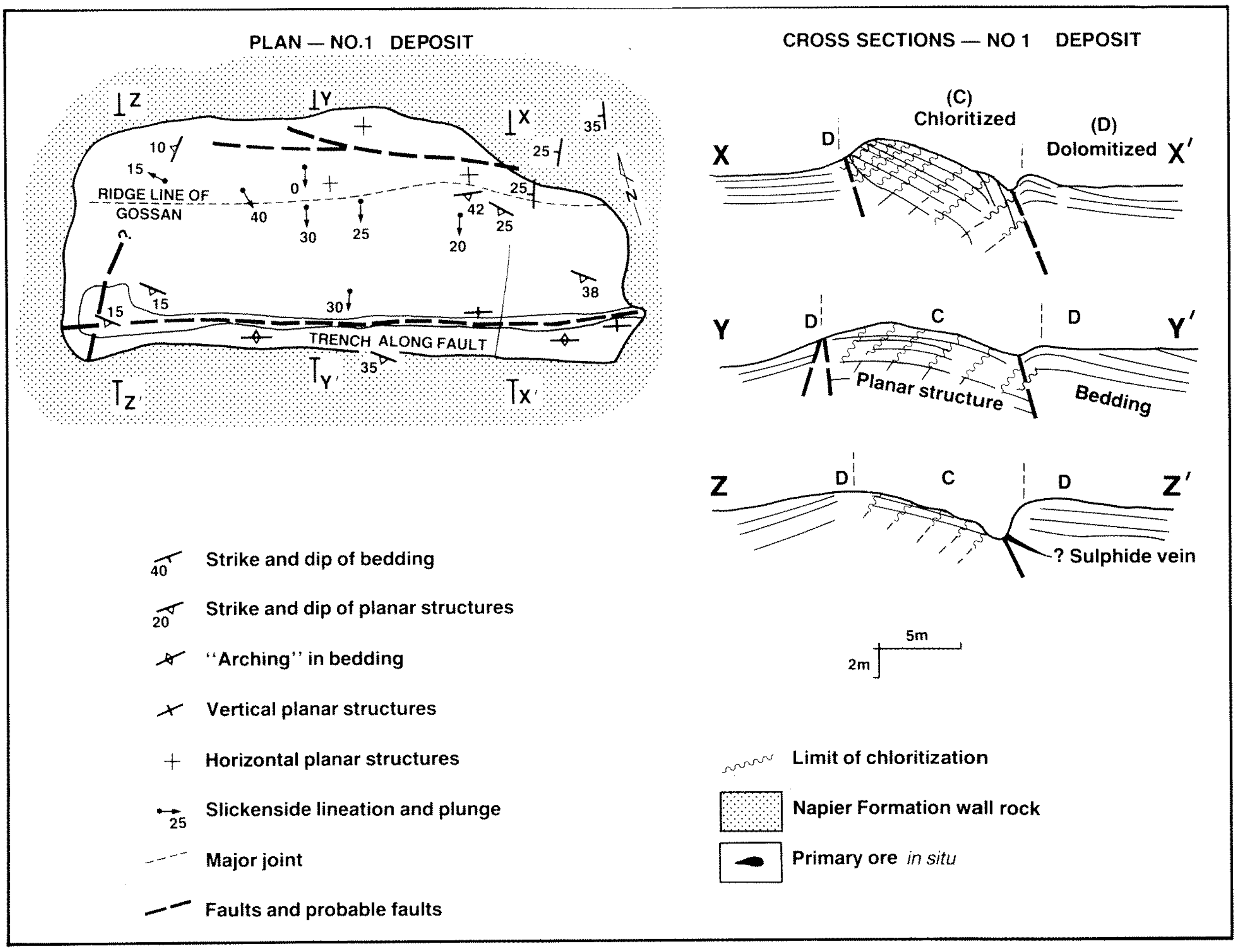


Figure 17. Geology of the Narlarla No. 1 deposit in plan and section.

Outcrops of the stromatolitic ridge terminate just to the east of the orebody, but portions of its marginal facies (stromatolitic lenses, numerous calcareous siltstone beds and lenses of intraclastic breccia) crop out in the northern face of the open cut. This stromatolitic build-up may mark the colonization of a debris flow and is considered to have been a prominent feature on the marginal slope during sedimentation.

The strike of bedding in the open pit is consistently about 310°. Dips generally range between 15° to 30° to the south, but increase locally, to 40°, adjacent to the ore (Fig. 18).

Bedrock is well jointed and cut by several small faults with a maximum displacement of 2 m. Two prominent joint sets strike at 360° – 030° and 090° – 110° respectively. The main fault bisects the open pit, trending about 110°, and has several ore pods localized along its length (Fig. 18). A near north-trending fault and another fault, subparallel to the main fault, cut the northern face (Fig. 18). Several smaller faults (displacement up to 0.2 m) with a strike of 040° – 070° (complementary to the 090° – 110° trend) cut the footwall of the orebody.

Faulting has previously been cited as a control on ore fluids for the Narlarla deposits. Halligan (1965) reported that the ore worked in the early days of mining was located on a fault (or faults) on the northeastern margin of the pit, and he measured their throw as less than 2 m. Halligan (1965) also suggested that post-ore fault movement had occurred.

SHAPE AND EXTENT OF THE NO. 2 DEPOSIT

The unmined, exposed remnants of the primary and secondary orebodies, at Nararla No. 2, are distributed within the open pit as illustrated in Figure 18. (The terms primary and secondary refer to unoxidized and oxidized orebodies of sulphide mineralization, respectively).

A large remnant of the original secondary orebody, measuring approximately 35 m long (elongated northwest-southeast), 3 to 10 m wide and up to 7 m thick, crops out on the northern corner of the open pit. In section this body is lens shaped, with an irregular, roughly horizontal base and steeply inclined (inwards) marginal contacts (Fig. 18).

A second remnant of the original oxidized orebody occurs within the southern wall of the open pit, close to point B[1] on Figure 18. This remnant is small, only 5 × 2 m, and lens-shaped, consisting of coarse-grained and coarsely porous, botryoidal, lilac-grey smithsonite (Fig. 19).

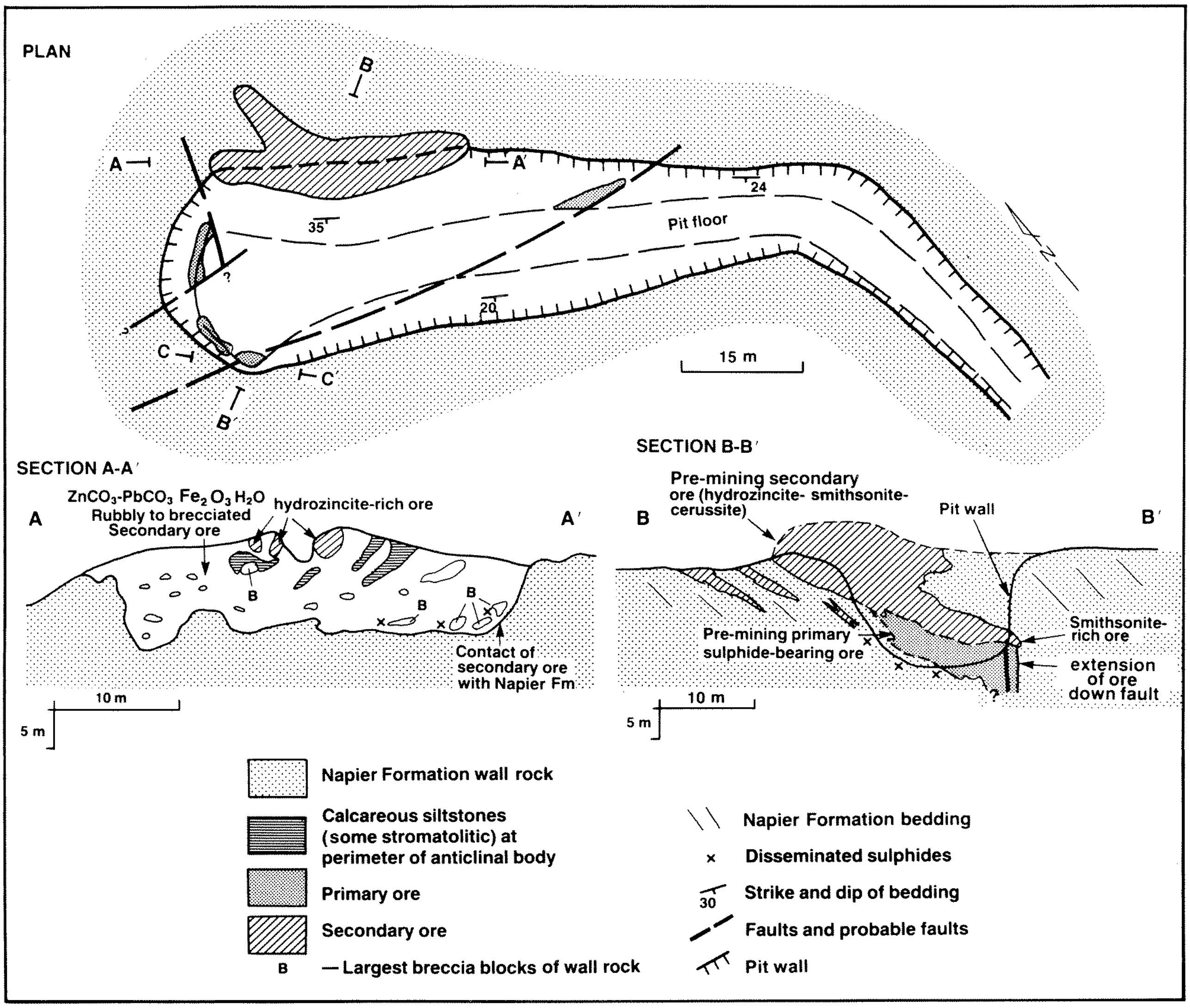


Figure 18. Geology of the Narlarla No. 2 deposit in plan and cross section of the remnant secondary orebody showing the pre-mining distribution of secondary and primary sulphide-bearing ore.

The northern and southern remnants of the secondary orebody described above are the extremities of a body which was originally a cap on the primary ore. The down-dip extension of the secondary ore was thickest in the north and thinned down dip to the west (Fig. 18). The mapped distribution of lead and zinc carbonates within this zone is consistent with the known relative solubility of these metals in groundwater; zinc, being more soluble, is deposited over a more extensive area than lead in the carbonate form (Sangameshwar and Barnes, 1983).

A diffuse zone of deep red discolouration, affecting the lower (down-dip) portions of the secondary ore zone, was shown by X-ray diffraction analysis to be iron oxide staining, superimposed on the primary and secondary mineralization and closely related to the modern water table.

TEXTURE AND MINERALOGY OF SECONDARY ORE, NO. 2 DEPOSIT

The texture of the gossanous secondary ore is rubbly to brecciated, comprising large (up to 3 m maximum dimension) to small (greater than 10 cm maximum dimension) sub-rounded to sub-angular blocks of Napier Formation wall rock, which are set in a matrix comprising fine to medium-grained, secondary ore minerals, with numerous vughs and minor amounts of sulphides. The ore is generally intensely limonitized with distinctive small areas (about 2 × 1 m) of white to pink, hydrozincite-rich, secondary ore, lenses of intercalated calcareous siltstone, and some large (up to 30 cm across) calcite-filled vughs. Minerals in this zone comprise smithsonite (to 40%), cerussite (to 15%) and iron oxides (to 25%) with minor and variable amounts of accessory hydrozincite (locally abundant), chamosite, quartz, calcite, azurite, and malachite.

TEXTURE AND MINERALOGY OF SULPHIDES, NO. 2 DEPOSIT

The primary sulphide ore zones exposed in the emptied pit occur near the base of the excavation, the majority being towards the northwestern end (Fig. 18). These pods, lenses and beds are very high grade, consisting of 70-90% of ore minerals with only minor amounts of interstitial gangue and

TABLE 3. SULPHIDE MINERALOGY, PARAGENESIS AND TEXTURES, NARLARLA No. 2 OREBODY

Sulphide	*Grain size (mm)*	*Grain form*	*Texture*	*Paragenetically associated sulphide(s)*	*Host (rock or mineral)*	*Distribution*	*Paragenesis*	*Comment*
Sphalerite (1)	0.01–0.5	Fine-grained, polycrystalline druses	Numerous, concentrically grown druses forming botryoids to 8 mm in width, growing in open spaces	Galena	Cavities in dolomitic limestone	Central parts of orebody	Main Stage	Botryoids often have cores of opaque, gel-like material, and may be composed in the inner part of mixed sphalerite-wurtzite polymorphs. Sphalerite colours in transmitted light include clear, yellow red-brown and purple.
Sphalerite (2)	0.1–0.4	Angular, anhedral to euhedral	Disseminated grains interstitial to dolomite rhombs of wall rock	Galena	Dolomitic limestone	Peripheral	Main Stage	Disseminated euhedra may coalesce to form 'beds'. In bedding-parallel fractures.
Sphalerite (3)	0.1–0.4	Euhedral, cubic, hexagonal to lathlike	Open-space filling and veinlets (-1 mm in width)	—	Sulphide	Irregular	Late Main Stage	Characteristically a very pale-grey colour in transmitted light
Galena (1)	0.5–2.0	Anhedral to cubic and octahedral	Inclusions in sphalerite botryoids and open-space filling	Sphalerite (1)	Sphalerite	Central	Late Main Stage	—
Galena (2)	2 –6	Skeletal octahedra, cuboids or laths	Inclusions in sphalerite botryoids	Sphalerite (1)	Sphalerite	Central	Main Stage	—
Galena (3)	0.05–0.5	Elongate 'blebs'	Inclusions in sphalerite	Sphalerite (1)	Sphalerite	Central	Early Main Stage	—
Galena (4)	0.1–2	Laths (some skeletal) and botryoids	Replacive after sphalerite	Sphalerite (1)	Sphalerite	Central	Main Stage	Botryoids formed by replacement of sphalerite
Pyrite (1) (bravoitic)	0.005–0.05	Cubic, hexagonal euhedra	Disseminations	—	Dolomite	Peripheral	?Early Main Stage	—
Pyrite (2)	0.4–1	Cubic euhedra	Open-space filling	Marcasite	Sulphide	Peripheral	Post-Main Stage	Fills relic porosity post-dating sphalerite-galena mineralization

(Continued overleaf)

TABLE 3. SULPHIDE MINERALOGY, PARAGENESIS AND TEXTURES, NARLARLA No. 2 OREBODY—*continued*

Sulphide	*Grain size (mm)*	*Grain form*	*Texture*	*Paragenetically associated sulphide(s)*	*Host (rock or mineral)*	*Distribution*	*Paragenesis*	*Comment*
Marcasite	0.1–0.8	Rectangular, rhomboidal euhedra	Open-space filling	Pyrite (2)	Sulphide	Peripheral	Post Main Stage	Intergrown with pyrite (1) but clearly post-dates it
Chalcopyrite	0.1–0.4	Anhedral 'blebs'	Disseminated inclusions or overgrowths	Sphalerite (1) galena (1) - (4)	Sphalerite (1) or pyrite (1)	Central to peripheral	Main Stage	Often formed at contact of sphalerite and galena grains
Digenite Covellite	0.01–0.05	Lath-like grains and 'amorphous' patches	?Replacive after sphalerite	Sphalerite (1)	Sphalerite	?	Late Stage	?Supergene

some primary porosity. Pods and lenses of ore are clearly epigenetic as they cross-cut bedding planes and pinch-out along small faults. Bedded sulphides are concordant with country-rock bedding but are also considered to be epigenetic in origin (see following data). The pods and lenses of sulphide are characterized by botryoidal-skeletal textures; the bedded zones have bulbous and evenly laminated textures (Plate 6). Microscopic textures of the orebody are summarized in Table 3.

Botryoidal-skeletal sulphide is generally composed of sphalerite (to 60%) and galena (to 30%) with only minor, but locally significant, iron sulphides (to 10%).

Sphalerite occurs as botryoidal masses composed of spherulitic, concentrically banded 'colloform' grains (to 8 mm diameter) that commonly form dendritic aggregates (Plate 6). The sphalerite spherules have cores which were formerly gel (very deep brown and opaque) around which bands of yellow-brown to pale-yellow sphalerite growth zones (transparent) are arranged (Plate 7). Botryoidal-skeletal ores are, invariably, free of included siliciclastic or carbonate detritus.

Galena occurs most commonly as coarse, often skeletal, cubic grains (up to 8 mm across) and as lath-shaped grains (up to 3 mm thick and 1 cm in length) in the cores of sphalerite spherules (Plate 6). Fine spindles and blebs, and laminae of 'colloform' galena also occur within sphalerite spherules (Plate 7).

By contrast, bedded-ore zones (Plate 6) consist mainly of closely packed, individual, zoned subsequent euhedra of sphalerite up to 0.5 mm across (Plate 8), in laminae up to 1 cm thick, and containing abundant interstitial and interlaminar carbonate and siliciclastic wall-rock remnants. Sphalerite crystals commonly have a nucleus of a minute opaque granule (iron-rich sphalerite or iron sulphide). In certain laminae the crystals coalesce to form pervasive sphalerite mineralization, and often, laminae of euhedra are capped with a crust of inclusion-free, bulbous to 'colloform' sphalerite. Variation in the concentration of sphalerite euhedra versus wall rock, across individual laminae, gives the impression of a "graded bed". Fine-grained, (to 1 mm) subhedral galena grains are sparsely disseminated throughout the laminae.

Iron sulphide, both marcasite and pyrite, generally occurs interstitially in botryoidal-skeletal galena-sphalerite ore where it is has been precipitated in open spaces. However, the iron sulphide locally replaces early formed galena-sphalerite ore.

Trace amounts of other sulphides including bravoite, covellite, chalcopyrite, chalcocite, and bornite also occur. Silver was not observed as a discrete phase.

IMPLICATIONS OF THE ORE TEXTURES

The presence of skeletal-botryoidal, 'colloform' textures is characteristic of Mississippi Valley-type ore deposits and typical of low-temperature formation. These textures are believed to indicate relatively high supersaturation of ore-mineral constituents and very rapid precipitation of sulphides (Anderson, 1975).

At Narlarla, skeletal-botryoidal ores are predominant and are considered to have formed by the very rapid precipitation of ore minerals, in regions of high porosity in the centre of the orebody. The relatively high recorded content of silver in the Narlarla ores, up to 162 g/t, may be a consquence of this very rapid 'dumping' process of ore precipitation which permitted the incorporation of 'foreign' elements (*e.g.* Ag and Cu) into the galena and/or sphalerite lattices. Alternatively, silver may be concentrated within the ore by secondary processes (see following data). By contrast, the laminated sulphide was formed by a combination of both replacement and open-space filling processes. It has developed along hydraulically dilated joints and fractures (parallel to bedding) leading outwards from the central ore zone and as rims to wall-rock breccia blocks.

Laminated textures in open fractures, parallel to bedding planes, are considered to indicate epigenetic sulphide precipitation within hydraulically dilated cavities together with gangue-mineral sedimentation. The floor of the cavity was the site of sphalerite mineralization by replacement, where zoned euhedra grew within carbonate and siliciclastic sedimentary detritus. In some cases replacive sphalerite laminae were capped by open-space-filling 'colloform' sphalerite growing into the ore fluid. By contrast, the roof of the open cavity was the site of semi-continuous precipitation of bulbous, colloform sphalerite in open space. Similar textures have recently been described from Navan (Andrew and Ashton, 1985) and an epigenetic origin ascribed.

The occurrence of 'sedimentary' features (compaction, flame structures, and slumping) associated with the laminated ore are considered to reflect the plastic behaviour of the saturated gangue detritus within the cavity zone, during the passage of ore fluid (*cf.* Gellatly, 1970).

WALL-ROCK ALTERATION

Adjacent to the remnants of sulphide-bearing ore, the partially dolomitized limestone wall rocks have been converted, for a distance of up to 0.5 m, to a grey-green, friable and incompetent rock consisting of 'sanded' smithsonite grains (to 50%), siliciclastic detritus (to 30%), and chamosite (to 20%).

This grey-green smithsonite-chamosite alteration aureole passes outwards through gradational zones of smithsonite rock (containing about 40 – 50% ZnO by weight in ankeritic, or iron-bearing dolomite up to 2 m in width) into unaltered dolomitic limestone within 5 to 10 m (Fig. 19).

In the inner smithsonite-chamosite alteration facies, smithsonite consists mainly of small, rounded to subequant, (hexagonal or elongate) dark-rimmed grains (up to 1 mm across) in a friable aggregate. Smithsonite rock consists of interlocking euhedral to subhedral grains (to 2

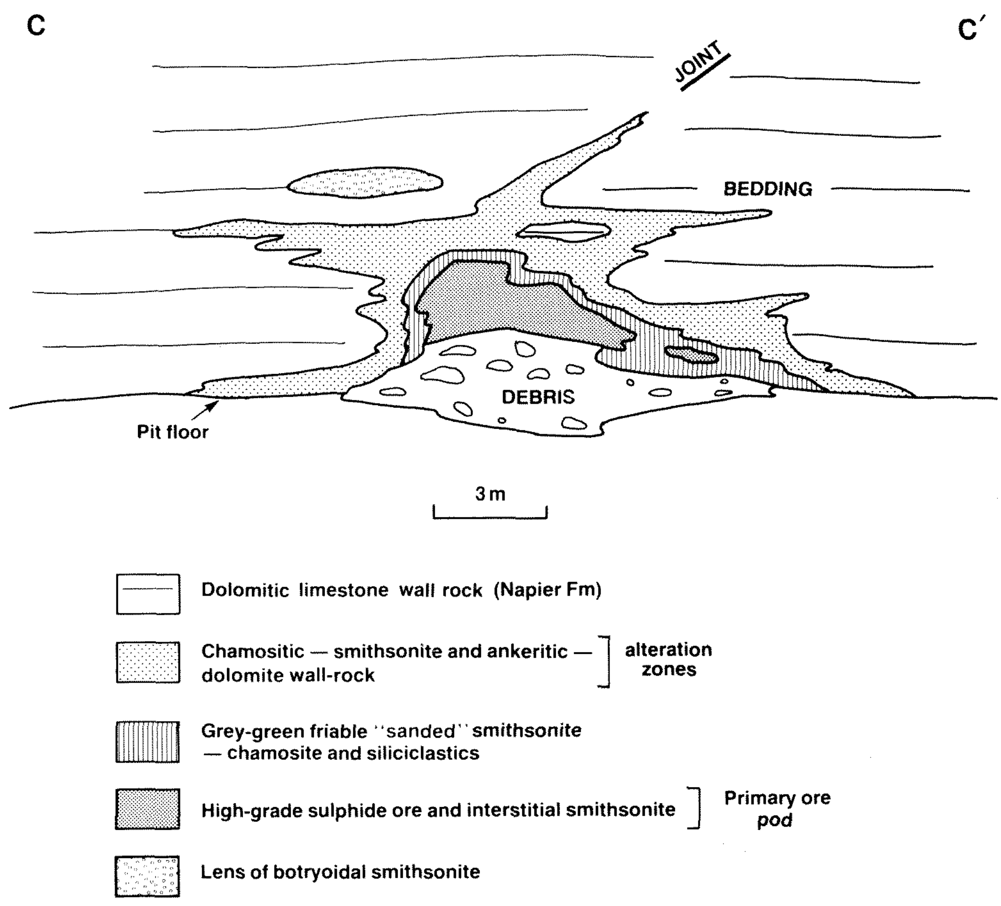


Figure 19. Sketch cross section (C – C[1] located on Fig. 18) illustrating the distribution of alteration zones around a remnant sulphide-bearing pod.

mm) that include a proportion of siliciclastic detritus. Euhedral crystals, of hexagonal cross-section or elongate petal-shape, occur less commonly throughout these facies.

Bedded and skeletal-botryoidal samples of sulphide-bearing ore also include crystals of smithsonite filling pore spaces. The mineral lines vughs interstitial to dendrites and botryoidal masses of sphalerite and galena. It is a translucent to bluish-grey, fine-grained mineral (to 1 mm in length) in crystalline, pyramidal aggregates. Hexagonal and petal-shaped euhedra are commonly observed in thin section.

Smithsonite grains are colourless to cloudy with weak to moderate cleavage, high relief (varying upon rotation), extreme birefringence and symmetrical extinction. Most crystals are finely zoned.

Sanded or pulverant carbonate grains (Lovering and others, 1949; Heyl and others, 1955; Jakucs, 1977) are rounded, cracked and etched, being the products of dissolution and disaggregation of wall-rock carbonate by fluid activity. Similar sanded carbonate textures in dolomite have been reported to be associated with the wall rocks of some Upper Silesian Pb-Zn ores (Sass-Gustkiewicz and others, 1982). However, chloritic and smithsonite-bearing alteration haloes are not associated with these deposits and are atypical of Mississippi Valley-type ore deposits in general.

Sanded wall rock, like the gangue of bedded ore, behaves plastically when water-saturated, and this property may have contributed to the creation of open spaces by wall-rock collapse during ore-fluid activity.

PARAGENESIS OF SMITHSONITE

The paragenetic position of smithsonite surrounding, and interstitial to, unoxidized sulphide is problematic. Smithsonite in this facies may have originated locally, as a metasomatic replacement of dolomitic-limestone wall rock and elsewhere as a precipitate, almost contemporaneous with sulphide precipitation. Alternatively, smithsonite of this facies may be the lowermost stratigraphic zone of the secondary orebody.

A primary origin for smithsonite is suggested by the following features:

(a) the smithsonite-chamosite wall-rock alteration aureole surrounds sulphide occurrences and decreases in intensity outwards;

(b) locally, smithsonite-chamosite pinches out upwards along faults and fractures;

(c) cross-cutting relationships of smithsonite-chamosite to sulphide are rare;

(d) sulphide pods and beds, which are surrounded by friable and incompetent smithsonite-chamosite wall-rock, show limited signs of fragmentation and/or disruption suggesting that wall-rock alteration was contemporaneous with sulphide precipitation.

A secondary origin for smithsonite of this facies is suggested by:

(a) its proximity to the oxidized secondary orebody which contains abundant smithsonite throughout.

(b) the occurrence of smithsonite between sulphide dendrites as the last-formed mineral of the paragenesis, clearly post-dating sulphide precipitation.

The formation of smithsonite in the primary, sulphide-forming environment requires that exceedingly high levels of zinc were present, in the absence of reduced sulphur, during ore-fluid activity. Specifically, if the ore fluid was similar to a basinal brine in terms of acidity, salinity and temperature, then over 23 000 ppm zinc would be required to form smithsonite (Ringrose, 1985).

Such high levels of zinc in basinal brines are highly unlikely given the known data from the analysis of oil-field brines and this would account for the absence of primary smithsonite in Mississippi Valley-type deposits. However, limited analyses (Czmanske and others, 1963) indicate that such high zinc levels in ore-forming solutions are not impossible. A primary origin for smithsonite at Narlarla, if correct, would imply that the ore fluid was not analogous to a typical basinal brine.

It is conceivable that the Nararla ore fluid was a basinal brine, with a major fluid component from a deep-seated magmatic source, and it carried sufficient metals in solution to form primary smithsonite. Alternatively, fluid-mixing processes at the ore site, that are indicated by ore textures (Ringrose, 1984), may have created local concentrations of zinc in solution by the dissolution of early-formed sulphide. However, neither of these possibilities is considered likely. There is no isotopic or fluid-inclusion evidence (Etminan and others, 1984) to indicate the activity of an ore-fluid with a magmatic-fluid component; also the remnant sulphide-bearing ore pods and lenses show no evidence of dissolution during growth.

Although the textural evidence remains equivocal, it is now considered more likely that the sulphide-smithsonite facies is secondary, being the boundary zone between truly unaltered primary ore below and oxidized ore above, at the level within the secondary orebody which is coincident with the top of the recent, fluctuating water table (Fig. 20). At this level, zinc-bearing groundwaters (percolating downwards through the sulphide orebody) precipitated smithsonite when they either became sufficiently reduced, or reacted with the carbonate wall rock (Fig. 20). 'Sanded' smithsonite and smithsonite rock formed by replacement of carbonate wall rock. Whereas, euhedral smithsonite occurring between sulphide dendrites and botryoids (close to the wall-rock contact) was precipitated from solution in open spaces. The redox potential of these groundwaters was also sufficiently low, during smithsonite precipitation, to preserve sulphide in an unoxidized state.

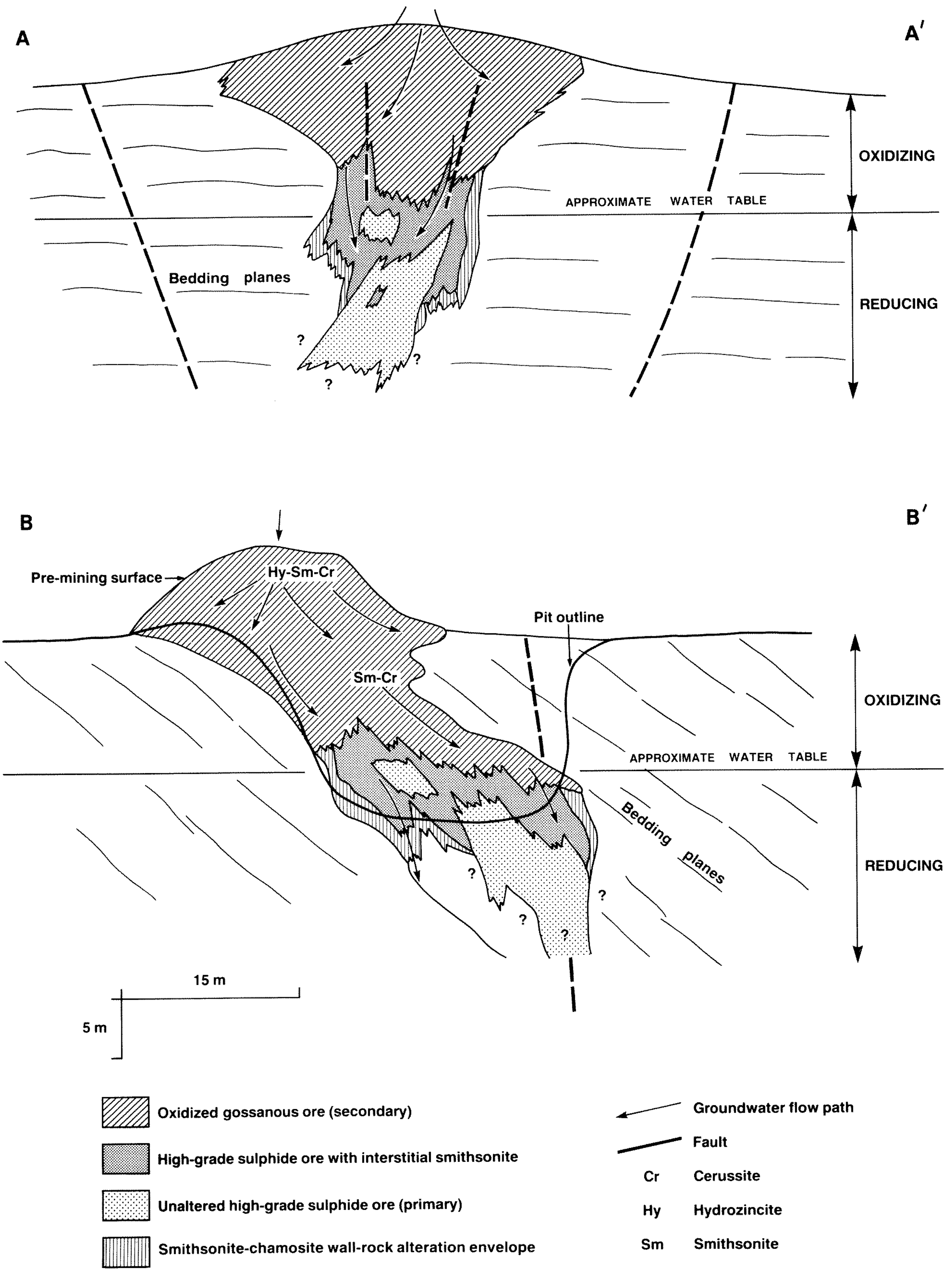


Figure 20. Cross sections (A – A[1] and B – B[1] located on Fig. 18) illustrating the pre-mining distribution of primary and secondary ore and alteration mineral zones. Groundwater flow paths and the approximate level of the water table during oxidation of the orebody are indicated.

The manner in which smithsonite alteration surrounds sulphide pods may be explained by the percolation of groundwaters through high-grade sulphide and out into wall rock, in a manner illustrated diagrammatically in Figure 20.

Primary wall-rock alteration most probably consisted of chamositic, ankeritic dolomite upon which secondary smithsonite replacement is superimposed. Groundwater flow has eroded this chamosite in places to be later deposited as chamosite-rich infillings, within pore spaces of skeletal-botryoidal sulphide.

SUMMARY OF PARAGENETIC SEQUENCE OF MINERALIZATION

The sequence of events (Fig. 21) which best accounts for the petrographic relationships and chemical equilibria observed, at both the No. 1 and No. 2 deposits, is as follows:

(a) During early diagenesis the calcareous and siliciclastic detritus, of the late-Devonian marginal-slope sediments, was lithified by submarine precipitation of calcium carbonate.

(b) Later in their burial history these rocks were compacted, dolomitized and stylolitized. In the Napier Range, dolomitization was patchy but locally pervasive and probably resulted from the regional migration of basin-derived compaction fluids. Precipitation of very fine-grained, disseminated pyrite (some nickeliferous, *i.e.* bravoite) and some sphalerite accompanied and marginally post-dated the activity of dolomitizing fluids.

(c) Chloritization which occurred patchily throughout the Napier Range was partly contemporaneous with, but mainly post-dated, dolomitization. Within this region chloritization was locally intense, along faults, and extended outwards into more permeable horizons. Faults acted as fluid conduits and as sites where fluids of diverse chemistry and/or temperature first mixed. An increase in porosity was associated with chloritization due to the reactivity of hydrogen ions generated.

(d) At some later time, metal-bearing solutions were localized at both the No. 1 and No. 2 deposits by these east-south-easterly trending faults. Sulphide deposition occurred where metal-bearing solutions intersected pre-existing, fluid-saturated zones of relatively high porosity. Mixing of the fluids caused rapid

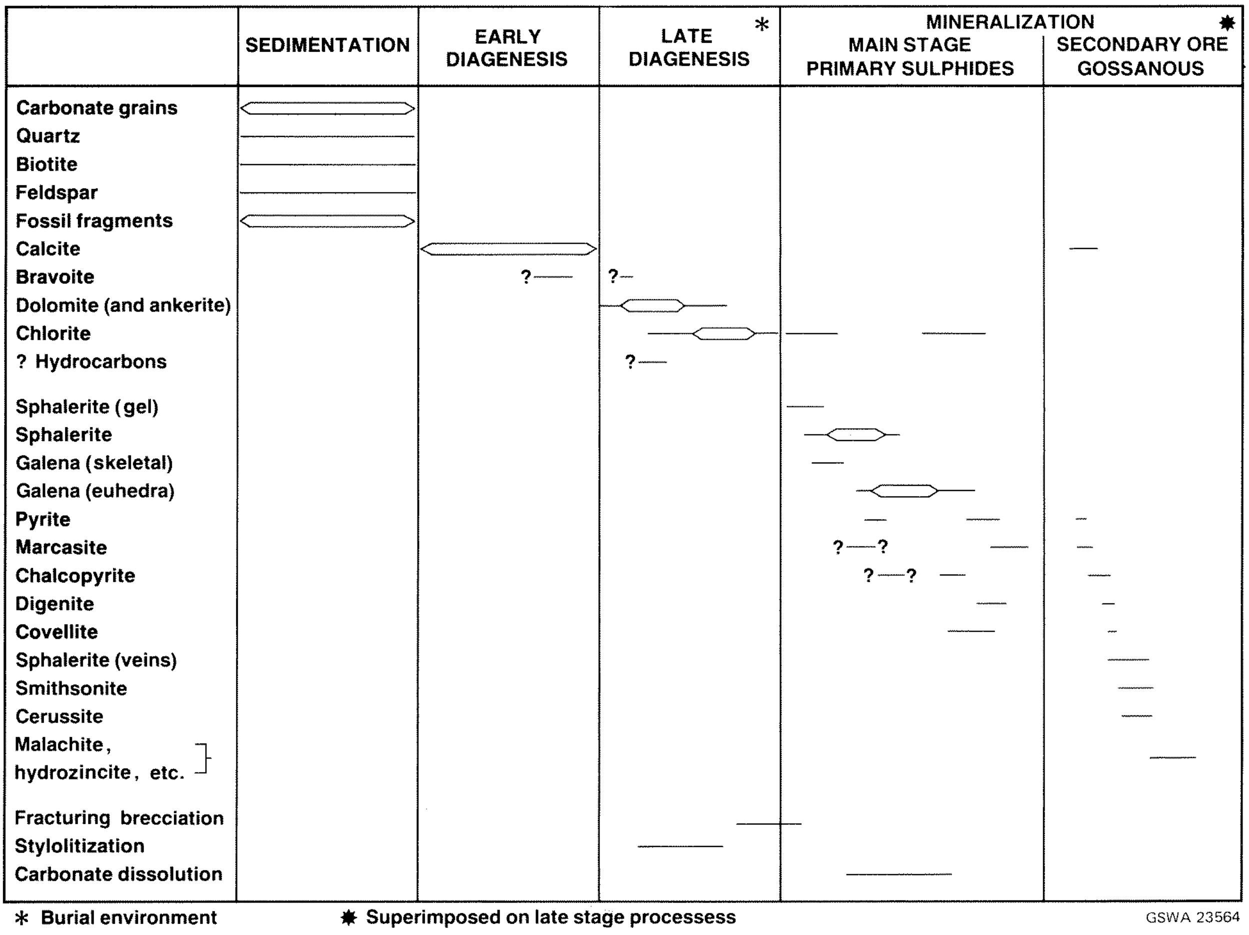


Figure 21. Paragenetic sequence of mineralization, Narlarla.

sulphide precipitation and chloritization with coincident local wall-rock dissolution, collapse, and open-space formation. These processes were recurrent and overlapping. The waning stage of metal-ion reactivity was accompanied, and post-dated, by further chloritization.

(e) Primary-sulphide ore was later oxidized by meteoric fluids.

DISCUSSION

Magnesium-rich brines, probably originating during compaction of basinal sediments to the southwest of Narlarla, were responsible for dolomitization and chloritization. These fluids may have incorporated the relatively high concentrations of iron, aluminium and silicon required for chloritization, by interaction with the large volumes of permeable, siliciclastic-rich units within the Napier Range embayment.

A basin-derived brine, containing metals, is favoured for ore formation which followed dolomitization and chloritization. The botryoidal-skeletal primary-ore textures are consistent with relatively rapid sulphide precipitation, and the mixing of two fluids seems to be the most likely mechanism to generate the required state of supersaturation. A second fluid may have supplied reduced sulphur to the metal-bearing brines or caused cooling and dilution of such a brine. It is conceivable that metal-bearing brines mixed with meteoric fluids, associated with the karst development of the pre-Grant unconformity, or 'spent' dolomitizing fluids within which sulphate ions had been reduced to H_2S.

The mineralized breccia, which hosts the secondary orebody and the extensive porosity exploited by sulphide precipitation, is considered to have developed in part during dolomitization and chloritization but mainly during sulphide precipitation. Sulphide formation, involving the interaction of zinc chloride ions with hydrogen sulphide, may have produced acid solutions which caused dissolution and brecciation of carbonate wall rock locally, as follows:

$$ZnCl^-_{(aq)} + H_2S = ZnS + Cl^-_{(aq)} + 2H^+_{(aq)}$$

The development of porosity during sulphide precipitation has been described from the Upper Silesia deposits by Saas-Gustkiewicz (1982).

It is also possible that the No. 2 orebody is developed within a karst cavity-breccia zone developed on the pre-Grant unconformity.

The east-southeasterly trending faults described as ore-fluid conduits to the Narlarla bodies are small structures of fairly insignificant displacement (up to 2 m). However, several faults of a similar trend have been mapped in the Napier Range, which suggests the possibility of a suite of approximately east-west structures in the region. These structures may be an expression of, or are complementary to, more significant basement faults. Large faults may have acted as primary conduits for basin-derived brines along which fluids were dispersed into permeable horizons and along minor adjoining faults. For example, the Narlarla deposits may be one locality where a set of small faults (easterly trending), shows a cross-cutting relationship with a large fault (northeasterly trending, as marked by the Barker River gorge).

At the Narlarla No. 2 site the orebody is localized along the main east-southeasterly trending fault at the intersection with the inclined facies boundary between the marginal-slope sediments and the anticlinal stromatolitic body. It is notable that the strike of this fault is subparallel to the bedding of the country rock and favoured fluid flow into the wall rock, via the fault conduit. By contrast, at the No. 1 site, the strike of the main fault is at right angles to the country-rock bedding.

THE BLENDEVALE PROSPECT

LOCATION AND HISTORY OF EXPLORATION

The Blendevale prospect is in the Limestone Billy Hills, at the northwestern end of the Pillara Range, some 30 km southeast of Fitzroy Crossing (Fig. 22). Reports of surface mineralization in this range were first described by Matheson and Guppy (1949). These led to the exploration of the region in general for Mississippi Valley-type ore deposits. Trend Exploration Pty Ltd initiated this search in 1971 and worked in conjunction with Shell Minerals between 1973 and 1976. Since then a joint venture partnership between BHP Minerals and The Shell Co of Australia Ltd (Minerals Division)*, who incorporate the interests of Trend and Amax Inc, have been undertaking a detailed geological investigation of the Limestone Billy Hills.

The early work by Trend, utilizing stream-sediment sampling and reconnaissance geology, identified the 'Pillara Spring area' (which included the whole of the Limestone Billy Hills) as a prime target. These studies were followed up with soil-sampling, I.P. surveying, and percussion drilling over the next two years. This drilling yielded a best intersection of 6.27% Zn and 4.35% Pb over a 28 m interval.

Shell became involved in 1974 and continued I.P. surveying and drilling without further success. BHP joined the exploration program in 1976 and commenced a grid-drilling program. To the end of 1977, this had yielded a best intersection of 10.58% Zn, 2.06% Pb and 17 g/t Ag, over the interval 168 m to 179 m.

Between 1978 and 1980 grid-drilling and geological investigations continued, with an expanded utilization of geophysical techniques including gravity, I.P., ground and airborne magnetics, natural gamma-ray, and downhole logging. By 1980 a large part of the exploration effort was being concentrated in the Blendevale area, a structural graben in the northern Limestone Billy Hills, which had emerged as the area of principal prospectivity (Fig. 22).

In 1981, work concentrated on a reassessment of the geology of the Blendevale prospect in order to provide a clearer picture of the stratigraphy, structure, distribution, and reserves of ore. This work was stepped-up in 1982 with detailed geological mapping (at a scale of 1:2500) and culminated in the publication of an integrated picture of the stratigraphic and structural development of the

* Now Billiton Australia.

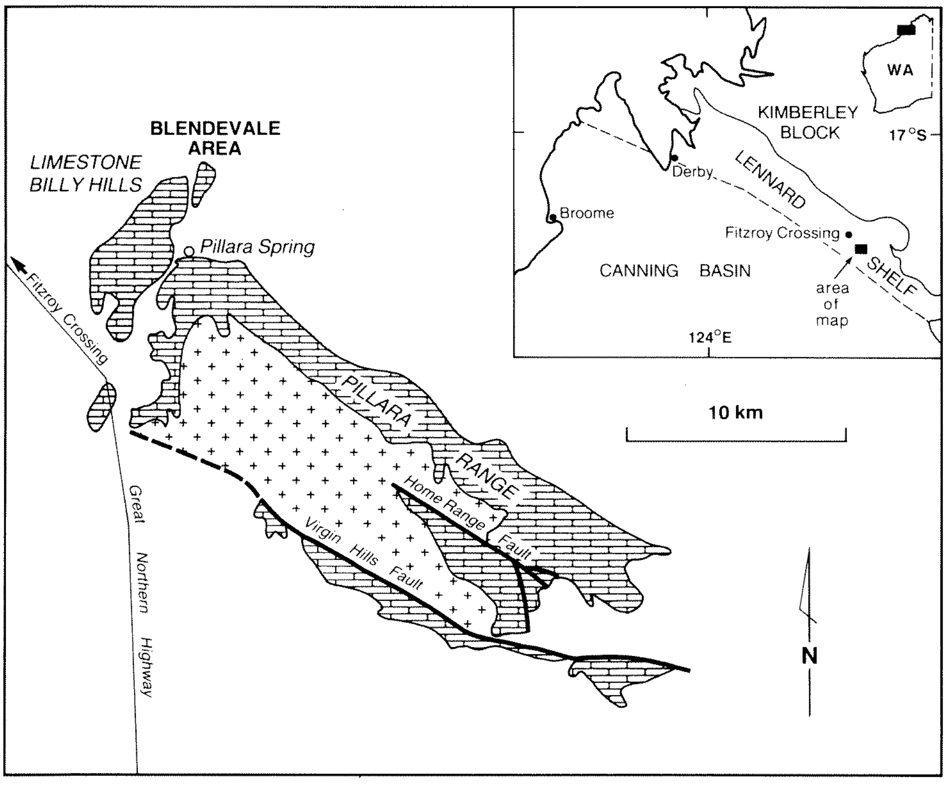


Figure 22. Location and geological setting of the Blendevale prospect, Limestone Billy Hills (from Hall, 1984).

Limestone Billy Hills (Hall, 1984). Drilling continued abreast of this mapping program with a steady increase in ore reserves defined.

During 1983, drilling was concentrated along faults, bounding the Blendevale graben, and some spectacular intersections were made, including 26% Zn, 8% Pb over the interval 520 – 550 m. By the end of 1983, the detailed drilling provided 311 diamond drill holes for 121 000 m of core (Hall, 1984). Recently published reserves suggest Blendevale is a marginal low-cost mine with 10 – 20 Mt grading 7% Zn and 4% Pb*.

GENERAL GEOLOGY

The Limestone Billy Hills is a reef-atoll complex of Givetian to Frasnian age cropping out over an area of 3 km by 9 km and separated, by a narrow gap, from the Pillara Range (Fig. 22). This gap is filled by clastic sediments indicating that the two ranges developed as individual carbonate platforms surrounded by deeper water (Hall, 1984).

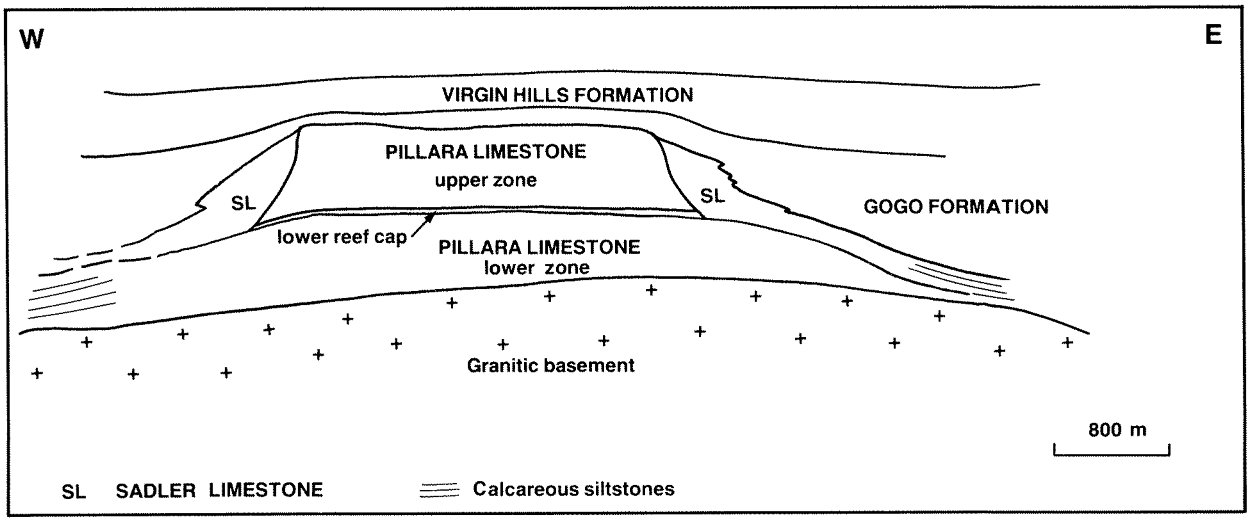
The reef complex is composed of fossiliferous, platform-facies limestone up to 750 m thick (Pillara Limestone, Fig. 23) built on Precambrian basement. In the lower part, the platform is flanked by calcareous siltstone and intercalated bioclastic debris flows. The upper part is fringed by distinctive reef-margin and marginal-slope limestones (Sadler Limestone, Fig. 23). This platform-facies limestone was buried beneath thinly bedded calcareous siltstone of basinal facies (Gogo Formation), during drowning of the reef, and (later) by maroon and green striped mudstone of the Virgin Hills Formation (Fig. 23). The latter facies is known only from drill core where it is up to 450 m thick in the area north and northeast of the Limestone Billy Hills.

The lower half of the platform limestone sequence consists of laminar and spherical stromatoporoid and coral-bearing, fenestral limestones. This section is separated from the upper half by a distinctive *Renalcis*-bearing, reef-cap limestone. The upper half comprises thick, stromatoporoidal and fenestral units bounded by a *Renalcis*-bearing, reef-margin limestone.

Throughout the Limestone Billy Hills the beds dip from subhorizontal to 30°, except in the marginal-slope facies where dips are up to 60° (of which 30° is depositional). The dips are uniformly to the north and northeast in the central and southern part, and in the north are directed both east and west defining broad folds with northeasterly axes (Fig. 24).

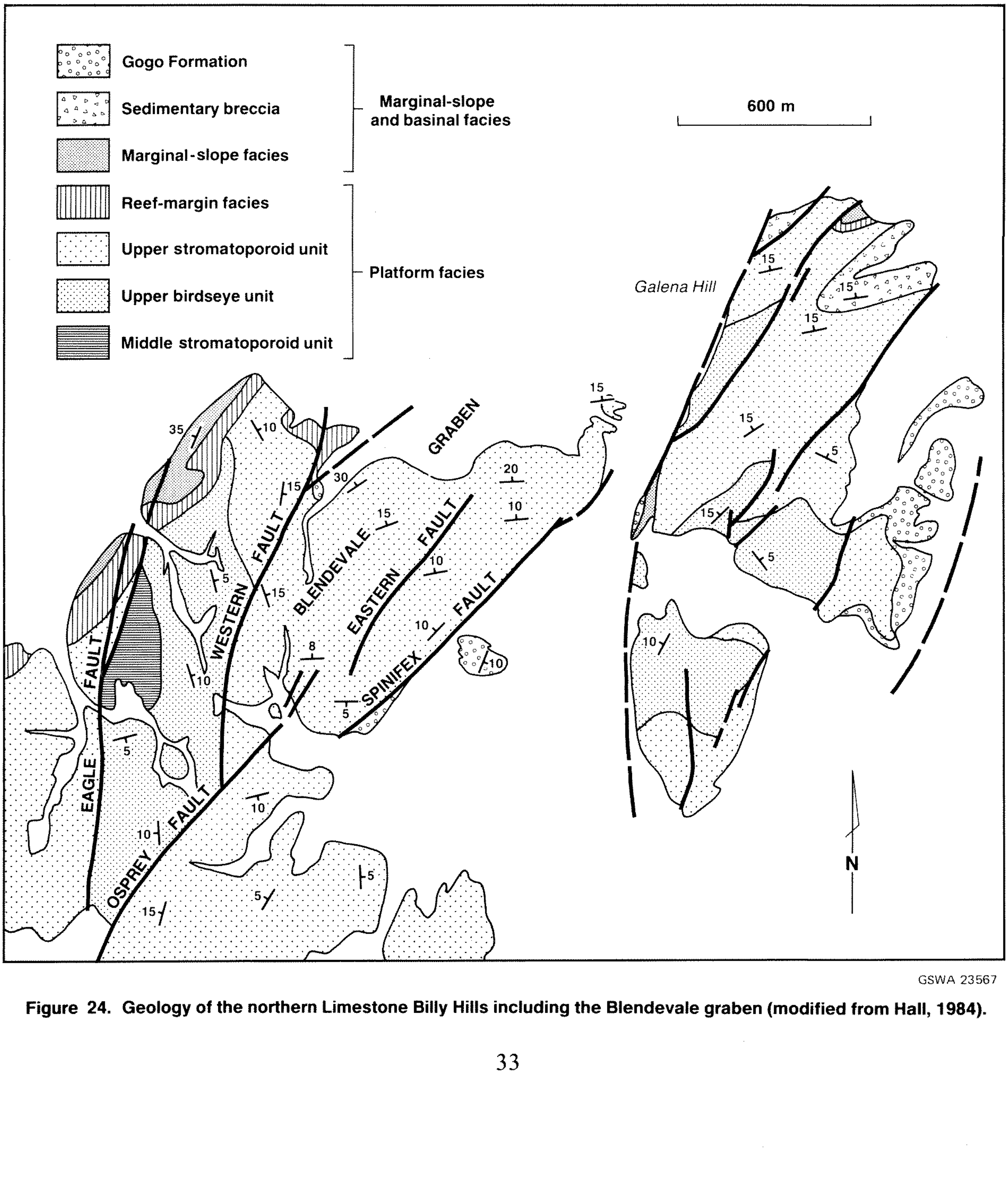
From an economic point of view, the most important structural feature is a series of northerly to northeasterly trending faults (Fig. 24). The southern Limestone Billy Hills consists of a graben and east and west horsts, with displacements on bounding faults ranging from 80 m to 150 m. In the northern area, the principal faults are named the Eagle, Spinifex (and its possible southern, *en echelon* extension, the Osprey Fault), Western and Eastern (Hall, 1984); the latter two faults bound the Blendevale graben (Fig. 24).

*Since the compilation of this report, the latest published figures for the Blendevale deposit are indicated geological reserves of 20 Mt of ore grading 8.3% Zn and 2.5% Pb, using a cut-off grade of 3% lead plus zinc, and 2.5 m minimum true width (Murphy and others, 1986).



GSWA 23566

Figure 23. Sketch cross section of the Limestone Billy Hills illustrating the main stratigraphic units and their relationships (modified from Hall, 1984).

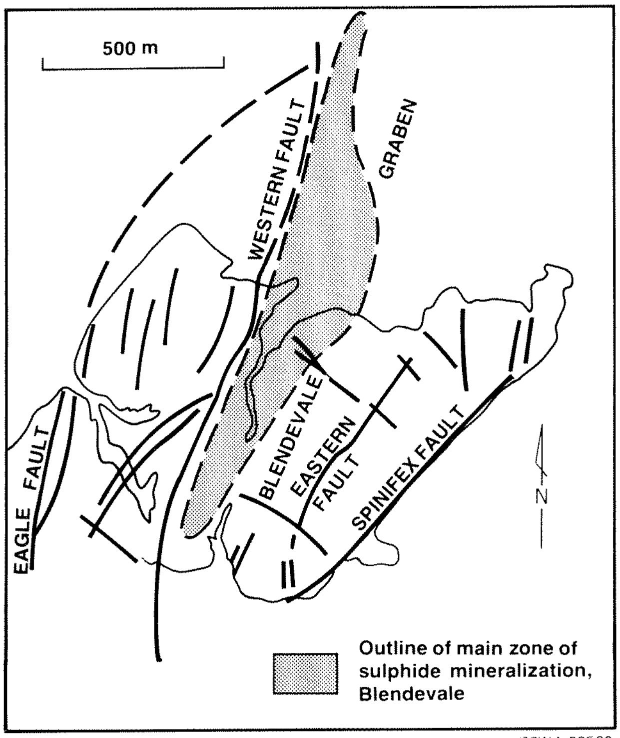


GSWA 23567

Figure 24. Geology of the northern Limestone Billy Hills including the Blendevale graben (modified from Hall, 1984).

GSWA 23568

Figure 25. Example of surface expression of sulphide mineralization at Blendevale. Tectonic and rubble breccia with a matrix of smithsonite-limonite-calcite after primary sulphides.



GSWA 23569

Figure 26. Outline of sulphide ore zone at depth in the Blendevale graben.

Displacement on the Western Fault, which is the principal structure localizing mineralization, is 100 m, while that on the Eastern Fault is 50 m. East of the Spinifex Fault, the Galena Hill area is cut by a series of northeast-trending faults, with mainly east-side-down displacements, which step the atoll carbonates down beneath the present surface.

Mineralization at surface consists of oxidized sulphide and coarse-grained calcite (spar) that rim coarse, angular fragments of limestone breccia (Fig. 25). The results of drilling in the Blendevale area have indicated that sulphides are localized irregularly, both horizontally and vertically, along the western margin of the Blendevale graben.

SHAPE AND EXTENT OF MINERALIZED ZONES

In plan view, the zone of sulphide mineralization within the Blendevale graben is an elongate body of variable width that runs parallel to the trace of the Western Fault. This zone, trending north-northeast, lies beneath the northern part of the Limestone Billy Hills and extends for approximately 1 km beneath the plains to the north (Fig. 26). The depth to sulphide varies from close to the surface (50 m) in the south to 600 m at about 1 km to the north of the northernmost outcrop of the limestone platform.

In section, the sulphide mineralization lies along the plane of the Western Fault and associated imbricated structures. It is preferentially developed in a zone where the fault intersects a thick fenestral-limestone unit of the upper half of the platform. Stratabound mineralization is developed within this limestone unit and accounts for the varying width of the sulphide zone in plan. The distribution of sulphide is further complicated by the presence of numerous complementary and accessory faults.

STYLES OF MINERALIZATION

The sulphide mineralization in the Blendevale graben consists predominantly of marcasite, sphalerite, and galena, with gangue calcite. There are four styles of mineralization: veins and veinlets; disseminations within wall rock adjacent to breccia zones; replacements and open-space fillings of breccia matrices; and crusts rimming breccia clasts. Only trace amounts of other sulphides (chalcopyrite and bravoite) are present. Wall-rock alteration, such as silicification or dolomitization, is absent.

Veins and veinlets observed in drill core consist of broadly sinuous to 'zig-zagging' fissure fillings of sulphide and/or calcite, which vary in width from 1 to 10 cm (Plate 9). Individual veins are generally thin (to 2 cm), impersistent, irregular, and anastomosing. The sequence of mineral precipitation within any vein is consistent with marcasite precipitated first, followed in turn by sphalerite, sphalerite with galena, galena, and calcite.

Disseminated sulphides occur most commonly in *Amphipora*-bearing, fenestral limestones. Grains of sphalerite (up to 2 mm in diameter) line the fenestrae and appear to pre-date the equant spar that fills these cavities (Plate 9).

Mineralized breccia is the most common sulphide-bearing lithology (Plate 10). Four main breccia types are defined in this report: tectonic; rubble; mosaic; and crackle (Plate 11).

Tectonic breccias generally consist of small, rounded to subangular fragments of limestone wall rock, with some sulphide fragments, from 0.1 to 2 cm in size. These clasts are set in a very fine-grained, dark-grey matrix of milled calcite with disseminated-sulphide granules.

Rubble breccias consist of angular to subrounded fragments of limestone of various facies, (generally from 1 to 5 cm in size) in a chaotic arrangement. The clasts are randomly oriented and unsorted and may be either clast-supported or matrix-supported. Open spaces in these breccias may be filled by sulphide and/or calcite and clasts are often rimmed by a thin rind (up to 1 cm) of sulphide.

Mosaic breccias are the most common sulphide-bearing breccia type. They consist of angular, irregularly-shaped fragments of limestone cemented by calcite and/or sulphide. Fragments are generally of a similar rock type, and although locally rotated, they are not displaced any distance from their original position.

Crackle breccias consist of anastomosing vein-networks of spar (up to 0.5 cm in width) that criss-cross limestone. The veinlets may represent more than one generation. A few breccia samples contain very minor amounts of barite intergrown with calcite as matrix.

SPATIAL INTERRELATIONSHIP AND GENESIS OF BRECCIAS

The breccia types described above are considered to have formed by a combination of tectonic, hydraulic, and solution-collapse effects, that were related to the activity of mineralizing fluids ascending along fault zones (Fig. 27).

Tectonic breccias mark the actual plane of fault movement and the immediate wall rock, for a distance of up to a maximum of 1 m. Cataclasis was responsible for the crush and fault breccias developed within the brittle limestone.

Tectonic breccias have margins of rubble breccias formed by the dual effect of carbonate dissolution and hydraulic fracturing. It is envisaged that mineralizing fluids were introduced periodically along fault planes, concomitant with fault movement. The fluids acted upon wall rock to cause hydraulic fracturing, some carbonate dissolution, and paring-off of fragments. These gathered (chaotically) into open voids and small caves, along the length of the fluid conduit. "Snow-on-roof" sulphide textures in rubble breccias indicate that downward-percolating fluid also precipitated sulphides during breccia formation. Fluids may have been dammed at depth as a water sill (against an impermeable fault) before fault movement permitted them to ascend locally under high pressure. After the loss of hydraulic head and permeation into wall rock, fluids would descend locally along conduits.

Rubble breccias grade into mosaic breccias as the heterogeneity and disorientation of breccia clasts decreases. Mosaic breccias grade into crackle breccias in a similar manner. (Fig. 27).

SULPHIDE MINERALOGY AND TEXTURES

The sulphides occurring in the mineralized zone of the Blendevale graben are a simple assemblage of marcasite, sphalerite, and galena, with minor amounts of pyrite and accessory chalcopyrite; their properties are summarized in Table 4. The majority of sulphide grains were formed by growth in open spaces, while the rest are replacive and disseminated.

Marcasite is the most widely distributed sulphide. It occurs dispersed throughout the platform limestone and marginal-slope facies in minor quantities, but is generally absent from the Gogo and Virgin Hills Formations. Two principal forms are recognized: very fine-grained, disseminated euhedra (0.02 to 0.2 mm in size); and coarse-grained euhedra (0.2 to 2 mm in size, averaging 0.6 mm). Both forms occur as rinds to breccia clasts, they line fissure walls, and they are rarely disseminated within micritic infillings of breccias.

Very fine-grained euhedra are generally rectangular to rhombic in form and occur most commonly in the silty, micritic matrices of breccias. The coarser grained disseminated euhedra (occurring as breccia-clast rinds and cavity fillings) are rectangular, bladed, and 'spear-shaped' marcasite forms (Plate 12). Locally, coarse-grained euhedra form thick, botryoidal bands up to 1 cm in width.

Zinc sulphide is the most abundant economic mineral of the prospect. The proportion of zinc to lead ranges from 10:1 to 1:1, with a ratio of 4:1 being typical. Both wurtzite (hexagonal) and sphalerite (cubic) polymorphs are present.

Previous studies (Moyle, 1980) have concluded that wurtzite (hexagonal) is the dominant zinc sulphide polymorph and that sphalerite (cubic) is subordinate (5 to 35% of the zinc sulphide present). This study confirms that, in transmitted light, there is an anisotropic zinc sulphide phase (probably wurtzite). However, the presence and abundance of sphalerite developed from wurtzite has not been tested by x-ray methods (optical examination is indeterminative). The relative abundance of wurtzite and sphalerite is therefore not defined in this report. For simplicity both zinc sulphide polymorphs are henceforth referred to as sphalerite. No genetic significance is attached to the presence and possible dominance of wurtzite over sphalerite.

Sphalerite occurs in three forms: as fine to coarse-laminated 'colloform' bands and botryoidal overgrowths to breccia clasts and linings to fissure walls; coarse-grained, zoned euhedra in veins and vughs; and disseminated euhedral grains.

Bands or crusts of colloform sphalerite make up the dominant form. They are composed of laminae (from 0.02 to 4 mm, averaging 0.1 mm in width)

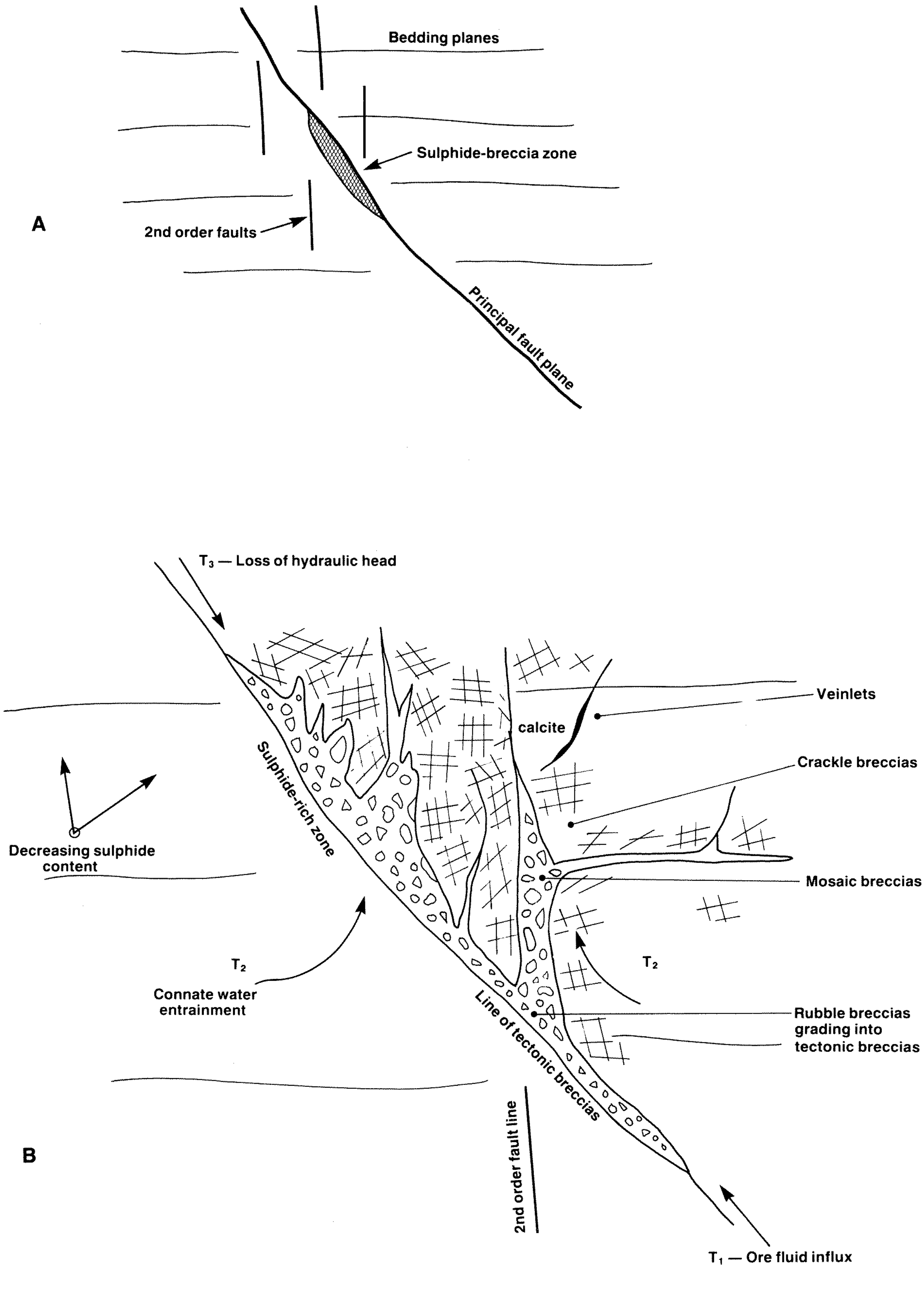


Figure 27. Idealized spatial relationship of sulphides and breccia types along a fault in the Blendevale graben: A) in general, and, B) in detail. Fluid flow direction during a pulse of mineralization is indicated from early to late ($T_1 - T_3$).

TABLE 4. SULPHIDE MINERALOGY, PARAGENESIS AND TEXTURES, BLENDEVALE

Sulphide	*Grain size (mm)*	*Grain form*	*Texture*	*Paragenetically associated sulphide(s)*	*Host (rock or mineral)*	*Distribution*	*Paragenesis*	*Comment*
Sphalerite (1)	0.02–0.4	Fine to coarse grained, polycrystalline druses	Concentrically banded laminae of druses of different colours (yellow, brown, purple) as botryoidal overgrowths in open-spaces	Galena (1)	Fractures and cavities in limestones	Along fault conduit and in wall-rock breccias. "core" zone to mineralization	Main Stage	Tendency is for fine to coarsely laminated colloform sphalerite to develop with time during botryoidal growth.
Sphalerite (2)	0.2–0.6	Coarse-grained hexagonal or cubic euhedra	Coarsely laminated 'colloform' sphalerite often overgrown by euhedral grain growth towards vein centre	Galena	Fractures and cavities in limestone	Upper (stratigraphic) levels of mineralization	Main Stage	Characteristic sector twinning and sector colour zoning
Galena (1)	0.1–0.5	Anhedral, skeletal to lath-like	Inclusions in finely laminated 'colloform' sphalerite	Sphalerite (1)	Sphalerite	"Core" zone	Main Stage	—
Galena (2)	1–8	Euhedral, octahedral or cubic	Inclusions in finely or coarsely laminated sphalerite or as last phase of botryoidal rimming	Sphalerite (1) + (2)	Sphalerite	"Core" zone and upper stratigraphic levels	Main Stage	—
Galena (3)	5–20	Euhedral, cubic	Enclosed within vein filling, coarse-grained calcite	—	Calcite	Deep stratigraphic levels	Late Main Stage	—
Pyrite (1) (some bravoitic)	0.005–0.2	Euhedral, cubic	Disseminated in micritic matrices to breccias	Marcasite	Micrite	Upper stratigraphic levels	Early Main Stage	—
Pyrite (2) (marcasitic) colloform	0.01–0.2	Polycrystalline druses	Parallel orientation of elongate crystals in botryoidal growths	Sphalerite (1)	Fractures and cavities	Lowermost stratigraphic levels	Earliest Main Stage	Dark coloured pyrite in normal illumination and under reflected light, possibly due to included solid ?carbonaceous matter

(Continued overleaf)

TABLE 4. SULPHIDE MINERALOGY, PARAGENESIS AND TEXTURES, BLENDEVALE—*continued*

Sulphide	*Grain size (mm)*	*Grain form*	*Texture*	*Paragenetically associated sulphide(s)*	*Host (rock or mineral)*	*Distribution*	*Paragenesis*	*Comment*
Marcasite (1)	0.02–0.2	Euhedral, rhombic to rectangular	Disseminated in micritic infills and wall rocks	Pyrite (1)	Fractures and cavities	Upper stratigraphic levels	Early Main Stage	—
Marcasite (2)	0.4–1	Euhedral, rectangular bladed, and 'spear' forms	Rims to breccia clasts and vein wall; growth into open-space	Sphalerite (1)	Fractures and cavities	Lower to upper stratigraphic levels	Early Main Stage	—
Marcasite (3)	2–10	Euhedral, elongate	Parallel orientation of crystals in botryoidal growth	Pyrite (2)	Fractures	Lowermost stratigraphic levels	Earliest Main Stage	—
Chalcopyrite	0.4	Anhedral fragments	Fragments in brecciated sulphide zone	Sphalerite (1) galena (1)	Fractures	Lowermost stratigraphic levels	Early Main Stage	A few grains only

of differently coloured sphalerite ranging from white-yellow to red-brown (Plate 13) in bands growing up to 5 cm in total width. These crusts are not colloform in the genetic sense (*i.e.* deposited from colloidal suspension) but are similar in texture and origin to 'colloform' sphalerite described by Roedder (1968b) who considered that such textures had originated by crystallization of minute sphalerite druses from true solutions.

The individual laminae comprising each crust are crystals of sphalerite, elongated perpendicular to the vein wall or breccia-fragment surface. The colour-banding runs parallel to the vein walls or fragment surface. Individual crystals are arranged in a subparallel manner to yield a radial-columnar or fibrous appearance (Plate 13), which may cross several laminae. The laminae may be smoothly botryoidal to crenulated on their outer surfaces, depending upon the size of the crystals and the presence or absence of dissolution. Crenulated laminae are composed of a series of fine-grained, polycrystalline druses with euhedral terminations, whereas smoothly botryoidal laminae may be of extremely fine-grained sphalerite, or be formed by dissolution of euhedral crystal terminations. The length of the crystals yields a finely or coarsely laminated texture.

The earliest formed sphalerite exhibits the best developed and most finely laminated growth banding, whereas later formed sphalerite is coarser grained and uniform in colour. The coarser grained zones reflect periods of quiescence and uniformity of composition of the depositing fluid.

Although the sphalerite growth-zone 'stratigraphy' is very complex, in general it is evident that several repeated cycles occur. Sphalerite growth in each cycle begins with precipitation of a yellow, inclusion-rich zone grading through red-brown laminae, and ending with pale-yellow to watery clear laminae, with or without solid, dark, included material. Up to five of these cycles were counted in one sample.

Coarse-grained zoned euhedra of sphalerite (0.2 – 0.6 mm in size) occur as the outermost layer of botryoidal crusts or are disseminated within limestone wall rock or micritic-matrix infills.

Galena occurs in two principal associations: as anhedral to subhedral inclusions within banded sphalerite (Plate 13); and as coarse-grained, cubic euhedra in association with coarse-grained clear calcite (spar). Galena inclusions in banded sphalerite are octahedral to cubic (1 to 8 mm in size) where they have grown at the termination of a sphalerite-precipitating cycle; or they are subhedral, elongate or dendritic (0.1 – 0.5 mm in size) where they have grown contemporaneously with the elongate sphalerite grains that comprise colloform banding. A few samples in heavily mineralized intersections contain dendritic galena, in growths up to 1 cm across in association with sphalerite.

Coarse-grained, cubic galena euhedra are up to 2 cm across, averaging 1 cm, and are restricted in occurrence to paragenetically late, calcite veins.

Accessory sulphides occurring at Blendevale include: pyrite (some bravoite), 'colloform' pyrite, and chalcopyrite.

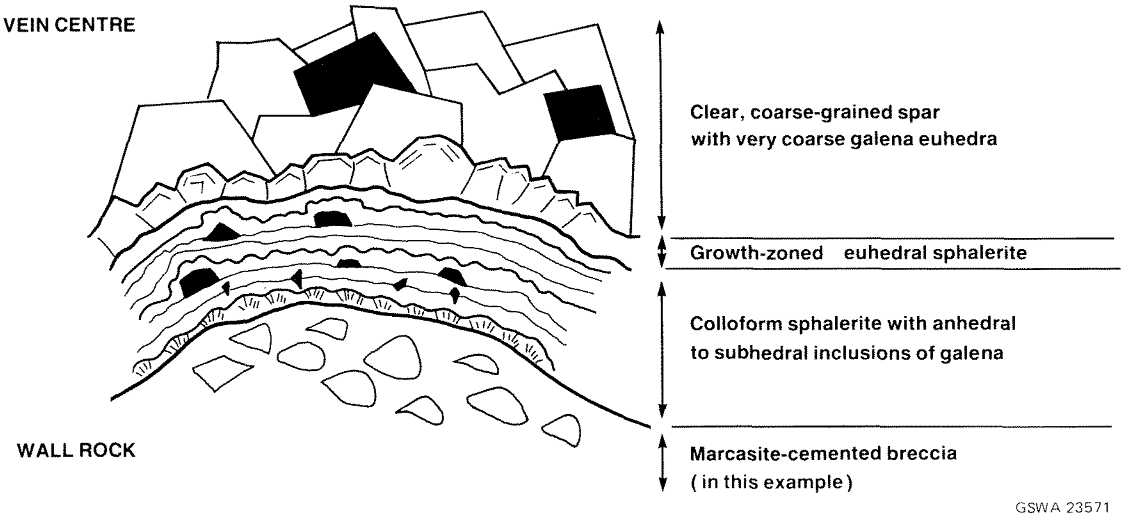


Figure 28. Idealized paragenetic sequence of mineralization within a vein or as a clast coating, Blendevale.

Pyrite and bravoite (nickeliferous pyrite) occur as very fine-grained disseminated grains (up to 0.2 mm) which accompany the very fine-grained marcasite granules, present within micritic matrices to breccias.

'Colloform' pyrite (or melnikovite pyrite) is a dark, inclusion-rich, yellow-brown sulphide in reflected light. It is composed of thin, botryoidal laminae (0.01 – 0.2 mm in width) of pyrite or marcasite whose crystals are arranged perpendicular to the growth surface, in a manner similar to that of 'colloform' sphalerite (Plate 12).

Chalcopyrite was observed in only one sample. It occurs along a fracture, cutting a strongly mineralized intersection (sphalerite and galena 30%) as grains (0.2 to 0.4 mm in size) and it replaces sphalerite clasts and marcasite grains, but is post-dated by further sphalerite growth.

PARAGENETIC SEQUENCE OF MINERALIZATION

The paragenetic sequence of mineralization is illustrated in Figures 28 and 29.

Samples of mineralized limestone, from throughout the Blendevale graben, *invariably* illustrate that marcasite was the first sulphide to have precipitated. Marcasite has grown as disseminations in micritic infills or in open-spaces around breccia clasts which themselves possess a thin to thick (2 – 10 mm) rind of coarse-grained, inclusion-rich, fibrous spar. This textural relationship indicates that, locally, breccias were cemented by spar-precipitating fluids, which occluded some porosity prior to the influx of sulphide-forming fluids.

The fine-grained variety of marcasite, which is spatially associated with bravoitic pyrite, is the

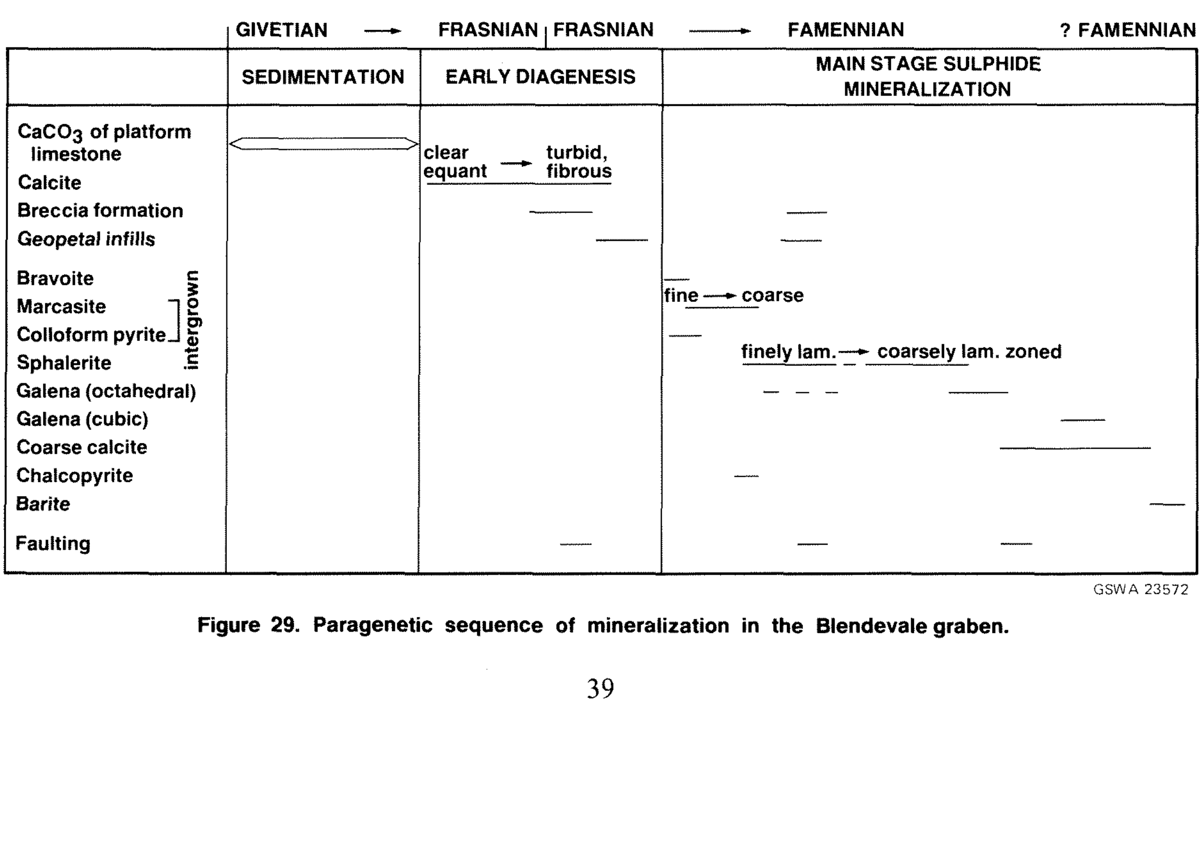


Figure 29. Paragenetic sequence of mineralization in the Blendevale graben.

earliest-formed of the marcasite mineralization followed by the coarser grained variety rimming the breccia clasts.

Marcasite growth is followed by the precipitation of finely laminated, colloform, botryoidal sphalerite which includes anhedral blebs of galena, and locally, octahedral galena subhedra at the termination of a sphalerite growth cycle. Only very minor dissolution (if any) of sphalerite or galena, interceding between each lamina of sphalerite in 'colloform' growth, has occurred.

Breccias containing clasts of finely laminated colloform sphalerite indicate that fault activity occurred during sulphide mineralization. Locally, sulphide breccia clasts are rimmed by sphalerite indicating that sulphide precipitation and fault activity were coincident.

With time, precipitated sphalerite becomes more even in colour and the 'colloform' laminae are of a coarser grain. The latter stages of sphalerite growth are accompanied by increased galena precipitation and are post-dated by the precipitation of a galena-calcite, fissure-filling event.

'Colloform' pyrite formed earlier than any other sulphide, including marcasite, in the deepest part of the mineralizing system in the north. Here also, the formation of 'colloform pyrite', sphalerite, and minor marcasite was accompanied by minor chalcopyrite.

DISTRIBUTION AND ZONATION OF SULPHIDES

An overall pattern of zonation of sulphide mineralization within the Blendevale deposit is suggested from available evidence (Fig. 30), although patterns of sulphide distribution are very complicated on a local scale.

A limited number of barite-bearing samples were examined which suggest that the upper and outermost zone of mineralization may be marked by calcite-barite precipitation in veins, open spaces and breccia matrices.

Within the platform limestone in general, marcasite is ubiquitous and has a large vertical and lateral distribution. It forms a definite, broad, dispersed aureole to more localized fault-controlled sphalerite-galena mineralization.

Lying within this aureole of iron sulphide impregnation is a zone of relatively rich galena mineralization which is accompanied by coarsely laminated, euhedral-granular sphalerite, marcasite, and spar.

This zone is laterally controlled by bedding. A zone of mixed sphalerite-galena mineralization (with sphalerite dominant) accompanied by marcasite and spar lies closer to the main fault (the ore-fluid conduit) within this zone.

In the deepest part of the mineralized-fracture system, in the northern area, sphalerite is dominant. Here the sphalerite is finely laminated, with anhedral inclusions of sphalerite, and is associated with 'colloform' pyrite and very minor chalcopyrite. The distinctive calcite-galena vein-filling mineralization is also restricted to this portion of the mineralizing system.

DISCUSSION

The rigid, cemented, platform limestone of the Blendevale area was apparently first fractured and faulted towards the end of its development as a reef atoll, *i.e.* just prior to deposition of the Gogo Formation in the Frasnian (Hall, 1984). The

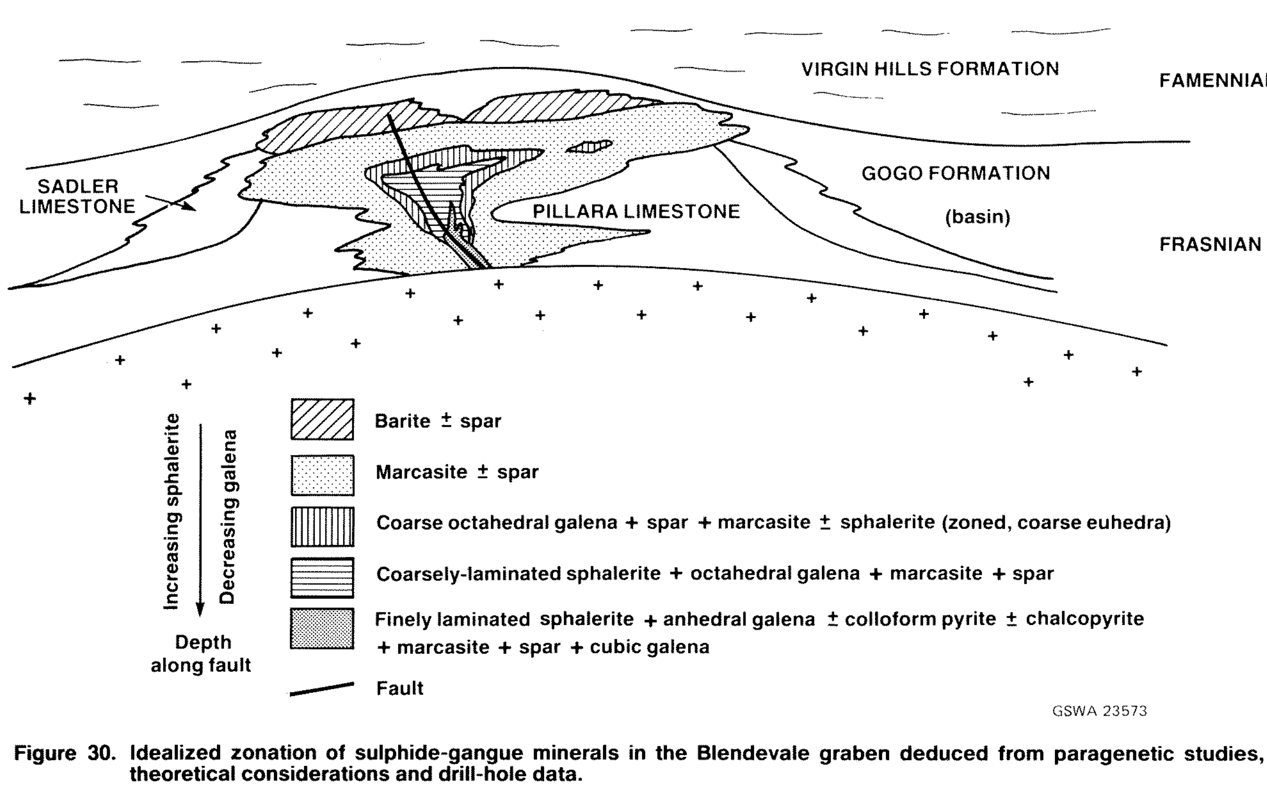


Figure 30. Idealized zonation of sulphide-gangue minerals in the Blendevale graben deduced from paragenetic studies, theoretical considerations and drill-hole data.

earliest fault activity reactivated neptunian dykes and opened new fractures that became the loci of breccia formation and fluid flow.

At this time, sediment of the Gogo Formation filtered downwards into breccia cavities in the shallowest parts of the platform. However, seawater penetration probably occurred to a greater depth causing cementation of breccia fragments by a fibrous, turbid calcium carbonate.

The incursion of metal-bearing fluids occurred at some later time and followed a further period of fault activity and brecciation. Fluids permeated the western fault zone of the graben and the well-fractured wall rocks adjacent to this zone, depositing marcasite, sphalerite and galena. Precipitation of sulphides occurred in open spaces of tectonic rubble and mosaic breccias and within the upper fenestral limestone, where some stratabound mineralization developed. The occurrence of geopetal infills, that post-date some sphalerite, suggest that at least some sulphide mineralization occurred at a time when the platform was still shallow enough to receive fracture-controlled, downward-filtering sediment.

The increase in the depth to ore and the intensity of mineralization in a northerly direction (in general within the Blendevale graben) suggest that the metal-bearing fluids were derived from the north. In this area basinal-facies sediments accumulated contemporaneously with the Givetian-Frasnian and Fammenian reef-atoll development. It seems probable that these shales were undergoing compaction while the reef atoll was undergoing burial and fracturing, and that fluids expelled from these shales carried the metals that were introduced episodically into the platform.

The first to precipitate were the finely laminated, 'colloform' sphalerite and the small amount of sphalerite with dendritic galena. These textures are consistent with relatively high supersaturation, which resulted in relatively high rates of nucleation and crystallization (Roedder, 1968b). These conditions may have been brought about by cooling, drop in pressure, or mixing with an H_2S^- bearing fluid. The change to coarse-grained minerals with time is consistent with a decrease in the concentration of solutions, possibly due to dilution of ore fluids by connate waters from the wall rocks.

The origin of the colour variation in laminated sphalerite is unknown. Studies of similar sphalerites have revealed no differences in major or minor element content (Roedder, 1968b; Sverjensky, 1981). They may reflect variations in trace element content or they could be caused by films of coloured organic compounds on sphalerite growth surfaces.

THE SORBY HILLS PROSPECT

LOCATION AND HISTORY OF EXPLORATION

The Sorby Hills lead-zinc prospect lies within the southeastern, onshore portion of the Bonaparte Basin, approximately 55 km by road northeast of Kununurra, in the far northeastern corner of Western Australia (Fig. 31).

Indications of lead-zinc mineralization in this basin were first recorded from Cuesta Ridge by Mines Administration, in 1956, while mapping during an oil-search program. However, evidence from sample piles and stones forming claim corners suggests that cerussite had been discovered by the early (pre-1900) prospectors (Legge and others, 1984).

Other early indications of base-metal mineralization were recorded prior to the 'discovery' of Sorby Hills, but no great significance was attached to these reports. For example, in 1960, lead mineralization was intersected in the Spirit Hill No. 1 oil well (Fig. 31) and galena in a dolomite outcrop near the northeast tip of the Pincombe Range was reported by Rod (1966).

It was not until July/August 1971 when geologists of Bureau de Recherches Gēologiques et Miniēres (BRGM) sampled the area around Sorby Hills and recognized the significance of the lead mineralization at outcrop, that the first mineral claims were pegged.

By September of 1972, 250 mineral claims had been pegged in the Sorby Hills, Jeremiah Hills and Ningbing areas (Fig. 31) by joint venturers Australian Aquitaine Minerals and Serem. Work completed in the first year of exploration included mapping, gravimetry, I.P. surveying, and drilling: twelve diamond drill holes and 118 auger holes (for bedrock geochemistry).

Although diamond drilling during this period yielded many intersections of low-grade lead-zinc mineralization, no continuous orebody was found. However, geochemistry identified a large, weak, northerly trending lead-zinc anomaly beneath the alluvial black-soil plain just to the east of the Sorby Hills. In 1973, BRGM completed work at the 'discovery' outcrops, confirming that no economic ore was present, before turning their attention to the site of the large, weak, geochemical anomaly.

During 1973, 485 holes totalling 6 930 m (of which 16 were diamond holes) were drilled into the anomaly. These together with I.P. surveys were intended to outline the extent of the geochemical anomaly. During this work, significant quantities of ore-grade mineralization were intersected and a substantial deposit was inferred.

In 1974, drilling in conjunction with I.P. surveys was undertaken (on a 400 m grid spacing) along east-west lines across the ore trend. An airborne-magnetometer survey was also flown to plot the gradient of the Precambrian basement. The conclusions of this work were that lead-zinc mineralization was stratabound, locally rich enough to form discrete orebodies, and that potential existed for northern and southern extensions of the ore trend.

By the end of 1975, drilling had delineated several pods of lead-zinc sulphide (labelled 'A' to 'J', Fig. 32) along the ore trend. In 1976 and 1977 work was directed at testing areas to the north and northwest of the Proterozoic Pincombe Inlier and successfully extended the known mineralization once more. Ore intersections were outlined in the

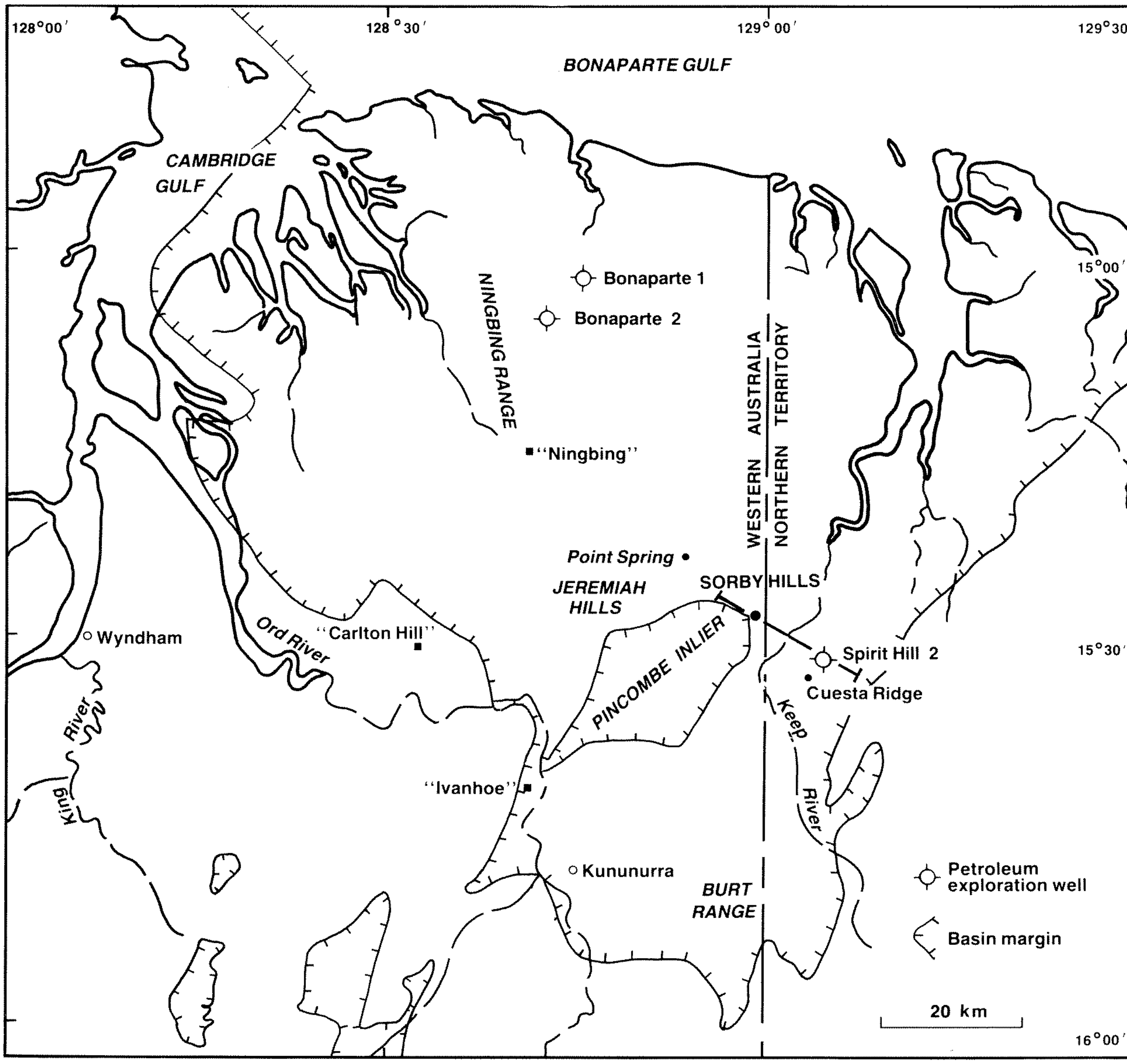


Figure 31. Location and geographical features of the Sorby Hills locality (from Laws and Brown, 1976).

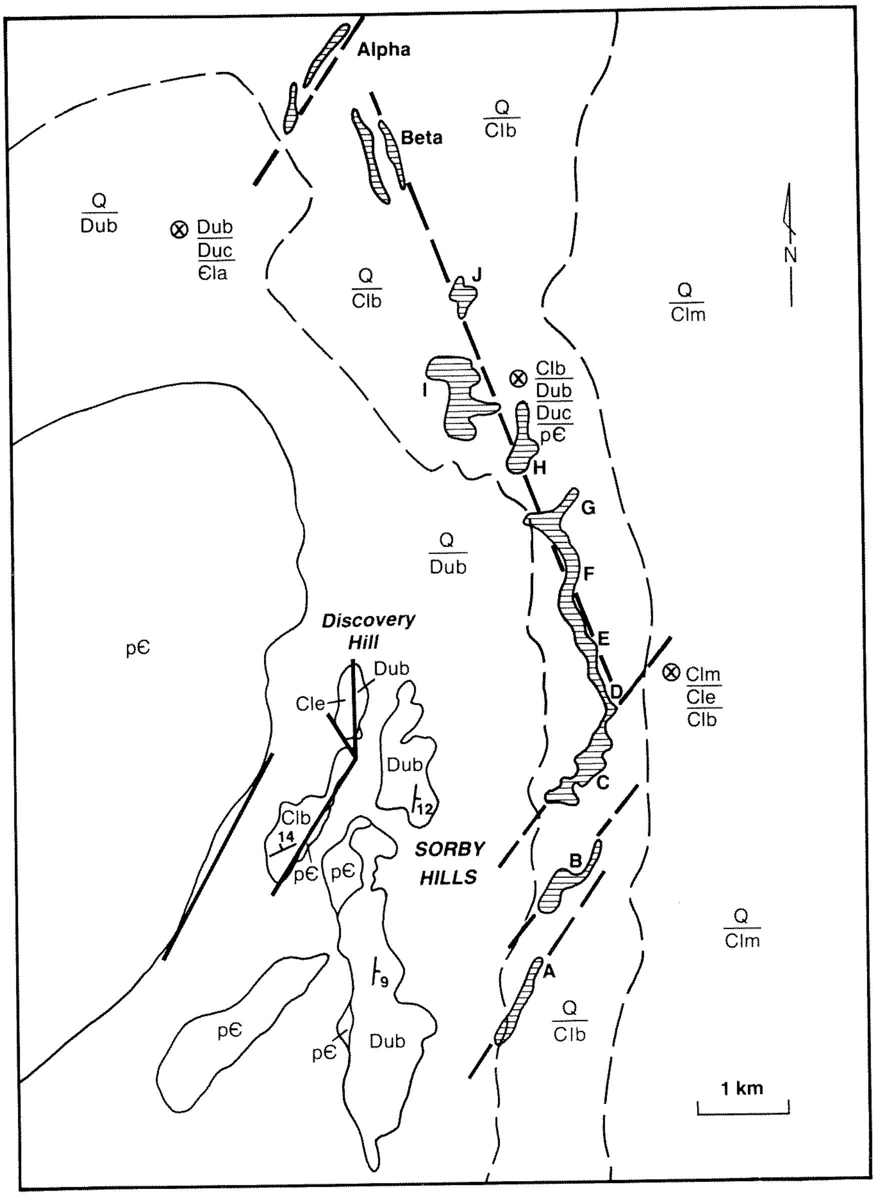
'Alpha' and 'Beta' trends, and to the north and west of the Alpha trend (Fig. 32).

The next significant development occurred in 1979 when an attempt was made to construct an exploration decline into ore pod 'I' (Fig. 32). The decline was abandoned due to excessive water inflow and ground instability problems. Also during this year, Mimets completed their acquisition of Serem's interest in the Sorby Hills and Jeremiah claim groups to form a joint venture with Aquitaine. By year's end, using geophysical surveys, gamma-ray logging, palaeontological studies and further drilling, it was concluded that the potential for a large tonnage of ore was not great and the easily extractable, closely spaced discrete orebodies offered the best chance for mine development. During 1980 a hydrogeological program was carried out as a follow-up to the abandoned decline.

In 1981, a significant development was the participation of St Joe Bonaparte Pty Ltd (who eventually became joint venturers with Aquitaine, MIM Holdings, and Mimets, in March 1982), a subsidiary of the St Joe Co. of the USA with interests in the world-famous South-East Missouri lead-mining district. During 1981 and 1982, drilling was undertaken to increase the known reserves and identify areas of greatest potential for thicker, high-grade lead ore adjacent to the known pods.

However, in 1983 the vigorous exploration was scaled down and work mainly involved relogging of old core. Also during 1983, the Sorby Hills camp equipment was auctioned off. In May 1984 the Jeremiah Hills exploration licence was relinquished and the joint-venture structure was rearranged. MIM Holdings Ltd withdrew from the joint venture in July 1984. The joint venture currently (1988) involves Triako Resources Limited and BHP Minerals*.

*Since the compilation of this report the latest published figures at Sorby Hills show a resource of 16.25 Mt grading 5.3% lead, 0.6% zinc and 56 g/t silver in several discrete areas, using a cut-off grade of 2.5% combined lead plus zinc and 3.0 m minimum thickness (Rowley and Lee, 1986).



Q	Quaternary	
Clm	Milligans Formation	Carboniferous
Cle	Enga Sandstone	
Clb	Burt Range Formation	
Dub	Buttons Formation	Devonian
Duc	Cockatoo Group	
Єla	Antrim Plateau Volcanics	E. Cambrian
pЄ	Precambrian	
⊗	Borehole, with sequence penetrated	

Outcrop boundary

Inferred boundary

Subcrop of ore pods 'A' to 'J' and Alpha + Beta

Faults and inferred faults

GSWA 23575

Figure 32. General geology of Sorby Hills and location of lead-zinc ore pods (geology from Mory and Beere, 1988).

GENERAL GEOLOGY

The Sorby Hills are five small hills that rise to approximately 80 m above the black-soil plain, at the northeastern tip of the Pincombe Inlier (Fig. 32) and comprise Proterozoic, Devonian and Carboniferous rocks (Mory and Beere, 1988). The Palaeozoic strata include the Buttons Formation, the Burt Range Formation, and the Enga Sandstone, which overlie Proterozoic quartz sandstone, conglomerate, ferruginous sandstone, red siltstone and shale of the Pincombe Inlier (Figs 32 and 33).

The Buttons Formation consists of fine to medium-grained, sandy carbonate units with interbedded green to grey shale and rare stromatolitic boundstone. It represents a lagoonal facies of the Devonian reef complex (Ningbing Group) and overlies the rocks of the Pincombe Inlier with angular unconformity, implying that this Precambrian island was emergent at the end of the Devonian.

The Burt Range Formation in this area consists of massive and thin to medium (0.3 to 1 m), parallel-bedded dolomite with minor thin interbeds of shaly dolomite. The Enga Sandstone is a unit of quartz sandstone with minor shale and calcarenite beds with body fossils and *Skolithos*. In general these beds dip 10° to 20° eastwards. There are no exposed contacts of the Burt Range Formation or Enga Sandstone against the Proterozoic Inlier in the Sorby Hills area, but form basinwide sedimentological considerations, Mory and Beere (1988) infer that the inlier was not an emergent feature in the Tournaisian.

Evidence from drill-hole data indicates that the sedimentary section to the east of Sorby Hills, beneath the black-soil plain, includes (locally) in addition to the outcropping units, Cambrian Antrim Plateau Volcanics, Devonian Cockatoo Group, Carboniferous Septimus Limestone, and an extensive area of Milligans Formation (Figs 32 and 33).

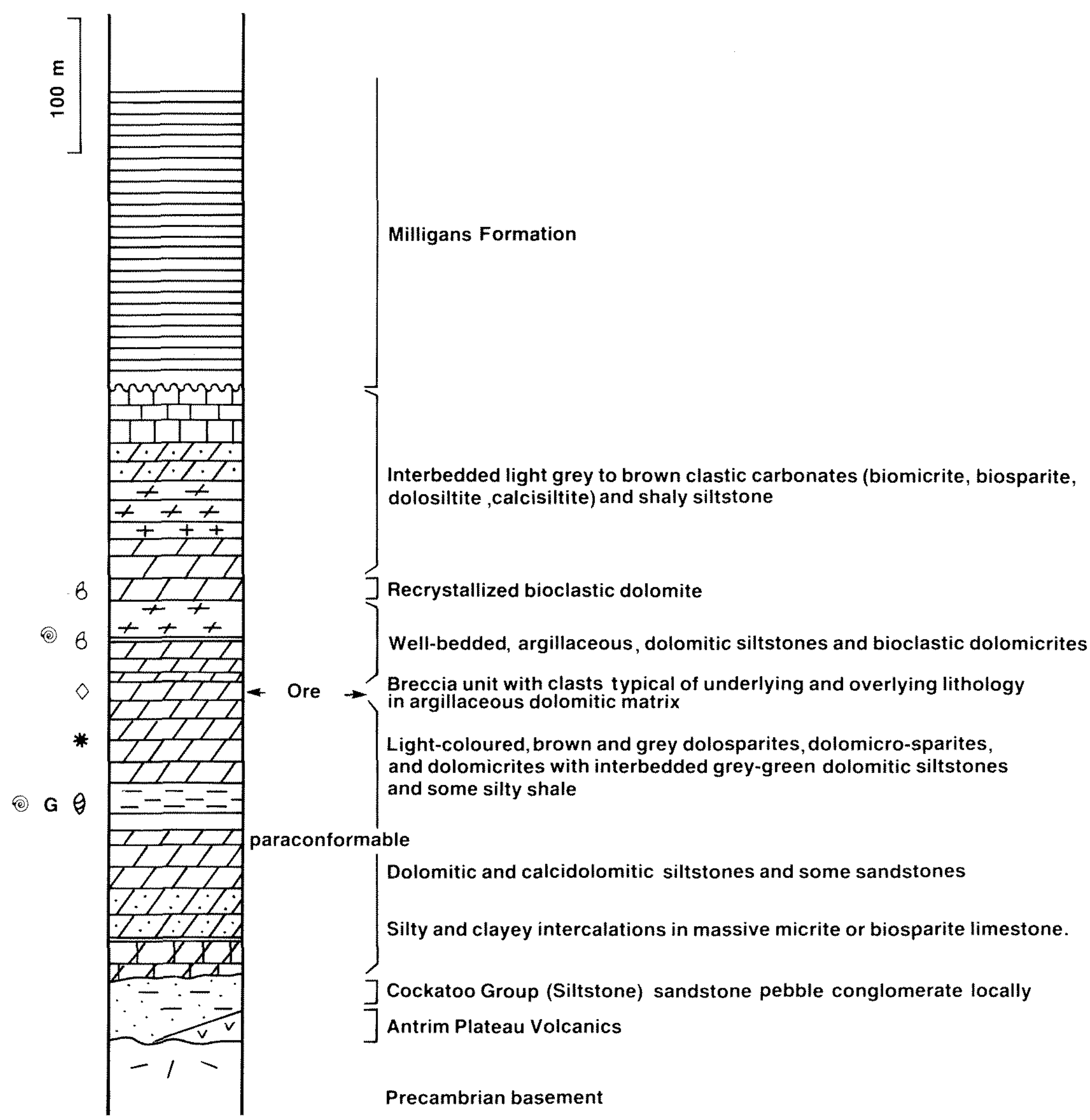


Figure 33. Generalized lithological section of the Sorby Hills area.

The Antrim Plateau Volcanics are purple, vughy, weathered, and altered basalts. The Cockatoo Group consists of a lower portion of sandstone and pebble conglomerate and an upper sequence of siltstone (buff, red to maroon, and green), rare sandstone, and sandy dolomite. The Septimus Formation is lithologically similar to the Burt Range Formation and has only been distinguished by age determinations on drill-hole samples. The Milligans Formation is a transgressive sequence consisting of Visean black shales which unconformably overlie the Tournaisian sediments.

Faulting of the Devonian and Carboniferous sediments includes north-northeasterly, northerly and north-northwesterly trends. North-northeasterly faults may be related to the faults of a similar trend cutting the Pincombe Inlier, which may have been active during Devonian and Carboniferous sedimentation and related (in turn) to movement on the Cockatoo Fault system. Northerly and north-northwesterly oriented faults may be related to left-lateral wrench movements on the northeasterly trending Cockatoo and related faults (Laws, 1981).

The northerly trending faults have strike-slip movement whereas the north-northwesterly features may represent tensional fracturing conjugate to the wrench movement. Such fault activity may have generated syndepositional breccias, bed thinning, and pinch-outs during the Tournaisian. These faults may also have acted as ore-fluid conduits.

An outcrop of sulphide mineralization occurs on the northernmost of the Sorby Hills, aptly named Discovery Hill (Fig. 32). Here, disseminations of medium- to coarse-grained euhedra of galena (0.2 to 0.8 mm in size) can be seen within brecciated sandy dolomite of the Burt Range Formation, along the length of the fault which bisects the hill (Figs 32 and 33). An oxidized zone of mineralization occurs near the southern tip of Discovery Hill, commonly referred to as the Discovery Hill gossan.

PETROLOGY OF THE HOST ROCKS

The sulphide mineralization at Sorby Hills occurs mainly within the lower portion of the Burt Range Formation, approximately 100 – 120 m above the basal, conformable contact of this unit with the underlying Buttons Formation (Fig. 34). The principal host horizon is a bedded sedimentary breccia, 0 – 15 m in thickness, with angular to subrounded fragments of underlying dolomite and other clasts in a matrix of dolomitic siltstone. This breccia developed during slumping and reworking, associated with fault activity, and is locally buried by shale, thus providing optimum conditions for sulphide deposition. Other breccias, which are also mineralized, occur locally. These include tectonic breccias and solution-collapse fault-related breccias.

Sulphide mineralization at a deeper level within the lower Burt Range Formation is present in mud wackestone and dense, argillaceous dolomite; locally, mineralization is found immediately below the overlying Milligans Shale contact and in the Buttons Formation.

As well as the abovementioned stratabound mineralization in the lower Burt Range Formation, an interesting, low-grade, lead-silver-barium

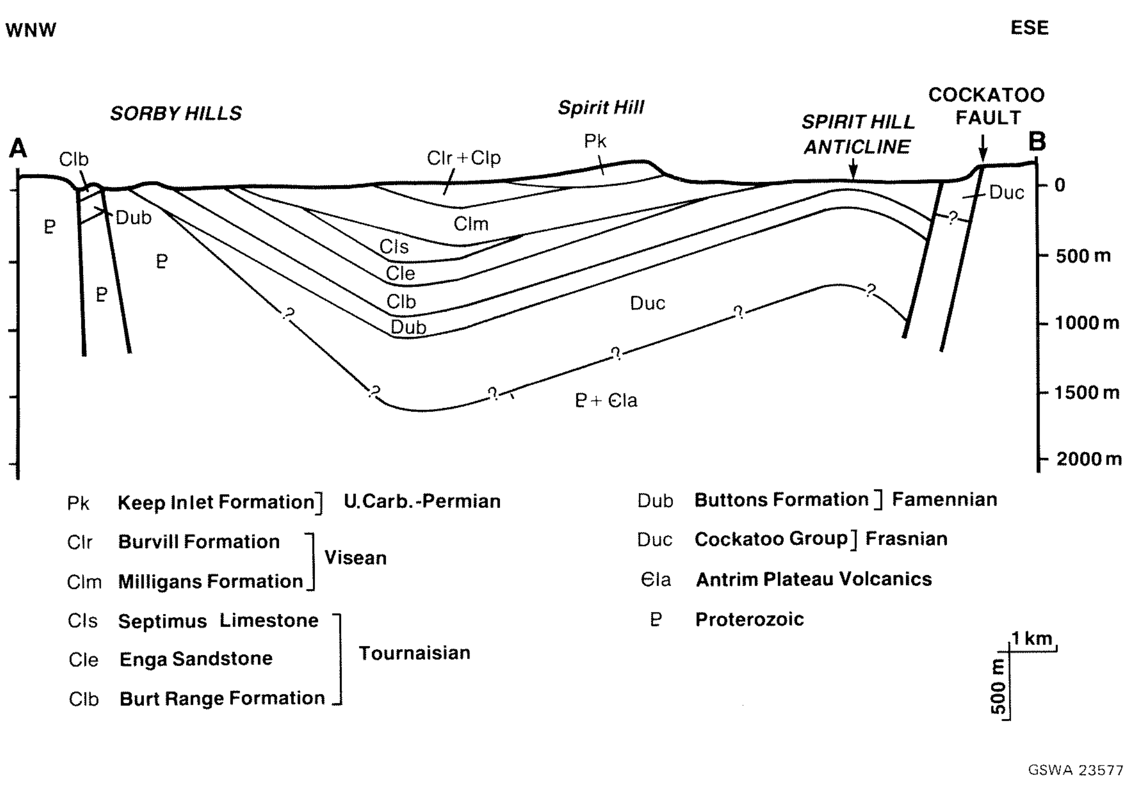


Figure 34. Generalized cross section of the Burt Range Shelf in the Sorby Hills to Spirit Hill area (drawn by G. Beere, GSWA).

(2% galena and 2 – 4% barite) mineralized zone has been intersected basinward of Pod D in a dolomitized fine-grained sandstone, within the upper 100 m of the Burt Range Formation.

Pervasive dolomitization of the silty, argillaceous carbonate of the Burt Range Formation has generally produced a rock consisting of fine- to medium-grained, interlocking dolomite euhedra approximately 0.1 to 0.4 mm in size. A second, cross-cutting, dolomitization event, in which veins of coarse-grained (or 'saddle') dolomite (0.6 to 1 mm in size) are dominant, occurs throughout the sequence. Saddle dolomite crystals, with characteristic undulose extinction and curved crystal faces, were precipitated in several pulses to form fracture linings (Plate 14).

Silicification, taking the form of secondary, euhedral overgrowths over sedimentary grains of silt locally accompanied dolomitization. Sphalerite mineralization with included doubly-terminated quartz crystals is common (Plate 14).

Barite occurs as bladed crystals (up to 5 × 3 mm), with poorly bedded orientation, and as a cement with calcite in some angular, ?tectonic breccias. In the bedded occurrences, barite clearly includes detrital grains indicating a post-sedimentation age (Plate 14).

In places, elongate, petal-shaped crystals (possibly pseudomorphs after gypsum) occur embedded in pervasive pyrite mineralization (Plate 14).

SHAPE, EXTENT, AND STYLES OF MINERALIZATION

The lead-zinc mineralization at Sorby Hills consists of a north-trending line of discrete bodies. These include seven ore 'pods' ('A' to 'J'), and two mineralized trends ('Alpha' and 'Beta', Fig. 32), that lie approximately 1.5 km to the east of the perimeter of the Pincombe Inlier. The spatial relationship of these mineralized pods to the stratigraphic units clearly indicates the stratabound nature of sulphide occurrence (Fig. 32). The linearity of some of the trends implies fault control of ore.

Individual pods are up to 700 × 500 m across, although three closely spaced pods ('E' to 'G') form a semi-continuous zone, 1.2 km in length, in the central part of the ore trend (Fig. 32). The mineralized intersections within these pods, dominated by galena and sphalerite, have a thickness of 1 to 10 m, averaging 5 m. The concentration of galena varies from 3 to 7%, averaging 5%, and of sphalerite from 0.5 to 2%, averaging 0.8%. Silver occurs in concentrations of 12 – 95 g/t (in sulphide) and has an average value of 40 g/t.

Sulphides occur in several different styles: as disseminations within dolomitized shaly siltstone and intraformational breccia matrices; as fracture or vugh linings with accompanying gangue of saddle dolomite or calcite; as rims to solution-collapse breccia clasts; as veins and thick seams or 'beds' of coalescing euhedra, without gangue, in dolomite; and as irregularly shaped replacement patches (Fig. 35 and Plate 15).

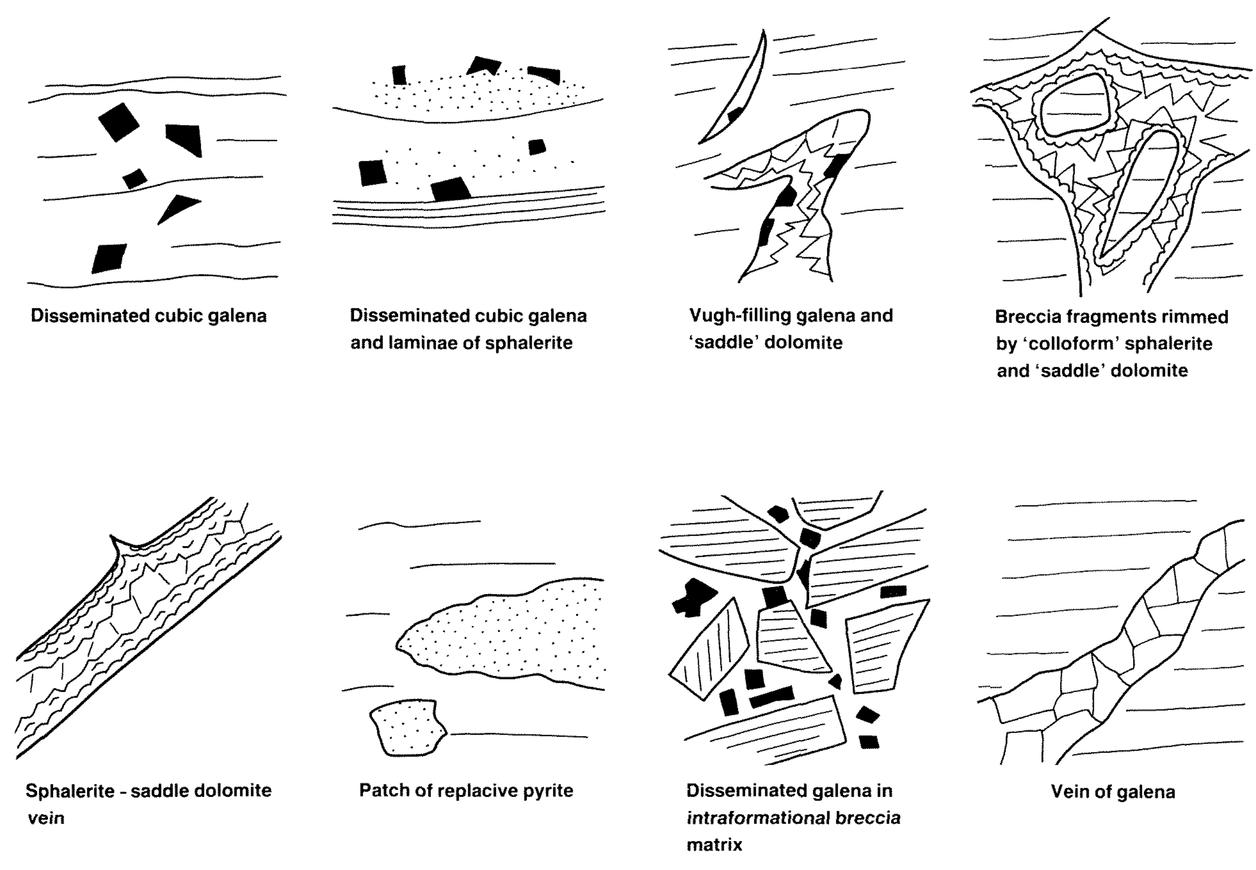


Figure 35. Styles of sulphide mineralization at Sorby Hills (host rock is dolomitized, shaly limestone).

SULPHIDE MINERALOGY AND TEXTURES

The sulphide-mineral assemblage at Sorby Hills is dominated by galena with abundant sphalerite and pyrite. Mineralized intersections contain galena and sphalerite in proportions that vary from 30:1 to 1:1, averaging 6:1. Iron sulphide may comprise up to 30% of the sulphides in mineralized intersections. Accessory sulphides include 'colloform' pyrite, marcasite, chalcopyrite, tetrahedrite-tennantite, and pyrargyrite-proustite. Sulphide-mineral characteristics are summarized in Table 5.

Galena is the most common economic sulphide. It occurs in dolomitized host rock as disseminated euhedra, coalesced euhedra in rich seams and veins, and euhedra lining fractures and vughs.

Disseminations of galena euhedra range in size from fine to coarse (0.1 to 8 mm) and include lath-like, cubic, and octahedral forms. Thee grains occur in dolomitized shaly siltstones, as rims to patches of sphalerite mineralization within a similar host rock, and commonly within the matrices of intraformational breccias (Plate 15). Individual euhedra locally coalesce to form galena-rich, bedding-parallel seams (up to 7 cm in width) or form sinuous, cross-cutting veins. Contacts between galena euhedra and carbonate grains are generally mutual with no evidence of corrosion. Growth of galena has occurred mainly by poikilitic growth *in situ*, as indicated by inclusions of silt or dolomite grains (Plate 16).

Galena euhedra, lining fractures and vughs, range in size from 1 to 7 mm, averaging 3 mm (Plate 16) and are spatially related to 'saddle' dolomite veins and vugh fillings.

Sphalerite occurs in three principal forms: as disseminated to coalesced fine- to medium-grained euhedra forming patches and bedded seams; as 'colloform' rims to breccia clasts; and as coarse-grained euhedra lining fractures and vughs.

The most common form of sphalerite is disseminated, zoned subhedra to euhedra of cubic or hexagonal shape. Grains range in size from 0.1 to 0.8 mm, averaging 0.3 mm, and in colour from pale yellow to reddish brown. Colour zonation is common, generally from light to dark brown outwards from the grain centre. Sphalerite grains have mutual to cross-cutting contacts with dolomite.

Locally, euhedra coalesce to form pervasive 'beds' up to 4 cm in width within which grains of euhedral quartz are conspicuous and carbonate is rare (Plate 16).

'Colloform' rims to breccia clasts consist of numerous very fine-grained laminae of sphalerite (0.1 to 0.4 mm) each composed of crystals, oriented perpendicular to the growth surface, to yield a radial to columnar structure (*cf.* Blendevale sphalerites). Intergrowth of 'colloform' sphalerite with dolomite is mutual.

Zoned euhedra, lining fractures, are coarse-grained and characterized by distinctive colour zones of yellow, red, brown, or black (Plate 16). These euhedra may be nucleated on a core of 'colloform' sphalerite.

Iron sulphides found at Sorby Hills include pyrite, marcasite and 'colloform' pyrite. Pyrite, which is most common, occurs as follows: as fine-grained, disseminated subhedra to euhedra (0.05 to 0.5 mm in size, averaging 0.3 mm) which locally coalesce to form replacement patches 2 to 10 cm across; as framboidal grains (0.05 mm in size); as large euhedra forming disseminated porphyroblasts 2 – 5 mm in size; and as veinlets up to 6 mm in width.

Disseminated, very fine-grained subhedra and euhedra are irregularly shaped to cubic and hexagonal in form. Replacement patches of coalescing euhedra are laminar, rounded, or irregular in shape, having formed by preferential replacement of individual bedding laminae, breccia fragments, or breccia matrices (Plate 17). The contacts of these patches may be sharp or grade outwards through zones of lesser replacement, in which the euhedra generally lie along the perimeters of dolomite grains instead of replacing them. A few very fine-grained disseminated euhedra are nickeliferous pyrite (bravoite).

Disseminated framboids are dispersed locally throughout argillaceous dolomitic siltstone. These grains are subrounded (Plate 17) and under very high magnification are seen to consist of numerous coalescing micrograins. Often framboids are included in zones of pyrite euhedra without any indication of recrystallization, and it is concluded that the two forms are paragenetically distinct.

Coarse-grained pyrite porphyroblasts (up to 5 mm) are fairly uncommon. They are disseminated and include dolomite and quartz grains of their host rock. Coarse-grained porphyroblasts may be surrounded by very fine-grained disseminated euhedra, again suggesting separate episodes of pyritic mineralization (Plate 11).

Marcasite occurs intergrown with pyrite in replacement patches, in 'colloform' pyrite (see below), and rarely in veinlets. In replacement patches, marcasite occurs as interlocking laths and rectangular grains which tend to form towards the centre of pyrite zones. Some large 'pyrite' porphyroblasts are partly pyrite and partly marcasite.

'Colloform' pyrite is a dark, banded form of iron sulphide (composed of interlaminated zones of pyrite and marcasite) which occurs in pervasive patches or bands 1 to 10 cm in width and, interestingly, as rare breccia clasts. The individual laminae are 0.01 to 2 mm in width and are composed of dark, botryoidal, inclusion-rich, pyrite (up to 0.2 mm), granular marcasite (up to 0.2 mm) or coarse, elongate pyrite crystals (up to 2 mm) arranged in a columnar to radial structure (Plate 17).

Chalcopyrite is a common accessory sulphide. It occurs in general as anhedral blebs (up to 0.05 to 0.2 mm in size) disseminated within dolomitic host rocks (Plate 18) and as similar-sized inclusions within galena crystals. Locally, (which is chalcopyrite) overgrown by, or adjacent to galena shows associated, fine-grained irregular patches of tennantite-tetrahedrite and sphalerite.

TABLE 5. SULPHIDE MINERALOGY, PARAGENESIS, AND TEXTURES, SORBY HILLS

Sulphide	*Grain size (mm)*	*Grain form*	*Texture*	*Paragenetically associated sulphide(s)*	*Host (rock or mineral)*	*Distribution*	*Paragenesis*	*Comment*
Sphalerite (1)	0.1–0.8	Subhedral, angular to rounded cuboid hexagonal	Disseminated grains, locally coalesced and locally overgrown by 'colloform' sphalerite laminae	Sphalerite (2), (3), galena (2)	Dolomite and silicified dolomite zones	Widespread	Main Stage	Colour zoned from pale yellow cores, through red-brown zones to pale yellow rims
Sphalerite (2)	0.2–1	Euhedral, cubic hexagonal	Lining fractures, open-space filling	Sphalerite	'Saddle' dolomite	Peripheral, concentrated in northern 'trends'	Main Stage	—
Sphalerite (3)	0.1–0.4	Elongate, subhedral	Coalescing grains of elongate subhedra of common orientation in 'colloform' growth	Sphalerite (1)	'Saddle' dolomite	Peripheral	Main Stage	—
Galena (1)	1–8	Euhedral; generally cubic some octahedral	Disseminated grains	Sphalerite (1)	Silty dolomites in general	Widespread distribution throughout N-S 'ore trend'	Main Stage	—
Galena (2)	1–6	Euhedral, generally cubic, some octahedral	Lining fractures and vughs, open-space filling, and some disseminations	Sphalerite (2)	'Saddle' dolomite-bearing veinlets, and wall rock	Widespread distribution	Main Stage	Pre-dates and post-dates saddle dolomite precipitation
Galena (3)	0.1–8	Octahedral, cubic to lath-like	Disseminated and locally coalescing to form pervasive seams and veins	Tennantite-tetrahedrite proustite-pyrargyrite	Silty dolomites and dolomite breccias	Localized and discrete with respect to other sulphides	?Late Stage	Finest grain sizes apparently related to highest silver content
Pyrite (1)	0.01–0.05	Framboids	'Raspberries' of micro-granules	—	Pre-dolomitization	Pervasive	Diagenetic	—

Pyrite (2)	0.01–0.2	Elongate subhedral	Coalescing grains of common orientation (perpendicular to growth surface) in 'colloform' laminae	—	Dolomite	Irregular	?Diagenetic and early Main Stage	Forms beds and 'seams' to 5 cm in width following bedding planes. Breccia clasts of this mineral also occur. Formed by open-space filling and replacement.
Pyrite (3) (some bravoitic)	0.05–0.5	Cubic, hexagonal subrounded	Coalescing grains in irregular replacive patches, beds and veins and disseminated grains	—	Dolomite	Irregular	Early Main Stage	Patches are in part marcasitic of a similar grain size.
Pyrite (4)	2–5	Cubic to subrounded	Disseminated	—	Dolomite	Irregular, discrete	Not seen	—
Marcasite	0.01–0.2	Elongate	'Colloform' laminae	Pyrite (2)	Pyrite (2)	Irregular	Diagenetic and early Main Stage	—
Chalcopyrite	0.05–0.2	Anhedral	In mutual intergrowth with galena ± tennantite-tetrahedrite or as overgrowth on pyrite (3) disseminations	Galena (1), (2)	Sulphides	Irregular	Main Stage	—
Tennantite-tetrahedrite	0.1–0.2	Anhedral	Inclusions and oriented exsolutions in galena; or grains in mutual intergrowth with galena, sphalerite, chalcopyrite	Galena (3)	Galena or dolomite	In discrete, galena-rich zones	?Late Stage	Inclusions in galena (3) include a few grains (0.2 mm) of pyrargyrite-proustite

Tennantite-tetrahedrite mineralization occurs most commonly as exsolution blebs and laths enclosed in galena where lead mineralization has its thickest development. Tennantite-tetrahedrite inclusions in galena are locally orientated and vary in size from 0.01 to 0.2 mm, and in shape from spindles to needle-like (Plate 18).

Discrete, silver-bearing phases also occur as rare inclusions in galena. Only one or two silver mineral grains were identified; these were of the pyrargyrite-proustite ($Ag_3SbS_3 - Ag_3AsS_3$) solid solution series (Plate 18). Pyrargyrite-proustite is a light-grey to blue mineral of medium reflectance which is readily identified by deep-red internal reflections.

SPATIAL RELATIONSHIP OF SULPHIDE MINERALS

In general, galena-rich mineralization is dominant at Sorby Hills, for example in pods 'A' to 'J'. Within these pods, mineralized zones which are relatively rich in sphalerite are spatially unrelated to galena-rich ore, which is characterized by a high silver content, in addition to inclusions of tennantite-tetrahedrite and chalcopyrite. Iron sulphide mineralization is not spatially associated with either galena or sphalerite-galena mineralization in the general area of sulphide occurrence.

Areas of sphalerite-dominant mineralization are known from south of Pod 'A' (Deep South Sorby), to the northwest of the Pincombe Inlier and to some extent around the Alpha and Beta trends. In the northwest Sorby area, stratabound-zinc mineralization occurs in the breccia horizon of the Burt Range Formation and near the top of the Buttons Formation; the mineralization appears to thicken westwards.

PARAGENETIC SEQUENCE OF MINERALIZATION

The paragenetic sequence of mineralization at Sorby Hills is illustrated in Figure 36.

The earliest mineralizing event in the argillaceous, calcareous siltstones of the Burt Range Formation, was the formation of diagenetic pyrite as framboids, and locally, as 'colloform' laminae and nodules. The precipitation of these sulphides occurred in local reducing environments of lagoonal to intertidal sedimentary settings, probably immediately below the sediment-fluid interface. Minor ?gypsum mineralization, which is clearly post-dated by iron sulphides, may also have formed in the early diagenetic environment during periods of emergence of the lagoon.

During deposition of the lower Burt Range Formation, periodic fault activity caused uplift of portions of the shelf. The semi-lithified sediments were brecciated, reworked, slumped and redeposited. These breccias are composed mainly of clasts of argillaceous siltstone but locally include clasts of 'colloform' pyrite.

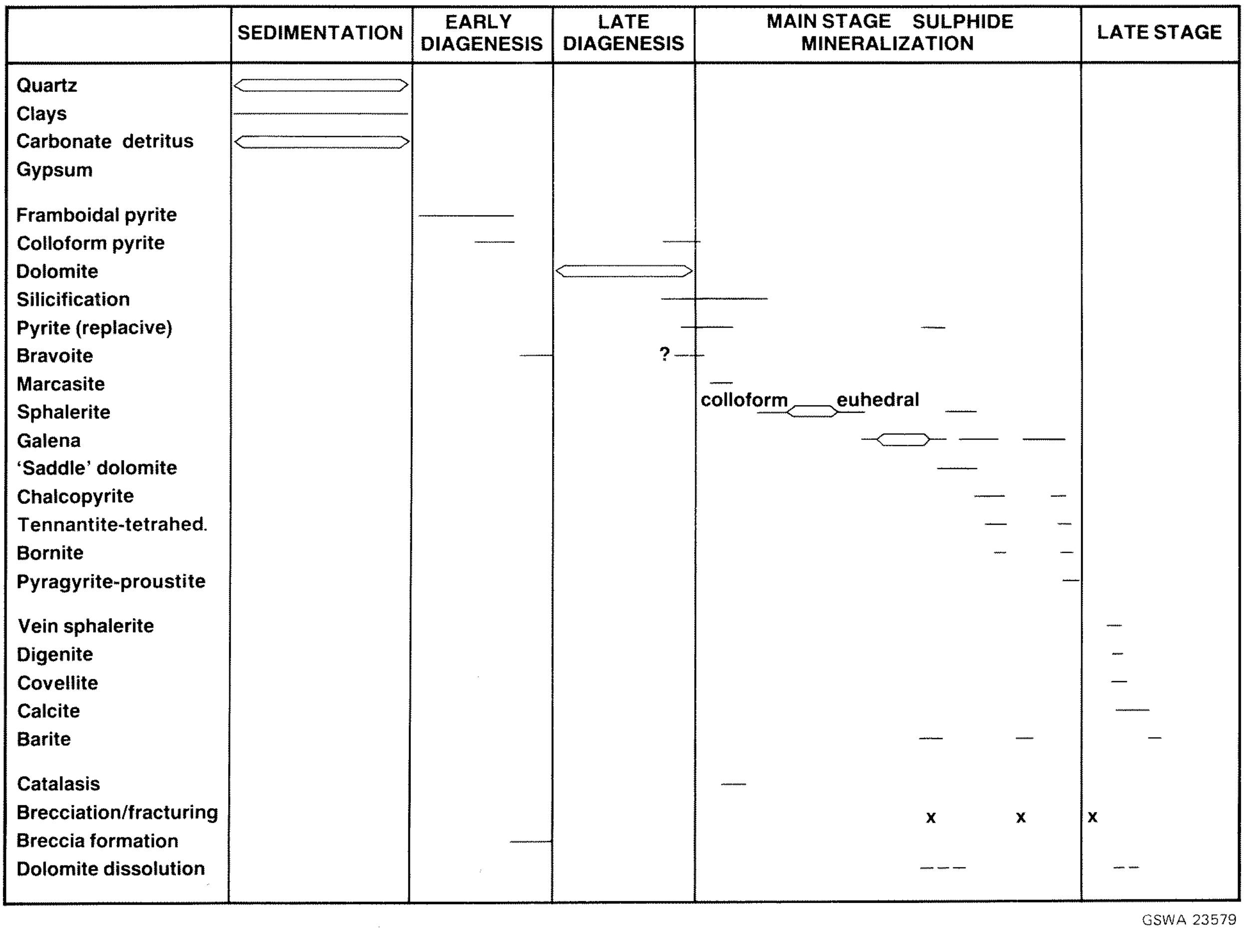


Figure 36. Paragenetic sequence of mineralization at Sorby Hills.

Later in the burial history of these breccias, the Burt Range Formation was widely dolomitized and locally silicified and mineralized. Fine-to medium-grained dolomitization, which consisted of disseminated to pervasive replacement of pre-existing textures, generally preceded silicification and sulphide precipitation.

During and mainly following dolomitization, iron sulphide was precipitated as pervasive replacive patches and, locally, as colloform growths. The period of dolomitization and formation of iron sulphides was followed by the formation of sphalerite and galena, in turn. Silicification is most conspicuous in zones of pervasive sphalerite and generally preceded the growth of galena.

In general, only limited dissolution of dolomite occurred during this initial phase of iron sulphide-sphalerite-galena mineralization. However, at some time during 'main-stage mineralization', a period of fracturing and dissolution of dolomite occurred, possibly due to fault activity, and renewed incursion of basinal brine.

Fracturing was followed by the precipitation of coarse-grained, saddle dolomite and further galena-sphalerite mineralization. Where galena is thickest, it is accompanied by minor chalcopyrite, tennantite-tetrahedrite, and silver-bearing minerals.

The 'main stages' of sulphide precipitation were post-dated by the precipitation of calcite in remnant porosity, accompanied locally by minor chalcopyrite, bornite, and digenite.

DISCUSSION

The sulphide mineralization within the Burt Range Formation at Sorby Hills is spatially related to a sedimentary breccia facies, and intimately related, (spatially and temporally) to dolomitization of the host rocks. The host breccia was probably formed by synsedimentary fault movements which caused slumping and reworking of semi-consolidated sediments, which were later buried beneath finer grained, shaly sediments.

At some later stage, further fault movements, possibly on the same structures that had generated the slump breccias, permitted the upwelling of mineral-bearing solutions. These fluids mineralized the faulted sedimentary horizons of the greatest permeability (slump breccias) along their length.

The timing of most mineralization is unknown, however, it is possible that fluids moved through the host sediments, via fault conduits, periodically from sedimentation to deep burial. Although there is some evidence of early diagenetic (and ?synsedimentary) sulphide formation, the most important sulphide mineralization is associated with epigenetic dolomitization.

Dolomitizing fluids moved through the host sediments in several pulses. The earliest pulse caused the generation of fine- to medium-grained dolomite with minor sulphides. These fluids probably originated during compaction of basinal sediments to the east and northeast of Sorby Hills and flowed up-dip, and along faults, towards the basin margins. The later fluids caused dolomitization characteristic of deep burial environment (Mattes and Mountjoy, 1980). The change in dolomitic texture with time is consistent with increasing depth of burial of the host sediments and movement from a syngenetic to epigenetic environment.

The sulphides range in texture from 'colloform' through fine to coarse grained, and indicate changes in the saturation of ore solutions with time. In general the later sulphides are more coarsely crystalline.

The latest sulphides of the main-stage mineralization are also characterized by the presence of arsenic, antimony, and silver-bearing sulphides. This indicates a change in chemistry of the ore solutions, towards the termination of the sulphide mineralization, and may suggest the input of metal-bearing, hydrothermal fluids from a 'deep-seated' source. Dolomite dissolution which preceded this stage of mineralization may imply input of a hot, slightly acidic fluid.

SUMMARY AND DISCUSSION

The carbonate-hosted, lead-zinc prospects of the Canning and Bonaparte Basins, described here, have many similar and some significant contrasting features (Table 6). However, the principal characteristics of each (namely: structural setting, ore mineralogy, host-rock lithology, and ore-gangue mineral textures) lead to the conclusion that these sulphide accumulations have the closest genetic affinity with Mississippi Valley-type deposits.

The generalized genetic model for such ores proposes the following: saline pore solutions (squeezed out of basin strata as the basin subsides, thickens and compacts) migrate downwards (at least in part) to warmer portions of the basin and move, laterally, along a basal aquifer to places where the solutions intersect faults or reefal structures and can migrate to the surface.

Although this generalized model is accepted for the Kimberley prospects, the following factors are considered important in accounting for the mineralogical and textural variations amongst the prospects: differences in the source, evolution, and escape pathways of the basin-derived ore fluids; and sites and mechanisms of precipitation.

LEAD TO ZINC RATIO OF SULPHIDES

The lithology of the source of the metals (and of the basinal brine aquifer) and the nature of fluid-aquifer chemical reactions have led to a striking variation of Pb:Zn amongst the prospects (Table 6).

Bjorlykke and Sangster (1981) suggest that ore fluids, relatively rich in zinc (as at Blendevale), derive their metals from a carbonate-evaporite-shale sequence, whereas lead-rich fluids (as at Sorby Hills) are derived by greater interactions of basinal brines with arkose and basement rocks (see Table 1). By contrast, Sverjensky (1984) has proposed that deposits with low Zn:Pb ratios are associated with sandstone aquifers (*e.g.* southeast Missouri) whereas high Zn:Pb ratios are associated with carbonate aquifers (*e.g.* East Tennessee). It

TABLE 6. CHARACTERISTICS OF PROSPECTS

	WAGON PASS	*NARLARLA*	*BLENDEVALE*	*SORBY HILLS*
TECTONIC SETTING	On the Lennard Shelf, northern margin of the Canning Basin, approximately 70 km from the edge of the Fitzroy Trough (8km of sediment) and adjoining the Napier Embayment (sediment 2km thick) MARGIN OF INTRACRATONIC BASIN	As before—12km along strike from Wagon Pass	At the 'apex' of a limestone platform island adjoining basinal shales to 2km, and 20km to the Pinnacle Fault across the Lennard Shelf MARGIN OF INTRACRATONIC BASIN	Along the eastern margin of a Precambrian inlier of the Bonaparte Basin. Northern perimeter of inlier adjoins the Petrel Sub-basin (sediment 5km) MARGIN OF INTRACRATONIC BASIN
STRATIGRAPHIC SETTING	At depth of 220m below present surface, which is approximately coincident with the pre-Grant karsted unconformity. Lies immediately below a facies contact and lies >200m above Precambrian basement	At surface, coincident with pre-Grant karsted unconformity. Lies >200m above Precambrian basement.	Range of stratigraphic settings within a 700m thick platform limestone sequence (0–600m depth) on granite Precambrian basement. Platform limestone is overlain by the Gogo Formation with local unconformity	Sulphides lie at approximately 40 –180m, (av 90m) below the surface within the Burt Range Formation. This formation is underlain by 160–200m of Buttons Formation and a few tens of metres of Cockatoo Formation. A major overlying unconformity is formed by the Milligans Formation.
HOST LITHOLOGY	Stylobedded packstones and grainstones with debris flows, intraformational breccias, siltstones and stromatolitic boundstone units. Originally red sediments now pink and green due to wall-rock alteration around sulphide zone	As before (Wagon Pass)	Tectonic, solution-collapse and hydraulic breccias of platformal limestone and fenestral beds.	Intraformational breccia unit comprising clasts of dolomitized shaly siltstone in a matrix of similar composition
PERMEABILITY AND POROSITY OF HOST ROCKS	Post-dolomitization intergranular porosity and fractures, and bedding plane partings in argillaceous-rich interbeds	Fault-related fracture system developed as a fault and bedding parallel, porous zone contemporaneous with dolomitization-chloritization and sulphide precipitation	Fault-related fracture system. Enhancement of porosity by carbonate dissolution during sulphide precipitation. Some strata that remained relatively porous following burial, e.g. fenestral limestone, were exploited by ore fluids	Post dolomitization intergranular porosity and fractures. Bedding planes partings and porous breccia matrices exploited by ore fluids
SIZE OF RESOURCE*	No published data	11 000 t of ore produced from an ore pod 25% to 50% the size of the Wagon Pass lens	No published data	15 Mt of 5.5% Pb, 0.6% Zn, 60 g/t Ag with a lead cutoff of 3%
METAL RATIO (Zn/Zn + Pb)	0.45	0.57	0.82	0.22
SHAPE OF SULPHIDE MINERALIZATION	Bedding parallel lensoid	Bedding-parallel lensoid	Fault-parallel elongate sheet	Several discrete 'pods' or blanket deposits and some elongate trends
ORE MINERALOGY (+ ACCESSORIES)	Sphalerite Galena Pyrite Marcasite (Chalcopyrite) (Bravoite) (Digenite) (Covellite)	Sphalerite Galena Pyrite Marcasite (Chalcopyrite) (Bravoite) (Digenite) (Covellite)	Sphalerite Galena Marcasite (Colloform pyrite) (Pyrite) (Chalcopyrite)	Galena Sphalerite Pyrite Colloform pyrite Marcasite Chalcopyrite (Tennantite-tetrahedrite) (Pyragyrite-proustite) (Bravoite)

ORE TEXTURES	Disseminated euhedra formed by 'exertion' of crystal form in argillaceous-rich interbeds; open-space fillings in pores; vughs and fractures	Open-space-filling textures dominant with some 'disseminations' (as before) 'Replacement' also takes place by dissolution of carbonate contemporaneous with sulphide precipitation	Open-space fillings	Disseminations of euhedra formed by 'exertion' of crystal form, and open-space fillings.
ZONATION OF SULPHIDES	Central sphalerite-galena, grades outwards through sphalerite and sphalerite-iron sulphide zones to fringes of mineralization. Upper level (stratigraphic) copper-iron sulphides are superimposed	Closely intermixed sphalerite-galena, no obvious primary zonation	In general, from sphalerite-galena to galena, to marcasite, to calcite-barite upwards and outwards along fault conduit (generalized)	Discrete zones of sphalerite-rich and galena-rich mineralization.
WALL-ROCK ALTERATION AND GANGUE MINERALOGY	Dolomitized and chloritized host rocks with spar cements and fracture fillings	As before (Wagon Pass) although spar cements relatively rare (probably once overlying orebody, now eroded)	Spar cements, minor barite gangue, no dolomitization	Dolomitization and limited silicification. Gangue spar cements and minor barite.
MAIN PARAGENETIC EVENTS	Calcite cementation Dolomitization Chloritization Iron sulphides Sphalerite Galena Pyrite Marcasite Copper mineralization-iron oxides	As before (Wagon Pass)	Calcite cementation Breccia formation Geopetal infilling Fine-grained iron sulphides Sphalerite, Galena, Calcite } 2 cycles	Framboidal pyrite Colloform pyrite Dolomitization Silicification Sphalerite Galena Dolomite veining Galena Tennantite Proustite Calcite-barite Copper mineralization-iron oxides
TIMING	Post-Famennian (?pre-latest Carboniferous to earliest Permian)	As before (Wagon Pass)	Frasnian-Famennian	Post Tournaisian (? Visean)
SOURCE OF REDUCED SULPHUR	Reduction of sea-water sulphate by thermochemical or biogenic processes	As before (Wagon Pass)	More than one source or an evolving source. Ultimately sea-water sulphate from entrapped or descending sea-water and formational	No data
?INFLUENCE OF METEORIC WATERS	Indicated for late-stage calcites	No data	No apparent influence for spar	No data
FLUID TEMPERATURES AND SALINITIES	Dolomite: 75-95°C, 19-21.5 wt % NaCl Calcite (spar): 70°C, 2-21.5 wt % NaCl	No data	Zinc sulphide 17-27 wt % NaCl, 55-110°C, average 75-85C. Calcite (spar) 5-20 wt % NaCl, 45-90°C	No data

*Footnote: Since the compilation of this report, the latest published figures for Blendevale and Sorby Hills are:
Blendevale—20.0 Mt of 2.5% Pb and 8.3% Zn, using a cut-off grade of 3% lead plus zinc, and 2.5 m minimum true width (Murphy and others, 1986)
Sorby Hills—16.25 Mt of 5.3% Pb and 0.6% Zn, 56 g/t Ag, using a cut-off grade of 2.5% lead plus zinc, and 3.0 m minimum true width (Rowley and Lee, 1986).

seems likely that both the source rock for the metal-bearing fluid and the chemical evolution of the fluid, during migration from the basin, are important. Also, the variable importance of each process in a region leads to a very large range of possible Zn:Pb ratios in Mississippi Valley-type deposits.

MINERALOGY OF ACCESSORY SULPHIDES

As well as the proportions of lead and zinc sulphides present at each prospect, the proportion and mineralogy of chalcopyrite and accessory silver, arsenic, and antimony sulphides also vary (Table 6).

The level of accessory copper in the ores studied is characteristic of Mississippi Valley-type deposits, in general, and reflects the low solubility of copper (compared to lead and zinc) during brine-sediment interaction at low to medium temperatures and low pressures (Lentini and Shanks, 1983). The relatively higher levels of copper and accessory silver and arsenic-antimony sulphides, (pyrargyrite-proustite and tennantite-tetrahedrite) at Sorby Hills may reflect the interaction of basinal brines with basic-volcanic rocks in the Bonaparte Basin sedimentary pile (towards the base of the sequence) or input of some other, ?deep-seated, fluid component. Sporadic high levels of copper in ore at Wagon Pass are due to local supergene enrichments (indicated by digenite-covellite in iron oxide veinlets).

The distribution and control of silver is unknown for the Kimberley prospects. Although average silver contents are similar for each prospect (40 – 60 g/t) some sporadic high values (up to 200 g/t) do occur at each prospect.

At Narlarla and Wagon Pass such high values reflect the activity of oxidizing fluids (with silver enhancements) upon hypogene ore; whereas at Sorby Hills the occurrence of pyrargyrite-proustite inclusions in galena controls the distribution of silver and indicates a hypogene, silver-bearing ore phase. At Blendevale, sporadic high silver values are not readily explained in these terms, as no oxidation of primary ore is evident and discrete, microscopic, silver-bearing mineral phases were not observed.

NATURE OF WALL-ROCK ALTERATION

The presence and intensity of wall-rock alteration is also considered to reflect the source and evolution of the basin-derived brines.

At three of the four prospects examined, sulphides are intimately related, spatially and genetically, to dolomitization. Textural evidence suggests that dolomite is mainly of deep-burial origin forming after calcium carbonate cementation and some stylolitization of the host limestone. Fluid-inclusion evidence (see following data) suggests that dolomitization is due to the migration of warm, saline, hydrocarbon-bearing, Mg-Fe-Ca-Cl brines. Collectively these facts suggest that ore fluids, at least at three of the prospects examined, were closely related in time and space to dolomitizing, basin-derived brines.

The lack of dolomitization at Blendevale suggests that: either the sulphide-forming fluids were genetically distinct from typical basin-derived, dolomitizing brines; or that the sulphide-forming fluids were 'derived' from a typical, dolomitizing, basin-derived brine with dolomitization occurring outside the zone of sulphide precipitation (possibly 'back down' the plumbing system). Fluid-inclusion evidence from sphalerite at Blendevale (see following data) supports sulphide precipitation from a warm, saline, hydrocarbon-bearing fluid similar to typical basin-derived brines and the second alternative given above for the absence of dolomitization, surrounding sulphide formation, is favoured. Further, the dominance of zinc at Blendevale suggests a carbonate aquifer which could have been readily dolomitized en route to the ore zone, leaving the metal-bearing brine devoid of Mg ions at the higher, (stratigraphically) sulphide-bearing levels of the fluid system.

TEXTURAL VARIATIONS OF SULPHIDES

The range in sulphide crystal sizes, from microcrystalline in 'colloform' growth to very coarse-grained euhedral crystals, attests to a wide range of relative rates of sulphide precipitation exhibited amongst the prospects. 'Colloform' minerals indicate rapid precipitation. Every microlamina (each of a different colour and/or grain size) indicates a specific set of chemical and physical conditions during ore-fluid activity. Coarse-grained euhedra reflect relatively slower rates of sulphide precipitation. The variation of sulphide textures reflects pulsed migration of ore fluids (of slightly different chemistry and under different physical conditions) and/or mixing of ore fluids with other fluids (?meteoric) in the ore zone.

In the case of 'colloform' textures in Mississippi Valley-type ore deposits, two principal hypotheses for their genetic significance have been given. McLimans and others (1980) studied in detail the 'colloform' banding in sphalerites of the Upper Mississippi Valley and were able to recognize a sphalerite 'stratigraphy' in the banding, which was consistent throughout 23 km of mineralization along strike. This phenomenon was seen as clear evidence of a single fluid migration in which minor fluctuations of ore-fluid chemistry during migration gave rise to sphalerite colour changes and dissolution along certain sphalerite bands, prior to renewed deposition.

By contrast, Cathles and Smith (1983) suggest that each band in such 'colloform' sphalerites may be equated with a major pulse of brine from 'geopressurized zones' in the 'parent' basin. Cathles and Smith (1983) propose 'episodic pore-fluid expulsion' by basin dewatering in 50 pulses (one per million years) as a stratum subsides from 3 to 5 km in depth. They suggest that the dissolution of certain sphalerite laminae could be attributed to the penetration of near-surface waters in the ore zone.

In the case of the Narlarla and Blendevale ores, where 'colloform' sulphide textures are best developed, it seems unlikely that Cathles and Smith's proposal is applicable. Their theory requires a stable configuration of the plumbing system at the ore site, over a period of perhaps 50 million years, to permit the build up of numerous, individual, sphalerite bands. Both the Narlarla and Blendevale ore sites are characterized by brecciation, wall-rock 'collapse', and sulphide fragmentation, indicative of unstable environments during ore formation. It seems more likely that the colloform textures at Narlarla and Blendevale reflect rapid changes in ore-fluid chemistry, temperature, and pressure caused by: variation in the nature of (pulsed) ore fluid; and hydrological changes (and fluid mixing) at the ore site controlled by fault movements.

The variations in the shape of sulphide crystals and crusts also reflect the nature of the porosity exploited. Generally, sulphide precipitation occurred in intergranular and fracture-related porosity leading to anhedral to subhedral forms, and replacement of carbonate by sulphide is relatively unimportant. However, a proportion of sulphides grew *in situ* in a fluid-saturated, incompetent medium. This mechanism was particularly important for galena at Wagon Pass and Sorby Hills.

GENETIC IMPLICATIONS OF IRON SULPHIDE MINERALOGIES AND TEXTURES

Bravoite – $(Fe,Ni)S_2$ – is present in trace amounts at all of the prospects examined. It is 'a low temperature mineral almost always formed from descending meteoric waters or in an euxinic sedimentary environment' (Ramdohr, 1969). Occurrences of bravoite have been documented at Tynagh (Boast, 1981) and from southeast Missouri (Hagni, 1983) and in both of these occurrences, as at the prospects examined here, bravoite has an early paragenetic age. Bravoite in the Kimberley prospects may have formed at some stage prior to lead-zinc mineralization, or, if it is a facies of main-stage mineralization, then it suggests a role for meteoric water in sulphide precipitation.

'Colloform' pyrite (or melnikovite pyrite), which occurs at Sorby Hills and Blendevale, is thought to indicate low temperatures and has been reported from Upper Silesia and Missouri (Ramdohr, 1969). In southeast Missouri, 'colloform' pyrite apparently formed by open-space filling and replacement (Hagni, 1983). 'Colloform' pyrite therefore underlines the low temperature of at least some of the ore fluids, and the corrosive contacts of 'colloform' pyrite with host grains, documented here, indicate a slightly acidic ore fluid, at least during the early phase of sulphide formation.

The variable marcasite to pyrite ratios exhibited amongst the prospects also carry genetic implications. The change from marcasite to pyrite laminae, within 'colloform' pyrite, and the variation in abundance of marcasite versus pyrite in general, reflects either an increase in oxygen fugacity, or a decrease in pH (Taylor and others, 1979; Taylor, 1980). The dominance of marcasite versus pyrite at Blendevale may therefore reflect a generally higher oxygen fugacity and/or acidity of the ore fluids, in comparison to the other prospects examined. A higher acidity of ore fluids at Blendevale is consistent with the occurrence of carbonate solution-collapse breccias.

Framboidal pyrite, which occurs at Sorby Hills, is considered to indicate precipitation of iron, as sulphide, by bacteriogenic H_2S during diagenesis (Berner, 1969). The very fine-grained iron sulphides which occur at all other prospects could be recrystallized framboids. The formation of such early, diagenetic, iron sulphide may have been an important process common to all of the Kimberley prospects.

GENETIC IMPLICATIONS OF MINERAL PARAGENESIS

There are four broad features of mineral paragenesis common to the Wagon Pass, Narlarla and Sorby Hills prospects, namely: early pyrite mineralization; pre 'main-stage' dolomitization; sphalerite preceding galena during 'main-stage' sulphide mineralization; and late-stage spar precipitation.

These characteristics suggest the following: an early stage of ?diagenetic pyrite which was possibly a source of reduced sulphur for later fluids; the ore fluids became increasingly lead-rich with time; and that dilution of the ore fluids (?by meteoric and/or connate-pore waters) was of increasing importance with time, leading eventually to late-stage spar precipitation.

At Blendevale the lack of dolomitization and the dominance of marcasite over pyrite has been readily explained earlier, and a similar process of ore-fluid evolution overall is envisaged.

GENETIC IMPLICATIONS OF STABLE-ISOTOPE AND FLUID-INCLUSION DATA

Stable-isotope data

A limited amount of isotope data for carbon, oxygen and sulphur have been produced by I. Lambert and co-workers at the Baas Becking Laboratories. The initial results are reported here.

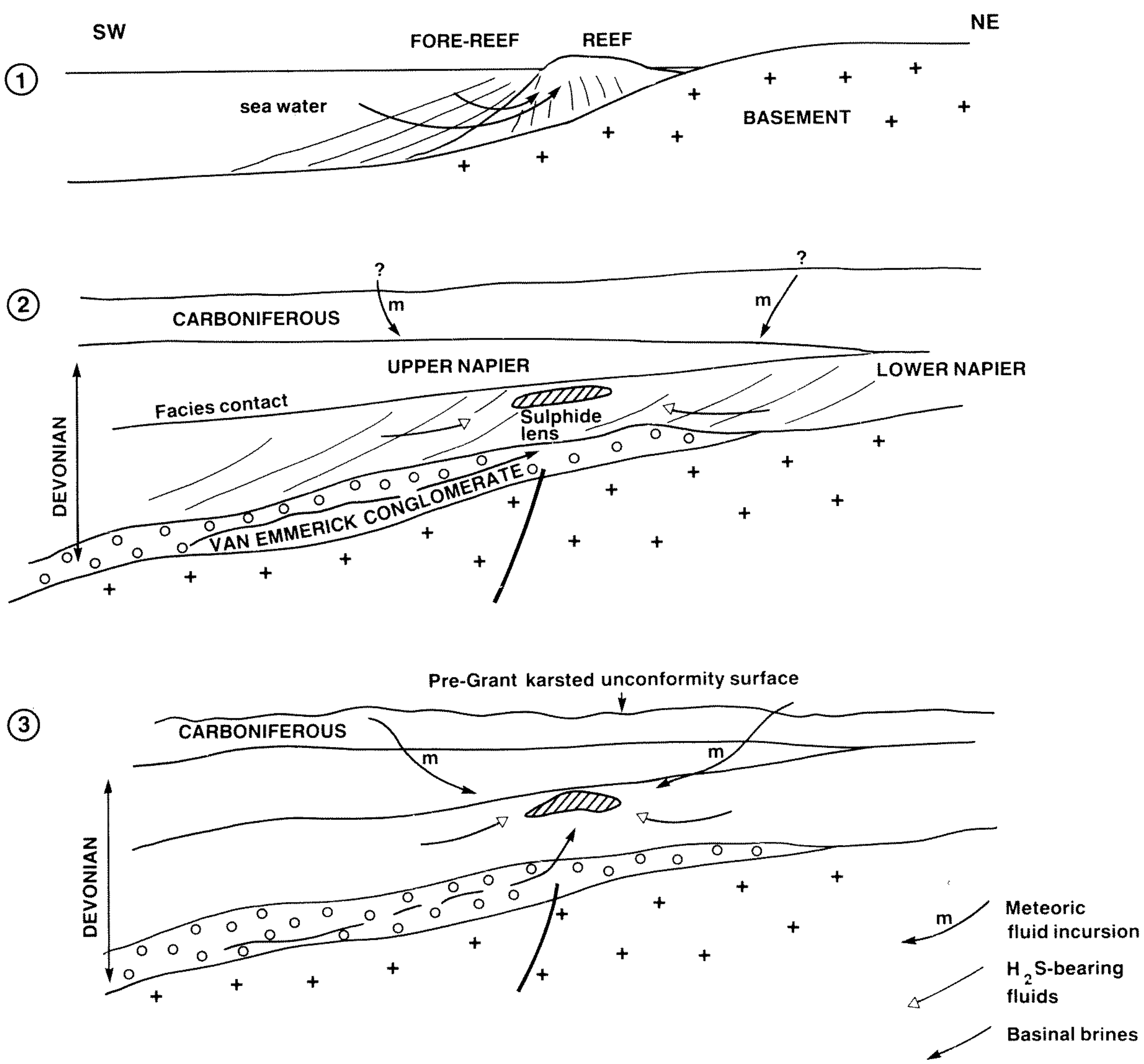
Wagon Pass: ^{34}S values for galena and sphalerite range from +1 to +9, while pyrite has generally lower ^{34}S values. There is no evidence of isotopic equilibration between the principal sulphide phases implying low temperatures of formation and/or precipitation of various sulphides at different times. The pyrite must have formed from a different source than that of the galena and sphalerite, or formed at an earlier stage.

The host dolomite has higher ^{18}O values, around 27 to 28 , than the limestones, which suggest an important role for basinal brines in its formation. A negative ^{13}C halo occurs in dolomite and indicates that sulphate reduction *in situ* was not influenced by dolomitization.

Clear black calcite (spar) also has low ^{13}C values and some has low ^{18}O values, which reflect the influence of meteoric waters.

Narlarla: The mean ^{34}S values for galena and sphalerite is around + 16 which implies relatively extensive reduction of sulphate in entrapped or descending sea water and formational waters.

Blendevale: The ^{34}S values for galena and sphalerite are in the range of +9 to +24 with a distinct concentration between +17 and +20 . Isotopic disequilibrium exists between these phases as at Wagon Pass. The range of ^{34}S values implies more



	TIME	ENVIRONMENT	FLUID PHASE	PROCESSES
(1)	Frasnian	Early diagenetic	Circulating sea water	i) Ca CO_3 cementation ii) Minor framboidal iron sulphides (bravoitic)
(2)	Tournaisian → Namurian	Deep burial	a) Warm, basinal brines + SO_4 + hydrocarbons	i) Stylolitization ii) Dolomitization — chloritization; reduction of SO_4 in wall rock fluids
		semi-continuous overlapping activity ↓	b) Warm, metalliferous basinal brines	i) Sphalerite — galena — pyrite — (cpy)
(3)	? Westphalian	Emergent	c) Meteoric groundwater convection	i) Iron sulphides — calcite — digenite etc — iron oxides

GSWA 23580

Figure 37. Wagon Pass – genetic model.

than one source of sulphur, or an evolving sulphide source. The bulk of marcasite, has ^{34}S values that are lower or higher than the sphalerite-galena range, indicating that iron sulphide formed using reduced sulphur from a different source to that of galena and sphalerite. The main sulphur source for the sulphide was probably reduced sulphate from entrapped or descending sea water and formational waters.

Values of ^{13}C and ^{18}O for spar cements are very scattered and are thought to reflect elevated temperatures of precipitation, as fluid-inclusion results for Blendevale negate any influence of meteoric waters enriched in ^{16}O.

Sorby Hills: There were no isotopic data for oxygen, hydrogen or carbon available to the author for this prospect.

Fluid-inclusion data

Fluid-inclusion data from Wagon Pass and Blendevale have been generated by H. Etminan of the Baas Becking Laboratories and are summarized here, with permission.

Wagon Pass: Dolomitic host rocks were formed from fluids that had salinities of 19 – 21.5 wt % NaCl equivalent and contained a proportion of calcium and/or magnesium ions. These fluids had temperatures of 75°C – 95°C. The spar-forming fluids, which post-date dolomite formation, have widely varying salinities from 2.0 to 21.5 wt % NaCl equivalent, with homogenization temperatures around 70°C.

Blendevale: The calcite (spar)-forming fluids had a wide range of salinities, variably more saline than sea water, (5 – 20 wt % NaCl), with a major component of calcium and/or magnesium ions. The fluids had temperatures of 50°C – 85°C.

Data from Moyle (1980) indicate that brines with salinities of 17 – 27 wt % NaCl equivalent and homogenization temperatures of 55°C – 110°C (mostly 75°C – 85°C) were responsible for the precipitation of the zinc sulphide. Moyle (1980) also found higher temperatures but lower salinities for calcite and barite. Contrary to positive reports by Etminan, he found no bitumen or hydrocarbons in any inclusions. These results are generally consistent with variable mixing of ascending basinal brines with waters of marine derivation.

Sorby Hills: There are no published fluid-inclusion data available for discussion.

GEOLOGICAL HISTORIES

Wagon Pass

The dolomitization of host carbonate and sulphide mineralization at Wagon Pass is interpreted as the result of semi-continuous passage of basinal brines throughout Tournaisian to Namurian times. The passage of these brines post-dated early-diagenetic processes, in the Frasnian, and was affected by the ingress of meteoric fluids towards the end of its activity, probably in the Westphalian. Four main stages of development are envisaged (Fig. 37).

At some time between the Tournaisian and Namurian, and approximately contemporaneous with compaction stylolitization, warm (90°C) brines containing hydrocarbons and Mg-Na-Ca-Fe-Cl-SO_4 species moved laterally along a broad front, in the Napier Range. These fluids originated in the Napier embayment and, in particular, in the Fitzroy Trough where sediments were undergoing rapid subsidence and compaction. They migrated up-dip along aquifers, mainly arkosic sands lying unconformably on Precambrian basement, and rose towards the surface where they intersected suitable, cross-aquifer permeability. During lateral migration and their rise to the surface, these fluids dolomitized and chloritized carbonate wall rocks. At Wagon Pass, basin-derived brines rose into the Napier Formation host rocks along a permeable fracture zone, formed by movement on an underlying, east-west, basement fault.

With time, during the Tournaisian to Namurian period, dolomitization and chloritization gave way to sulphide mineralization as the expelled basinal brines became warmer and metalliferous. These metal- and sulphate-bearing fluids were introduced in pulses, possibly coincident with repeated movements on basement faults.

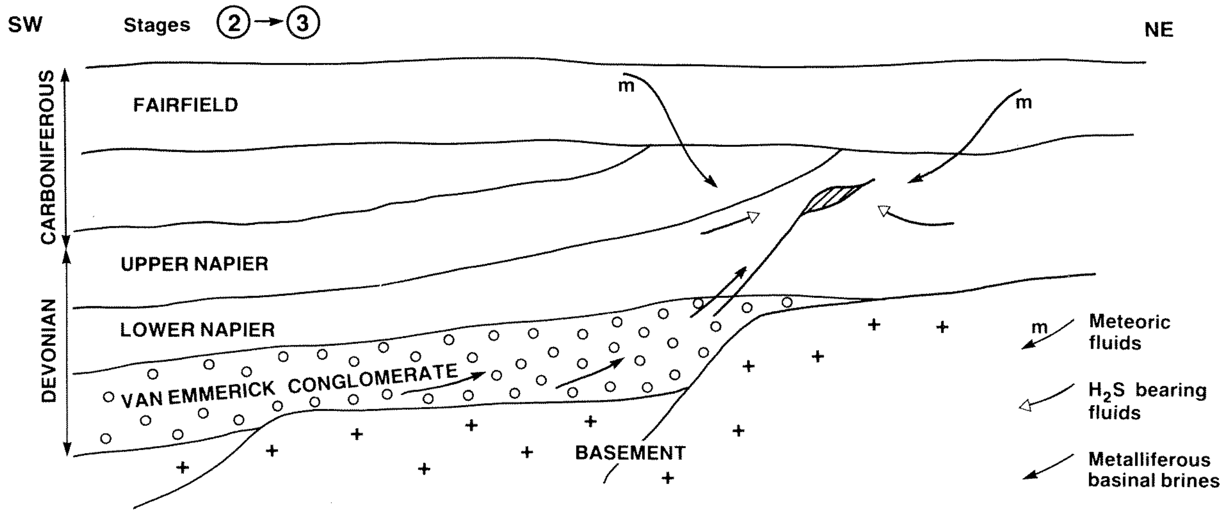
Each incoming pulse of warm brine at this stage was quickly cooled, by mixing with resident pore fluids, causing the precipitation of sphalerite and galena in significant quantities, together with minor chalcopyrite. Precipitation of sulphides was initially rapid, forming the finest grained sulphides, as metal ions utilized available H_2S at the ore site. Later precipitation proceeded at a slower rate, controlled by the influx of H_2S-bearing fluids from the wall rocks. Intermittently, the supply of reduced sulphur was locally exhausted and gypsum beds were formed from SO_4^{2-} in the presence of hydrocarbons (during and after dolomitization-chloritization).

In the later stages of sulphide precipitation, meteoric fluids became involved in the mineralization and alteration processes. Groundwater convection, through the ore site, removed and diluted acidic fluids produced by sulphide precipitation. Fluids flowing upwards and outwards from the ore site, at this stage, precipitated late iron sulphides, 'colloform' galena, sulphur-enriched Cu-Fe sulphides, coarse-grained calcite, and (as the system became more oxidized) iron oxides.

Narlarla

At Narlarla a very similar sequence of events to that envisaged for Wagon Pass is favoured (Fig. 38).

In the Tournaisian to Namurian, brines rose from underlying arkosic sand aquifers along highly permeable east-west faults. These fluids caused dolomitization and chloritization, mainly along the fault zones and their wall rocks, and locally along permeable bedding planes and facies contacts. At the site of the Narlarla No. 2 deposit, a highly porous, dolomitized and chloritized zone (saturated with H_2S-bearing pore fluids) was developed. The H_2S was probably produced in wall rocks by the reduction of SO_4^{2-} in the presence of hydrocarbons, and accumulated in zones of dilation.



TIME	ENVIRONMENT	FLUID PHASE	PROCESSES
(1) Famennian	Early diagenetic	Circulating sea water	i) $CaCo_3$ cementation ii) Minor framboidal iron sulphides (bravoitic)
(2) Tournaisian Namurian	Deep burial	a) Warm basinal brines + SO_4 + hydrocarbons	i) Stylolitization ii) Dolomitization — chloritization iii) SO_4 reduction to H_2S in pore fluids iv) Fluid accumulation in dilatant structures
		b) Warm, metalliferous basinal brines	i) Rapid sphalerite — galena — pyrite (cpy) precipitation ii) Contemporaneous wall-rock dissolution brecciation and collapse locally
(3) Westphalian	Emergent	Meteoric groundwater convection	iii) Iron sulphides — calcite — secondary ore sulphides
(4) Modern	Exposed	Meteoric	iv) Secondary ore formation

GSWA 23581

Figure 38. Narlarla — genetic model.

At some later time, metal and sulphate-bearing brines were introduced into the ore site, following fault movements, and a pod of zinc and lead sulphide mineralization was rapidly precipitated on mixing with the H_2S-bearing fluids. The initial rapid rate of sulphide precipitation locally generated relatively high concentrations of acidic fluids which dissolved and corroded the carbonate wall rocks. Precipitation of sulphide, dissolution of wall-rock breccia, collapse, and development of further porosity proceeded contemporaneously. These processes abated as the influx of hydrothermal brines eased, and groundwater convection (and acid-fluid dilution) became significant and dominant.

Although this late-stage groundwater convection may have had some oxidizing effects, the evidence has been obliterated by the imprint of secondary-ore formation during recent weathering.

Blendevale

Between the Givetian and mid-Frasnian the Limestone Billy Hills atoll, which was established as a rigid, brittle, cemented, limestone platform became submerged and covered by dark siltstone of the Gogo Formation (Fig. 39).

Shortly after this covering by sediments began, movement on basement faults initiated extensive fracturing of the limestone, and significant fluid conduits were formed. Sea water circulating through the shattered platform at this time precipitated turbid, fibrous calcite as a breccia cement and as fracture linings. Also at this stage, dark silt filtered downwards into the open fractures, in the upper part of the platform, from the sea floor forming geopetal in-fill within the limestone. Sea-water sulphate was reduced by bacterial activity in the Gogo sediments and dispersed into the porous platform by descending fluids and, locally, compaction fluids. A proportion of the marcasite at Blendevale may have been precipitated at this stage from an iron-bearing and H_2S-bearing fluid, flushed from the Gogo Formation.

At some time after the incursion and circulation of sea water, warm (about 90°C), metal-bearing brines migrated into the fractured carbonate platform from a northerly direction, via aquifers at the basement contact. These fluids permeated the porous platform and initially precipitated colloform iron and zinc sulphides rapidly, in open-spaces as they mixed with H_2S-bearing fluids. As the available H_2S became exhausted, sulphide precipitation proceeded more slowly, controlled by the diffusion of H_2S-bearing fluids from the Gogo Formation, and finer grained sulphides became dominant.

Metal-bearing brines entered the platform in pulses, following tectonic activity. Their episodic incursion enhanced tectonic brecciation along faults by fluid movement, locally under pressure, and carbonate dissolution took place during sulphide precipitation to form a range of breccia textures.

Initially the formation of sphalerite was the dominant process. However, towards the end of this phase, galena mineralization became quantitatively more important together with the precipitation of calcite (spar) in relic porosity. This transition to a spar-dominated precipitating system marked the waning of brine input and the re-establishment of formational water circulation.

There were two major pulses of zinc-rich fluid, both initiated and separated by fault activity. Each zinc-rich pulse passed, into a lead-dominant fluid with time. Both of these were followed, in turn, by a pulse of relatively lead-rich fluid, affecting only the deepest levels of the system.

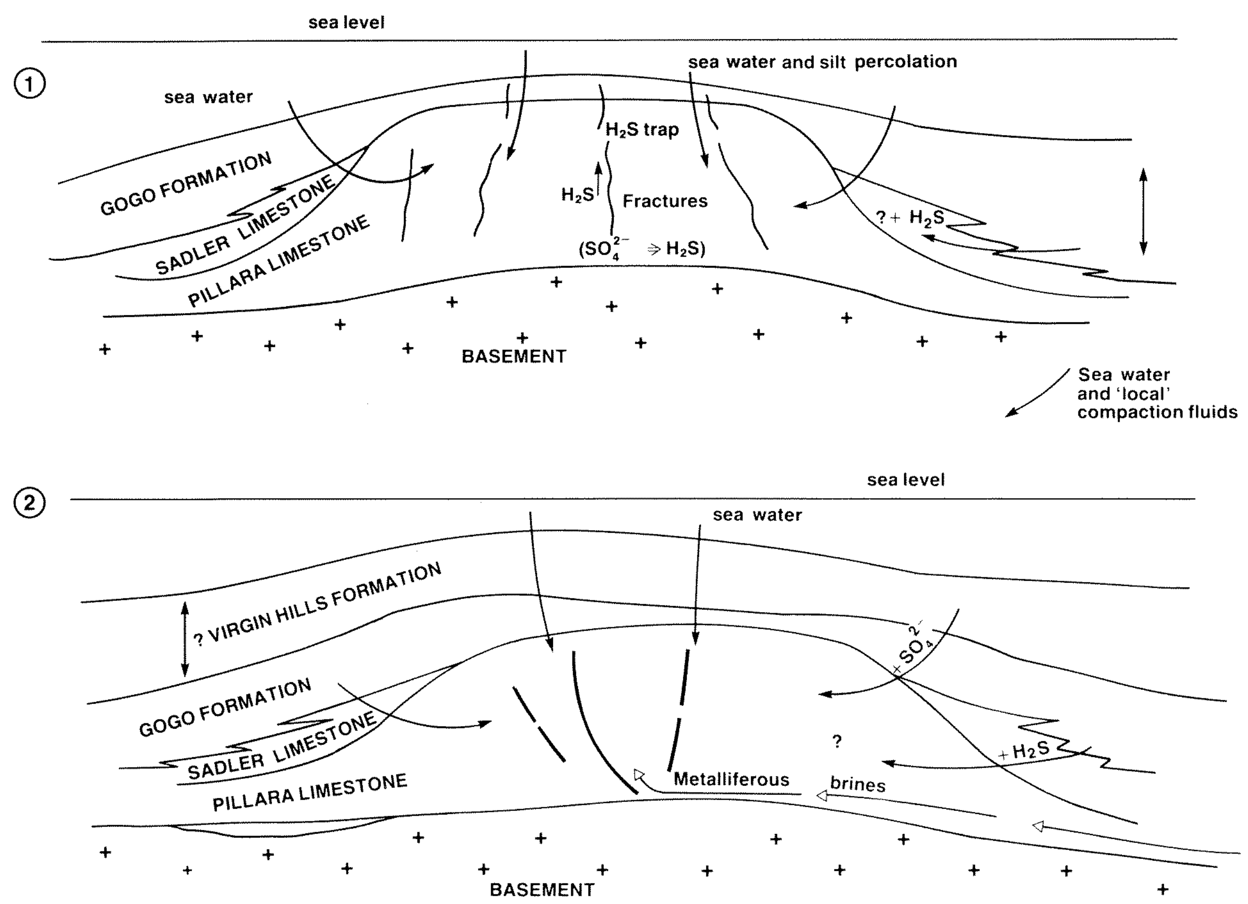
Sorby Hills

In Tournaisian times, a fine-grained, mixed carbonate-clastic sedimentary facies was laid down in a subtidal to intertidal environment along the margin of an island of Proterozoic bedrock (the Pincombe Inlier). Within this sedimentary environment, reducing conditions existed locally during early diagenesis (Fig. 40) where colloform iron sulphide (mixed pyrite and marcasite) and framboidal pyrite were precipitated in thin beds and as nodules, below the interface between sediment and sea water. Also during early diagenesis of Tournaisian sediments, fault movements occurred along northwesterly and northerly trending structures causing uplift, slumping and brecciation of semi-consolidated material. These breccias were locally reworked, and breccia horizons of variable thickness became incorporated into the Tournaisian section. Some minor hydrothermal activity may have been related to this stage of faulting, providing metals for diagenetic sulphides.

At some later time, during burial of these sediments, warm, basin-derived brines migrated from the Burt Range Shelf (to the east) and the Petrel Sub-basin (to the northeast). The direction of brine migration was controlled by the Pincombe Ridge, major northeasterly trending faults, and the permeability and disposition of bedding.

Initially these fluids were Mg-rich brines which caused pervasive dolomitization of the Burt Range Formation. Reduction of SO_4^{2-} in the presence of hydrocarbons provided an H_2S-bearing pore fluid. Later fluids precipitated dolomite and silica. During the later stages of basinal brine migration, zinc-bearing and lead-bearing brines rose along cross-strata faults and permeated favourable porous horizons. The best host rocks were breccia horizons, locally capped by shales, and the most strongly dolomitized sections with suitable secondary porosity. The brines precipitated metals as sulphides in intergranular pores, fractures, and intraclastic pores, where they encountered H_2S-bearing fluids. Locally, the metalliferous brines also migrated outwards from the fault conduit along bedding planes and facies contacts, where stratabound, barite-bearing mineralization was formed in the more oxidizing portions of the mineralizing system.

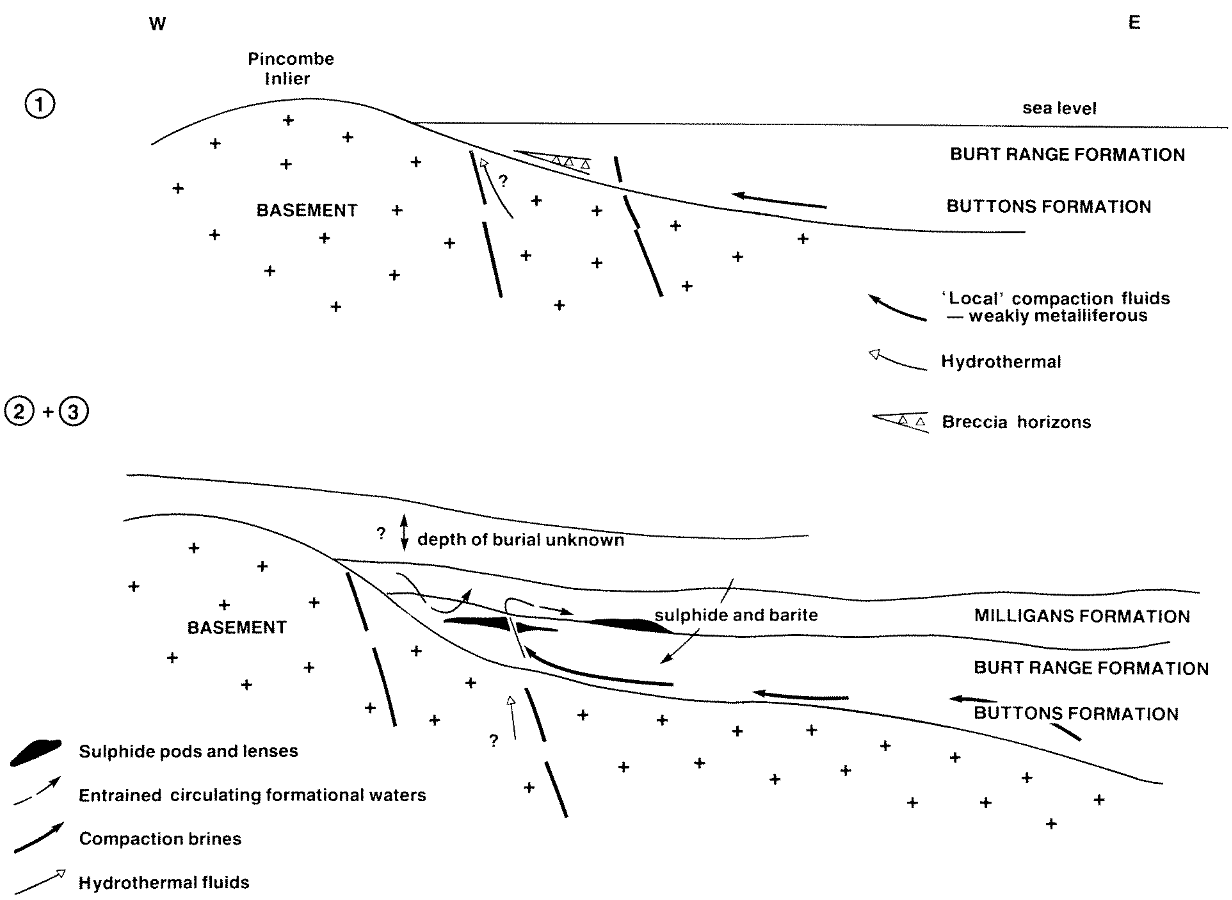
At some later time, input of basinal brine waned and only weakly mineralizing fluids were active. These fluids precipitated calcite spar, accompanied by a very pale sphalerite (of low-Fe content), with local covellite and digenite. This stage of mineralization may have marked the establishment of formation-water circulation only, or the influx and admixture of meteoric waters following fault movements and some local uplift.



TIME	ENVIRONMENT	FLUID PHASE	PROCESSES
(1) Givetian — Frasnian	Early diagenetic to late diagenetic	i) Sea water circulation ii) Early compaction fluids from Gogo sediments	i) Fracturing of platform i) Fibrous calcite cementation ii) Geopetal silts iii) ? biogenic reduction of SO_4 iv) Permeation of platform by H_2S-bearing fluids (H_2S-trap)
(2) ? Famennian	Deep burial	i) Metal-bearing basinal brines	i) Fault movements ii) Sulphide precipitated (sphalerite-marcasite) iii) Connate water entrainment and circulation iv) Sphalerite → galena → spar v) Repeated metal brine influx

GSWA 23582

Figure 39. Blendevale — genetic model.



	TIME	ENVIRONMENT	FLUID PHASE	PROCESSES
1	Tournaisian	Early diagenetic	Sea water	i) Framboidal and colloform pyrite formation ii) Slump breccia formation
2	Post-Tournaisian	Early to late diagenetic	Basinal brines	i) Dolomitization and minor silicification
3	Post-Tournaisian	Deep burial	Basinal brines	i) Sulphide precipitation ii) Saddle dolomite + galena
4	Post-Tournaisian	?	Meteoric fluids / basinal brines	

GSWA 23583

Figure 40. Sorby Hills – genetic model.

IMPLICATIONS FOR FUTURE EXPLORATION

Geological and petrological appraisals of the Wagon Pass, Narlarla, Blendevale, and Sorby Hills lead-zinc deposits suggest that the following features are favourable for the localization of similar deposits:

(a) proximity to major faults;

(b) the presence of fault-induced and/or secondary (post-dolomitization) porosity;

(c) proximity to basement highs;

(d) the presence of facies contacts providing pinchouts, permeability contrasts, and fluid traps;

(e) the presence of a cap-rock to the host lithology;

(f) proximity to a regional aquifer (*e.g.* Van Emmerick Conglomerate).

Much of the exposed Devonian reef complexes of the Canning and Bonaparte Basins and the exposed Carboniferous of the Bonaparte Basin have probably now been explored, at least at a reconnaissance level, using the above-mentioned criteria as guidelines. The reconnaissance techniques utilized have included aerial photography, gossan searching and sampling, stream and bedrock geochemistry, fracture-pattern analysis, gravity surveys, and magnetic surveys. Follow-up work has included mapping, rock-chip geochemistry, and grid-pattern drilling. Of these methods, gossan location and fault mapping, in conjunction with grid-pattern drilling, have proved most successful. Limited data from the Narlarla deposit (Ringrose, 1986) suggest that trace-element dispersion patterns in the wall rock are very 'tight' and may not be a particularly useful exploration technique. However, veins and veinlets may form a more dispersed leakage aureole to these sulphide occurrences, and may therefore offer a more promising geochemical target.

Future exploration activity should be guided, on a regional scale, by the presence of large basin-margin faults (*e.g.* the Pinnacle Fault in the Canning Basin) and their cross-faults (*e.g.* northwesterly trending faults in the Canning Basin), also by the presence of basement highs and ridges. Exploration should lead progressively from evaluation of the exposures of these features to detection and evaluation of such structures beneath cover rocks.

In the Canning Basin, the Pinnacle Fault system is prospective along its length as is the northwesterly projection of the Oscar Range (beneath cover) and its bounding fault (Fig. 10). Geophysical techniques should be used to establish the likely depth of the target strata and the presence of basement highs or ridges. In the Bonaparte Basin the eastern faulted margin and the Pincombe Range are generally prospective. However, in these examples, interest along the length of faults is likely to be limited by the excessive depth to favourable horizons.

Another direction for future exploration is a more thorough evaluation of the Carboniferous and Ordovician strata, bounding the generally more prospective Devonian rocks in the Canning Basin. The Carboniferous strata, especially their unconformable lower contact, include favourable horizons where basinal brines have transected the Devonian strata, via fault conduits, and migrated laterally along an impermeable interface (*cf.* the stratabound, barite-bearing mineralization of the Sorby Hills deposits).

The Ordovician strata may host Pb-Zn stratabound mineralization where the earliest formed basinal brines of the Fitzroy Trough exploited available porosity in the lowermost stratigraphic units of the sedimentary pile. More evolved basinal brines penetrated upwards and exploited Devonian strata during later pulses. Further, it is conceivable that the Ordovician strata may host stratiform, synsedimentary Pb-Zn sulphides where basinal and/or hydrothermal fluids escaped on to the sea floor. The geological setting for the Ordovician sediments of the Canning Basin, in late Ordovician times, is comparable to that of the Tournaisian sediments in the Bonaparte Basin which are host to the Sorby Hills lead-zinc sulphide and include a small portion of synsedimentary sulphide. In the Canning Basin during the Ordovician, hydrothermal-fluid activity may have been favoured by the initiation of rifting in the Fitzroy Trough, with attendant high heat flow, extensional tectonism, and fault-conduit formation. The thin sedimentary basin infill would have favoured escape of fluids on to the sea floor and formation of 'Irish-type' Pb-Zn deposits.

CONCLUSIONS

1. The Wagon Pass, Narlarla, Blendevale and Sorby Hills prospects are epigenetic accumulations of lead and zinc sulphides in carbonate host rocks that share numerous geological characteristics.

2. The prospects are Mississippi Valley-type in genetic character, and they show close parallels with the following deposits: Pine Point, Canada; southeast Missouri (similar to Sorby Hills); and Silesia, Poland (similar to Narlarla).

3. The Kimberley MVT ore prospects are generally spatially and genetically related to zones of dolomitization and have simple sulphide mineralogies. They were deposited from warm (about 100°C), basin-derived brines, utilizing reduced sulphur from an (ultimate) sea-water sulphate source.

4. The most striking geological differences amongst them are the Pb:Zn ratios and the forms of sulphide bodies. These properties mainly reflect the stratigraphic position of the host rock with respect to basement petrology and basement physical characteristics.

5. Detailed studies of the Kimberley prospects underline the validity of Sangster's classification (1983) and illustrate the spectrum of characteristics that MVT orebodies may exhibit: Sorby Hills is a 'cratonal' example of the MVT, whereas Blendevale is 'platformal' (Table 1).

6. The ore-forming process at each reflects the semicontinuous passage of basinal brines, which became warmer and more metalliferous with time.

7. The proposed genetic model in each case advocates the transportation of metals in a basin-derived brine (?as complex chlorides) and the precipitation of sulphides on mixing with resident H_2S-bearing pore fluids. Reduced sulphur was provided by the thermochemical reduction of seawater sulphate in the presence of hydrocarbons (both species introduced by pre-metal, dolomitizing brines) and/or bacterial reduction of sea-water sulphate (Blendevale).

Metal-bearing brines were introduced, following fault movements, and their influx produced brecciation by hydraulic-fracturing and solution collapse. Following the 'consumption' of available reduced sulphur and precipitation of very fine-grained sulphides, sulphide precipitation proceeded more slowly, controlled by the rate of influx of H_2S-bearing formational fluids from the wall rocks towards the fault-breccia zones. Pore-fluid entrainment that accompanied basinal-brine influx proceeded until fluid pressures were equalized and/or the system was sealed. However, repeated fault movement was common and the cycle of sulphide precipitation was repeated in several pulses.

ACKNOWLEDGEMENTS

This study has been made possible by the kind co-operation of the mining companies actively engaged in exploration for lead-zinc in the Kimberley region. The author would like to thank the management, geologists and field staff of Broken Hill Co. Pty Ltd, Shell Minerals Australia, St Joe Bonaparte and Elf Aquitaine for their assistance, co-operation and hospitality. Mr Vic Russell is also thanked for permitting access to the Narlarla mine.

In addition, the author acknowledges I. Lambert and co-workers of Baas Becking Laboratory for their helpful discussions and permission to publish the initial results of their work.

REFERENCES

AKANDE, S. O., and FERTILLI, M., 1984, Geologic, fluid inclusion and stable isotope studies of the Gays River lead-zinc deposit, Nova Scotia, Canada: Econ. Geol., v. 79, p. 1187-1211.

ANDERSON, G. M., 1978, Basinal brines and MVT ore deposits: Episodes, no. 2, p. 15-19.

ANDERSON, G. M., and MacQUEEN, R. W., 1982, Ore deposit models – 6. Mississippi Valley-type lead-zinc deposits: Geoscience Canada, v. 9, p. 108-117.

ANDREW, C. J. and ASHTON, J. H., 1981, Mineral textures; metal zoning and ore environment of the Navan orebody, Co. Meath, Ireland, *in* Mineral Exploration in Ireland – progress and developments 1971-1981, *edited by* A. G. BROWN and J. PYNE: Irish Association for Economic Geologists, Wexford, Ireland.

BADHAM, J. P. N., 1981, Shale-hosted Pb-Zn deposits: products of exhalation of formation waters?: Trans Inst. Min. Metall., Section B, v. 90, B70-76.

BEALES, F. W., and JACKSON, S. A., 1966, Precipitation of lead-zinc ores in carbonate reservoirs as illustrated by Pine Point ore field, Canada: Trans. Inst. Min. Metall., Section B, v. 75, p. B278-B285.

BERNER, R. A., 1970, Sedimentary pyrite formation: American Journal of Science, v. 268, p. 1-23.

BLOCKLEY, J. G., 1971, The lead, zinc and silver deposits of Western Australia: West. Australia Geol. Survey, Mineral Resources Bull. 9.

BOAST, A. M., COLEMAN, M. L., and HALLS, C., 1981, Textural and stable isotope evidence for the genesis of the Tynagh base metal deposit, Ireland: Econ. Geol. v. 76, p. 27-55.

BROWN, J. S., *editor*, 1967, Genesis of stratiform lead-zinc-barite-fluorite deposits: Econ. Geol., Monograph 3.

BROWN, S. A., BOSERIO, I. M., JACKSON, K. S., and SPENCE, K. W., 1984, The Geological Evolution of the Canning Basin – Implications for Petroleum Exploration, *in* The Canning Basin, W.A., *edited by* P. G. PURCELL: Geol. Soc. Australia/PESA Symposium, Perth, 1984, Proceedings, p. 85-96.

CALLAHAN, W. H., 1967, Some spatial and temporal aspects of the localization of Mississippi Valley – Appalachian type ore deposits, *in* Genesis of stratiform lead-zinc-barite-fluorite deposits *edited by* J. S. BROWN: Econ. Geol., Monograph 3, p. 14-19.

CATHLES, L. M., 1981, Fluid flow and genesis of hydrothermal ore deposits: Econ. Geol., Seventy-fifth Anniversary volume, p. 392-423.

CATHLES, L. M. and SMITH, A. T., 1983, Thermal constraints on the formation of Mississippi Valley-type lead-zinc deposits and their implications for episodic basin dewatering and deposit genesis: Econ. Geol., v. 78, p. 983-1002.

CZAMANSKE, G. K., ROEDDER, E., and BURNS, F. C., 1963, Neutron activation analysis of fluid inclusions for copper, manganese and zinc: Science, v. 140, p. 401-403.

ECKLEMANN, F. D., and KULP, J. L., 1959, Lead isotopes and ore deposition in the Southeast Missouri lead district: Geol. Soc. American Bull., v. 70, p. 1595.

ETMINAN, H., LAMBERT, I. B., BUCHHORN, I., CHAKU, S., and MURPHY, G. C., 1984, Research into diagenetic and mineralising processes, Lennard Shelf reef complexes, W.A., *in* The Canning Basin, W.A., *edited by* P. G. PURCELL: Geol. Soc. Australia/PESA Symposium, Perth, 1984, Proceedings, p. 447-454.

FINUCANE, K. J., and JONES, F. H.,1939, Barker River area, West Kimberley District: Aerial Geol. Geophys. Survey Northern Australia, Report Western Australia, No. 43.

GELLATLY, D. C., 1970, Textures and Genesis of lead-zinc ores from Narlarla West Kimberley region, Western Australia: Australia BMR Record 1970/117.

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA, 1974, Geology of Western Australia: West. Australia Geol. Survey, Mem. 2, p. 541.

GUSTAFSON and WILLIAMS, 1981, Sediment hosted stratiform deposits of copper lead and zinc: Econ. Geol, Seventy-fifth Anniversary Volume, p. 139-178.

HAGNI, R. D., 1983, Ore microscopy, paragenetic sequence, trace element content and fluid inclusion studies of the copper-lead-zinc deposits of the southeast Missouri lead district, *in* Mississippi Valley-type lead-zinc deposits: International Conference 1983, University of Missouri-Rolla, Proceedings, v.9, Rolla, Missouri, p. 243-256.

HALL, W. D. M., 1984, The stratigraphic and structural development of the Givetian-Frasnian reef complex, Limestone Billy Hills, western Pillara Range, W.A.: *in* The Canning Basin, W.A., *edited by* P. G. PURCELL: Geol. Soc. Australia/PESA Symposium, Perth, 1984, Proceedings, p. 215-222.

HALLIGAN, R., 1965, The Narlarla lead-zinc deposits, Barker River area, West Kimberley Goldfield: West. Australia. Geol. Survey Ann. Rept 1964, p. 43-45.

HANOR, J. S., 1979, The sedimentary genesis of hydrothermal fluids, *in* Geochemistry of hydrothermal ore deposits (2nd edition) *edited by* H. L. BARNES, New York, Wiley, p. 157-172.

HEYL, A. V., LANIS, G. P., and ZARTMAN, R. E., 1974, Isotopic evidence for the origin of Mississippi Valley-type mineral deposits: a review: Econ. Geol., v. 69, p. 992-1006.

HUTTON, G. J., 1965, The Devonian lead-zinc mine, West Kimberley District, Western Australia: B.Sc (Hons) thesis, Univ. of Western Australia (unpublished).

INTERNATIONAL CONFERENCE, MISSOURI, 1983, Mississippi Valley-type lead-zinc deposits: Conference 1983, University of Missouri-Rolla, Proceedings v. 9, Rolla, Missouri.

JACKSON, S. A., and BEALES, F. W., 1967, An aspect of sedimentary basin evolution: the concentration of Mississippi Valley-type ores during the late stages of diagenesis: Canadian Petroleum Geologists Bull., v. 15, p. 393-433.

JACKUCS, L., 1977, Genetic types of Hungarian karst: Karst es Berlang (Budapest), Special Issue, p. 3-18.

LAWS, R., 1981, The petroleum geology of the onshore Bonaparte Basin: APEA Jour., v. 21, pt. 1, p. 5-15.

LAWS, R. A., and BROWN, R. S., 1976, Petroleum Geology of the southeastern Bonaparte Gulf Basin, *in* Economic geology of Australia and Papua New Guinea – 3, Petroleum, *edited by* R. B. LESLIE, H. J. EVANS, and C. L. KNIGHT: Australasian Inst. Mining Metall., Monograph 7, p. 200-208.

LEGGE, P. J., HASLAM, C. O., and TAYLOR, S., 1984, Lead-zinc-silver explorations and development in Australia: Australasian Inst. Mining Metall., Proceedings 289, p. 119-135.

LENTINI, M. R., and Shanks, W. C. III, 1983, Experimental study of brine-arkose interaction at 200°C and 500 bars – origin of metalliferous oilfield brines and Mississippi Valley-type ore deposits, *in* Mississippi Valley-type lead-zinc deposits: International Conference 1983, University of Missouri-Rolla, Proceedings, v. 9, Rolla, Missouri, p. 195-205.

MATHESON, R. S., and GUPPY, D. J., 1949, Geological reconnaissance in the Mount Ramsay Area, Kimberley Division, W.A.: Australia BMR Record 1948/49 (unpublished).

MATTES, B. W., and MOUNTJOY, E. W., 1980, Burial dolomitization of the Upper Devonian Miette Buildup, Jasper National Park, Alberta: SEPM Special Publication, No. 28, 'Concepts and models of dolomitization', p. 259-297.

McLIMANS, R. K., BARNES, H. L., and OHMOTO, H., 1980, Sphalerite stratigraphy of the Upper Mississippi Valley lead-zinc district, southwest Wisconsin: Econ. Geol., v. 75, p. 351-361.

MOYLE, A. J., 1980, A fluid inclusion study of the lead-zinc mineralization of the Pillara Prospect, Western Australia: B.Sc. Hons thesis, Univ. of Adelaide (unpublished).

MORY, A. J., AND BEERE, G. M., 1988, Geology of the onshore Bonaparte and Ord Basins in Western Australia: West. Australia Geol. Survey Bull. 134.

MURPHY, G. C., BAILEY, A., and PARRINGTON, P. J., 1986, The Blendevale carbonate-hosted zinc-lead deposit, Pillara, Kimberley region, Western Australia, *in* Geology and Exploration, *edited by* D. A. BERKMAN: Council of Mining and Metallurgical Institutions Congress, 13th, 1986, Singapore, Publications v. 2, p. 153-161.

NEWHOUSE, W. H., 1932, The composition of vein solutions are shown by liquid inclusions in minerals: Econ. Geol., v. 27, p. 419-436.

NEWHOUSE, W. H., 1933, The temperature of formation of the Mississippi Valley lead-zinc deposits: Econ. Geol., v. 28, p. 774-750.

OHLE, E. L., 1959, Some consideration in determing the origin of ore deposits of Mississippi Valley-type: Econ. Geol., v. 54, p. 769-789.

OHLE, E. L., 1967, The origin of ore deposits of the Mississippi Valley-type, *in* Genesis of stratiform lead-zinc-barite-fluorite deposits: Econ. Geol., Monogaph 3, p. 33-39.

OHLE, E. L., 1980, Some considerations in determining the origin of ore deposits of the Mississippi Valley-type, Part II: Econ. Geol., v. 75, p. 161-172.

OHMOTO, H.,and RYE, R. O., 1979 Isotopes of sulphur and carbon, *in* Geochemistry of hydrothermal ore deposits, (2nd edition) *edited by* H. L. BARNES, New York, Wiley p. 509-567.

OLSON, R. A., 1984, Genesis of paleokarst and stratabound zinc-lead sulphide deposits in a Proterozoic dolostone, northern Baffin Island: Econ. Geol., v. 79, p. 1056-1103.

PLAYFORD, P. E., 1980, Devonian "Great Barrier Reef" of the Canning Basin, Western Australia: Am. Assoc. Petroleum Geol. Bull., v. 64, no. 6, p. 814-840.

PLAYFORD, P. E., 1984, Platform-margin and marginal-slope relationships in Devonian reef complexes of the Canning Basin, *in* The Canning Basin, W.A. *edited by* P. G. PURCELL: Geol. Soc. Australia/PESA Symposium, Perth, 1984, Proceedings, p. 189-214.

PLAYFORD, P. E., COPE, R. N., COCKBAIN, A. E., LOW, G. H., and LOWRY, D. C., 1975, Phanerozoic, *in* Geology of Western Australia: West. Australia Geol. Survey Mem. 2, p. 221-431.

PLAYFORD, P. E., and LOWRY, D. C., 1966, Devonian reef complexes of the Canning Basin, Western Australia: West. Australia Geol. Survey Bull. 118.

POWELL, T. G., and MacQUEEN, R. W., 1984, Precipitation of sulphide ores and organic matter: sulphate reactions at Pine Point, Canada: Science, v. 224, p. 63-66.

PURCELL, P. G., 1984, The Canning Basin, W.A.—An Introduction, *in* The Canning Basin, W.A., *edited by* P. G. PURCELL: Geol. Soc. Australia/PESA Symposium, Perth 1984, Proceedings, p. 3-20.

PRIDER, R. T., 1941, Hydrozinicite from Narlarla, West Kimberley District, Western Australia: Mineralogical Mag., v. 26, p. 60-65.

RAMDOHR, P., 1969, The ore minerals and their intergrowths: London, Pergamon Press.

REECKEMANN, S. A., and MEBBERSON, A. J., 1984, Igneous intrusions in the north-west Canning Basin and their impact on oil exploration, *in* The Canning Basin, W.A., *edited by* P. G. PURCELL: Geol. Soc. Australia/PESA, Symposium, Perth, 1984, Proceedings, p. 389-400.

RHODES, D., LANTOS, E. A., LANTOS, J. A., WEBB, R. J., and OWENS, D. C., 1984, Pine Point orebodies and their relationship to the stratigraphy, structure, dolomitization and karstification of the Middle Devonian Barrier Complex: Econ. Geol., v. 79, p. 991-1055.

RINGROSE, C. R., 1984, The geology and genesis of the Narlarla lead-zinc deposits, Napier Range, W.A., *in* The Canning Basin, W.A. *edited by* P. G. PURCELL: Geol. Soc. Australia/PESA, Symposium, Perth, 1984, Proceedings, p. 455-462.

RINGROSE, C. R., 1986, Occurrence, distribution, and origin of smithsonite in the No. 2 lead-zinc deposit at Narlarla, Western Australia: West. Australia Geol. Survey, Professional Papers for 1984, Report 19, p. 62-69.

ROD, E., 1966, Clues to ancient Australian geosutures: Ecologae Geol. Helvetiae, v. 59, p. 849-883.

ROEDDER, E., 1968a, Temperature, Salinity and Origin of the Ore-joining fluids at Pine Point, Northwest Territories, Canada, *in* Fluid inclusion studies: Econ. Geol., v. 63, p. 439-450.

ROEDDER, E.,1968b, The Norcolloidal origin of "colloform" textures in sphalerite ores: Econ. Geol., v. 63, p. 451-471.

ROEDDER, E., 1976, Fluid inclusion evidence in the genesis of ores in sedimentary and volcanic rocks, *in* Handbook of Stratabound and stratiform ore deposits *edited by* K. H. WOLF: Amsterdam, Elsevier. v. 4, p. 67-110.

ROEDDER, E., 1979, Fluid inclusion evidence on the environments of sedimentary diaagenesis: a review, *in* Aspects of diagenesis, *edited by* P. A. SCHOLLE and P. R. SCHLUGER: Soc. Econ. Palaeontol. Mineral., Special Publication 26, p. 89-107.

ROWLEY, M., and LEE, R. J., 1986, The Sorby Hills, W.A., lead-zinc-silver province, *in* Geology and Exploration, *edited by* D. A. BERKMAN: Council of Mining and Metallurgical Institutions Congress, 13th, 1986, Singapore, Publications v. 2, p. 173-180.

RUSSELL, M. J., 1975, Lithogeochemical environment of the Tynagh base metal deposit, Ireland, and its bearing on ore deposition: Trans. Inst. Min. Metall., Section B, v. 84, B128-133.

SAMSON, I. M., and RUSSELL, M. J., 1983, Fluid-inclusion data from Silver mines base metal/barytes deposits, Ireland: Trans. Inst. Min. Metall., Section B, v. 92, B67-71.

SANGAMESHWAR, S. R., and BARNES, H. L., 1983, Supergene processes in zinc-lead-silver sulphide ores in carbonates: Econ. Geol., v. 78, p. 1379-1397.

SANGSTER, D. F., 1983, Mississippi Valley-type deposits – A geological melange, *in* Mississippi Valley-type deposits: Interntional Conference 1983, University of Missouri-Rolla, Proceedings, v. 9, Rolla, Missouri, p. 7-18.

SASS-GUSTKIEWICZ, M., DZULYNSKI, S., and RIDGE, J. D., 1982, The emplacement of zinc-lead sulfide ores in the Upper Silesian district – a contribution to the understanding of Mississippi Valley-type deposits: Econ. Geol., v.77, p. 392-412.

SKALL, H., 1975, The palaeoenvironment of the Pine Point lead-zinc district: Econ. Geol., v. 70, p. 22-45.

SVERJENSKY, D. A., 1981, The original of a Mississippi Valley-type deposit in the Viburnum Trend, southeast Missouri: Econ. Geol., v. 76, p. 1848-1872.

SVERJENSKY, D. A., 1984, Oil field brines as ore-forming solutions: Econ. Geol., v. 79, p. 23-37.

SVERJENSKY, D. A., RYE, D. M., and DOE, B. R., 1979, The lead and sulphur isotopic compositions of galena from a Mississippi Valley-type deposit in the New Lead belt, southeast Missouri: Econ. Geol., v. 74, p. 149-153.

TAYLOR, P., 1980, The stereochemistry of iron sulphides – a structural rationale for crystallization of some metastable phases from aqueous solutions: Am. Mineralogist, v. 65, p. 1026-1030.

TAYLOR, P., RUMMERY, T. E., and OWEN, D. G., 1979, Reactions of iron mono-sulphide solids with aqueous hydrogen sulphide up to 160°C: Journal of Inorganic and Nuclear Chemistry, v. 41, p. 1683-1687.

TAYLOR, S., and ANDREW, C. J., 1978, Silvermines orebodies, County Tipperary, Ireland: Trans. Inst. Min. Metall., Section B, v. 87, B111-124.

VEEVERS, J. J., 1976, Early Phanerozoic events on and alongside the Australian-Antarctic platform: Geol. Soc. Australia Jour., v. 23, p. 183-206.

VEEVERS, J. J. and ROBERTS, J., 1968, Upper Palaeozoic rocks, Bonaparte Gulf Basin of Northwestern Australia: Australia BMR Bull. 97.

WALKER, R. N., GULSON, B., and SMITH, J., 1983, The Coxco deposit – A Proterozoic Mississippi Valley-type deposit in the McArthur River District, Northern Territory, Australia: Econ. Geol., v. 78, p. 214-249.

WHITE, D. E., 1974, Diverse origins of hydrothermal ore fluids: Econ. Geol., v. 69, p. 954-973.

WILLIAMS, N., 1978, Studies of the base metal sulphide deposit at McArthur River, Northern Territory, Australia: I. The Cooley and Ridge deposits: Econ. Geol., v. 73, p. 1005-1035.

WINSLOW, A., 1984, The lead and zinc deposits of Missouri: Missouri Geol. Survey, 1st Ser., v. 6-7, p. 135-156, 252-264.

WOLF, K. H., (*editor*), 1976, Handbook of stratabound and stratiform ore deposits, Part I, Principles and General studies (v. 1-4); Part II, Regional studies and specific deposits, (v. 5-7): Amsterdam, Elsevier.

WOLF, K. H., (*editor*) 1981, Handbook of stratabound and stratiform ore deposits, Part III (v. 8-10): Amsterdam, Elsevier.

WOODWARD, H. P., 1907, Mineral discoveries at Narlarla in the West Kimberley district: West. Australia Geol. Survey Ann. Rept 1906, p. 11-13.

WU, Y., and BEALES, F., 1981, A reconnaissance study of paleomagnetic methods of the age of mineralization along the Viburnum Trend, southeast Missouri: Econ. Geol., v. 76, p. 1879-1894.

YEATES, A. N., GIBSON, D. L., TOWNER, R. R. and CROWE, R. W. A., 1984, Regional geology of the onshore Canning Basin, *in* The Canning Basin, W.A., *edited by* P. G. PURCELL: Geol. Soc. Australia/PESA Symposium, Perth 1984, Proceedings, p. 23-56.

YORK, D., HANES, J. A., KUYBIDA, P., HALL, C. M., KENYON, W. J., MASLINEC, A., SCOTT, S. D., and SPOONER, E. T. C., 1980, The direct dating of ore minerals: American Geophysical Union, Spring Meeting, E. O. S., Abstracts v. 61, No. 17, p. 399.

PLATES

Abbreviations used on plates

Ba	barite
Bn	bornite
C	calcite
C(s)	calcite (spar)
C(v)	calcite vein
Ch	chlorite
Cp	chalcopyrite
D	dolomite
D(c)	dolomite clast
D(sa)	saddle dolomite
Fe	iron oxides
G	galena
G(co)	colloform galena
G(sk)	skeletal galena
Gy	gypsum
Mc	marcasite
Py	pyrite
Py(co)	colloform pyrite
Q(o)	overgrowths of quartz
S	sphalerite
S(bo)	sphalerite botryoids
S(co)	colloform sphalerite
S(ds)	disseminated sphalerite
S(ge)	'gel' sphalerite
S(v)	vein sphalerite
Sm	smithsonite
T	tennantite-tetrahedrite

f	framboids
os	open space
tfs	turbid fibrous spar
wr	wall rock
wrd	wall-rock detritus

T.L.	transmitted light
R.L.	reflected light

PLATE 1

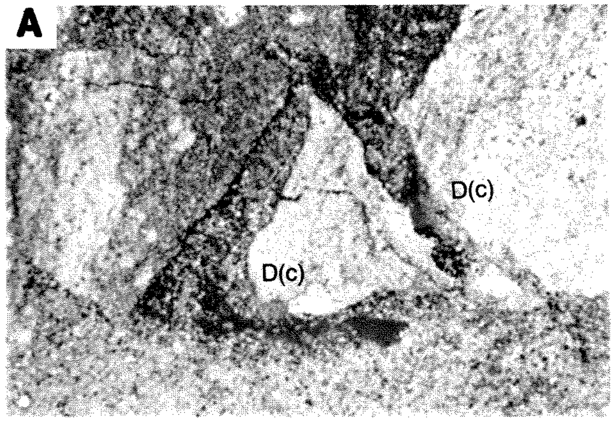
Host-rock textures and gangue mineralogy, Wagon Pass.

(A) Chloritized dolomitic breccia with patches and disseminations of chlorite interstitial to dolomite rhombs (76999).

(B) Sinuous fracture in medium-grained dolomite, lined with coarse-grained dolomite and filled with coarse-grained calcite (spar). The spar has been replaced at a later stage by an assemblage dominantly of chlorite with included dolomite rhombs (77758).

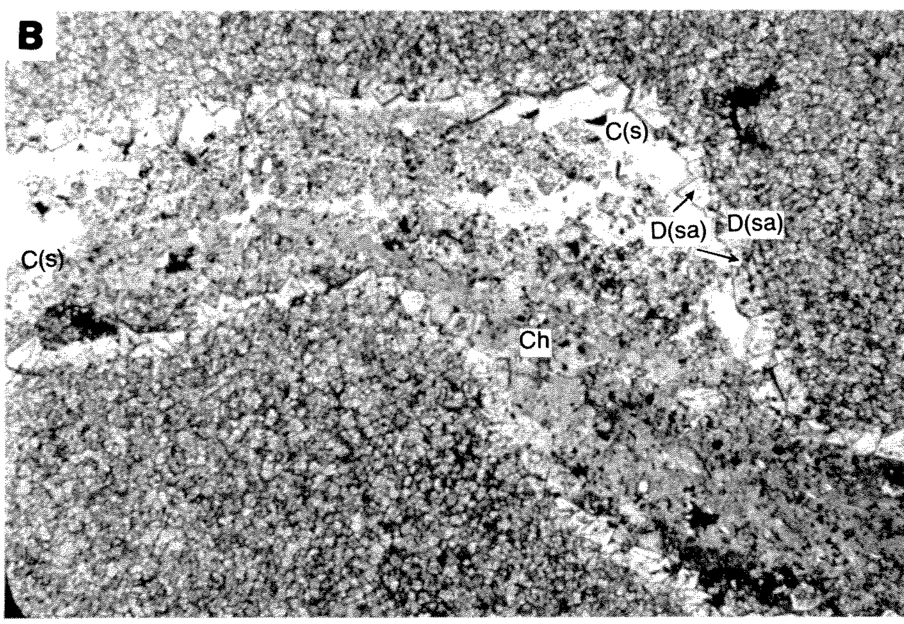
(C) Microlaminae of ?gypsum (calcite pseudomorphs after gypsum) in a sulphide-rich interbed (76991B).

(D) Close-up of ?gypsum laths (as above) with interstitial sulphide (76992).



2 mm

T.L.

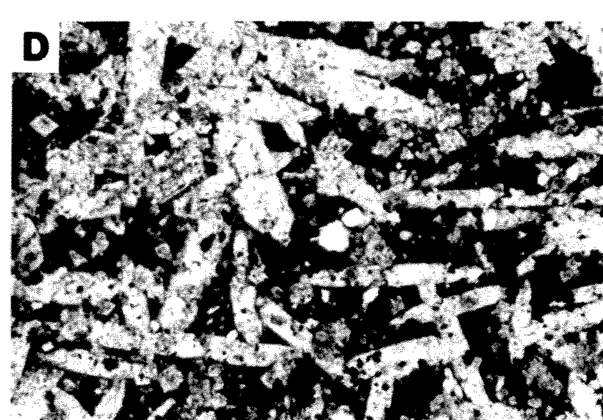


1 mm

T.L.

2 mm

T.L.



1 mm

T.L.

GSWA 23526

PLATE 2

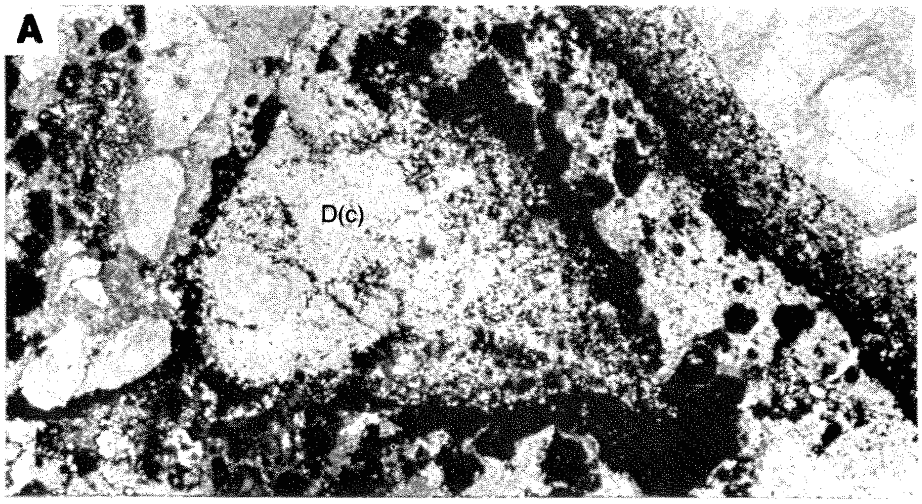
Styles of mineralization, Wagon Pass sulphide assemblage.

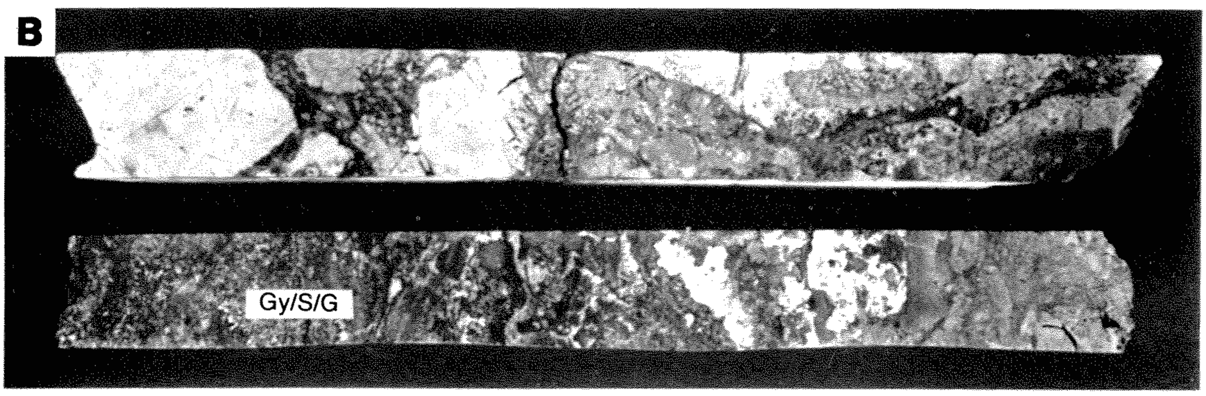
(A) Disseminated, low-density sphalerite filling the secondary porosity of dolomite clasts and forming rims to them in a dolomitic breccia. Sulphide mineralization, of sphalerite and galena, is heavier towards the perimeter of the breccia clasts and in the matrix (76990).

(B) Core sections illustrating a sulphide matrix to dolomitic breccia (upper-core piece) and very fine-grained disseminated sulphides in an argillaceous-rich interbed, with disseminated, pseudomorphed, ?gypsum laths throughout (lower-core piece) (79160 and 79155).

(C) Polished slab showing 'semi-massive' galena mineralization in a thin, argillaceous-rich interbed: galena occurs as laths and cuboids (77752).

(D) Vein-filling chalcopyrite mineralization, as rounded blebs in calcite, cross-cutting a sphalerite crust which itself lines an earlier fracture also filled with calcite (77751).


A
D(c)
5 mm
T.L.


B
Gy/S/G
1 cm


C
1 cm

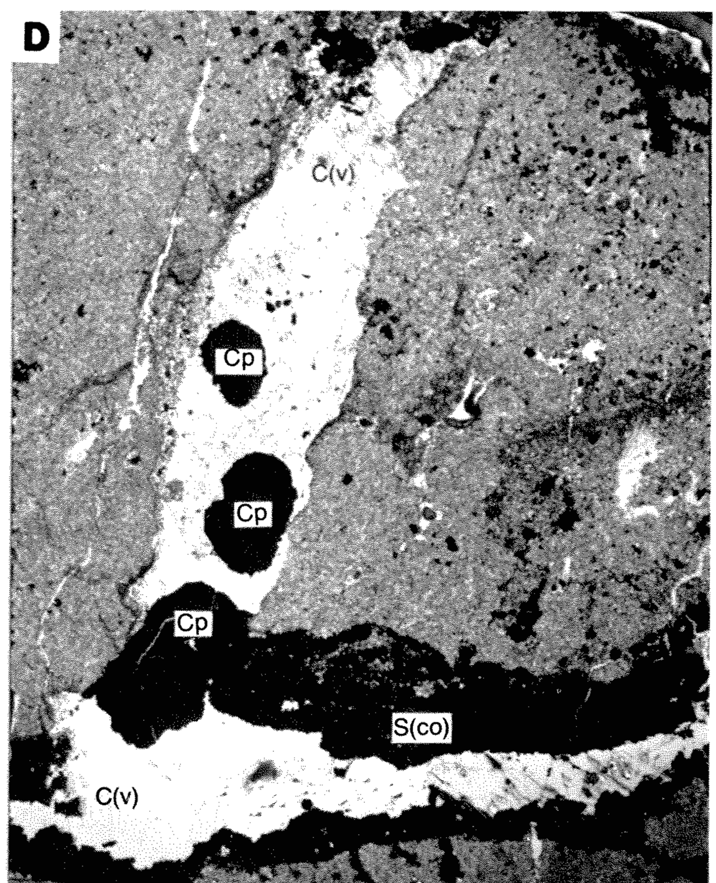

D
C(v)
Cp
Cp
Cp
S(co)
C(v)
5 mm
T.L.

PLATE 3

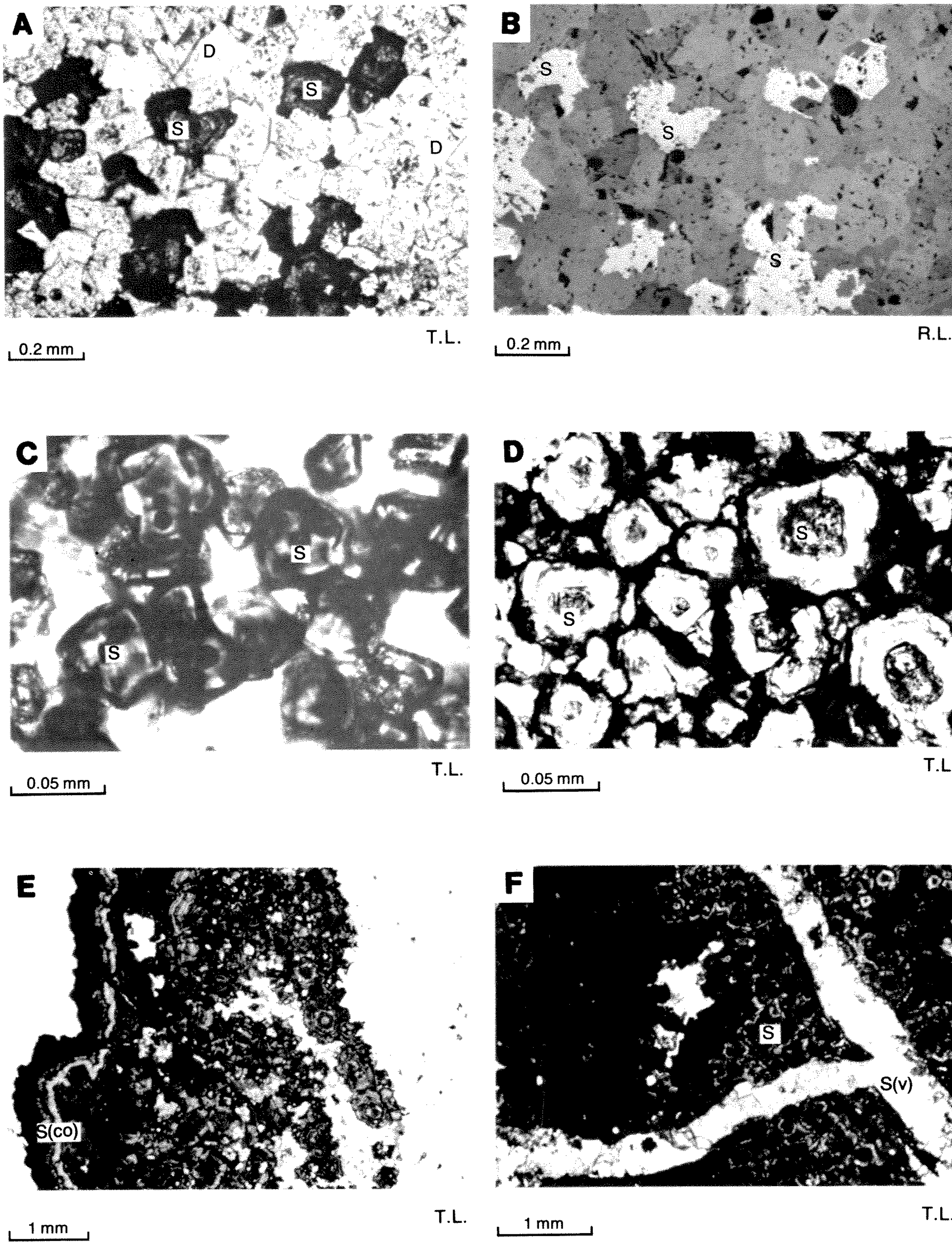
Microscopic textures of sphalerite mineralization, Wagon Pass.

(A) and (B) Anhedral and angular sphalerite grains growing in the intergranular, secondary porosity of dolomite as seen in transmitted (A) and reflected (B) light (76989A).

(C) and (D) Zoned sphalerite euhedra of cubic, rounded and hexagonal form showing (C) rounded, opaque nucleii (possibly of iron-rich sphalerite); or (D) diffuse zones of ?carbonaceous matter in central zones (77785A, 77785D).

(E) Illustration of the transition from disseminated intergranular sphalerite to 'colloform' sphalerite towards an open fracture (from right to left) (76990).

(F) Cross-cutting veinlet of very pale-grey sphalerite in coalescing euhedra of sphalerite (77771B).


A
D
S
S
D
0.2 mm
T.L.
B
S
S
S
0.2 mm
R.L.
C
S
S
0.05 mm
T.L.
D
S
S
0.05 mm
T.L.
E
S(co)
1 mm
T.L.
F
S
S(v)
1 mm
T.L.

GSWA 23528

PLATE 4

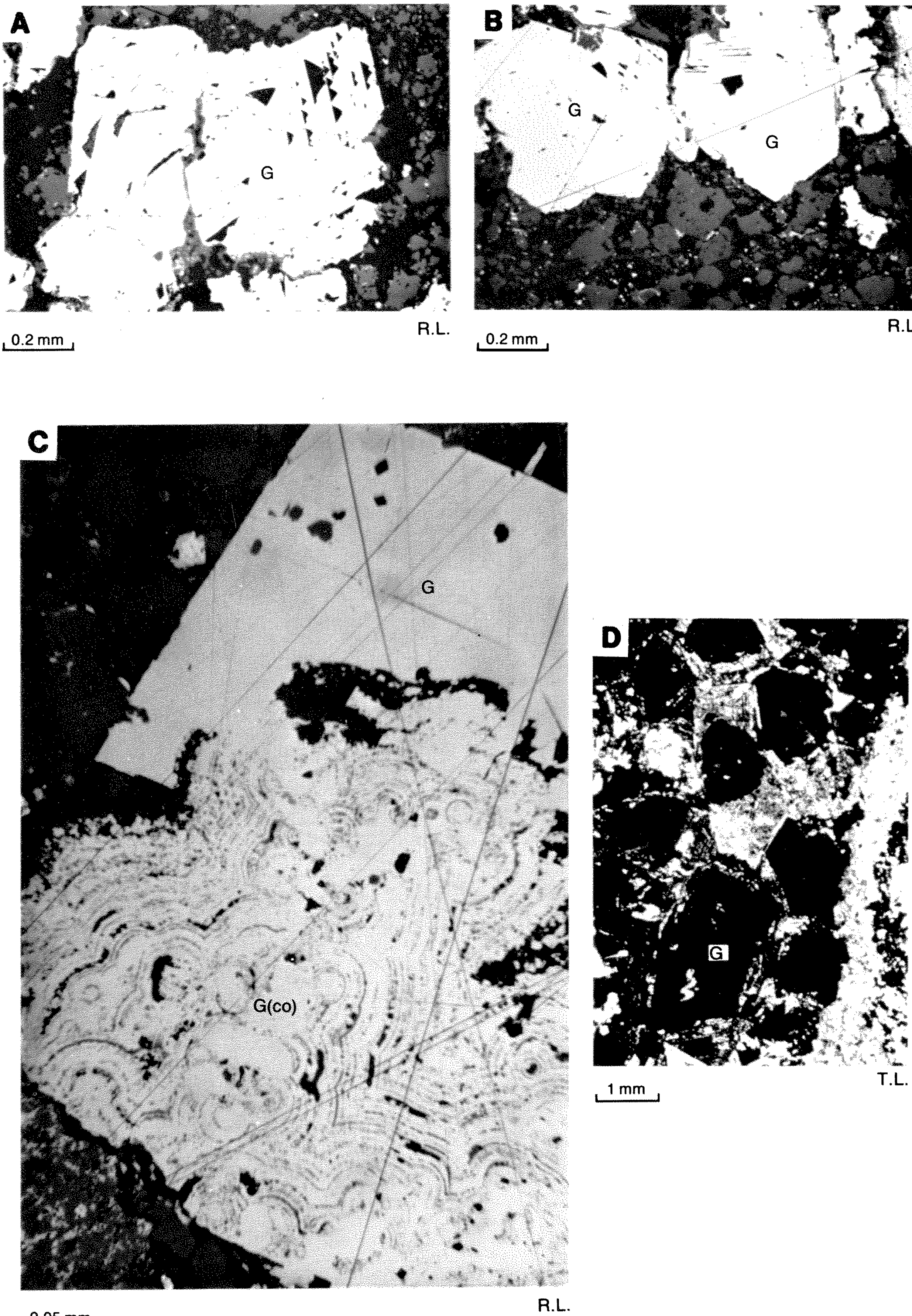
Microscopic textures of galena, Wagon Pass.

(A) Cubic galena euhedra rimmed and veined by iron oxides (goethite) (77752).

(B) Octahedral galena euhedra in dolomite (77752).

(C) Cubic galena euhedron 'replaced' by 'colloform' galena (77752).

(D) Galena euhedra in transmitted light showing corroded, oxidized rims (76994).



GSWA 23529

PLATE 5

Microscopic textures of iron and copper sulphides, Wagon Pass.

(A) Rounded blebs of chalcopyrite in calcite veinlets cutting sphalerite-rimmed breccia clast (76989A).

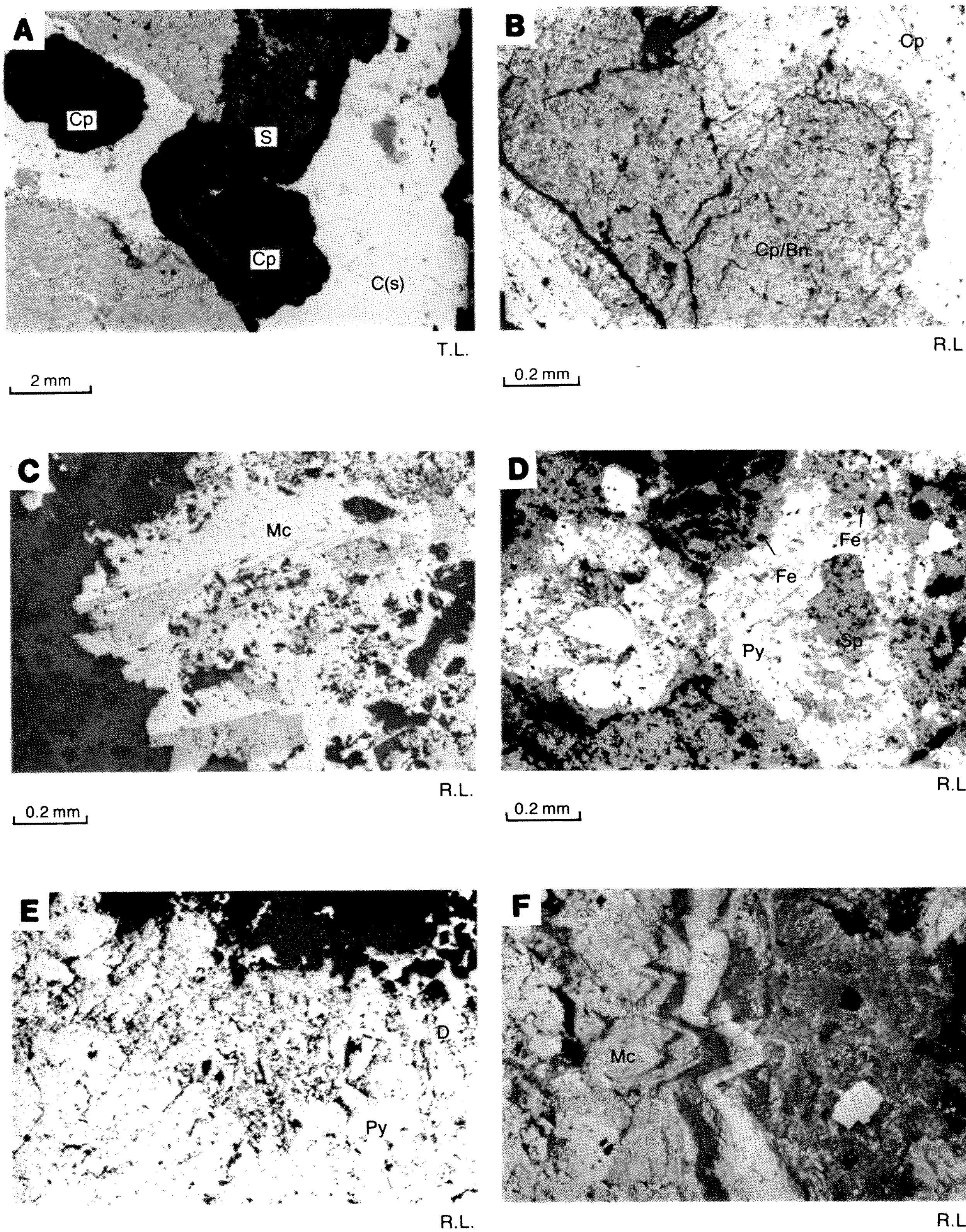
(B) Detail of chalcopyrite bleb in (A) shown in reflected light to illustrate intimate, internal intergrowth of chalcopyrite and bornite (76990).

(C) Marcasite rim to pyrite patch (marcasite is indicated by twinning and anisotropy, emphasized by slightly uncrossing the polars in reflected light) (76989A).

(D) Sphalerite euhedra surrounded by pyrite and replaced by iron oxides (a slightly lighter grey colour than sphalerite) (76989A).

(E) Replacive pyrite patch, the centre of which has completely replaced the host carbonate, whereas euhedral dolomite grains are discernable towards the edge of the pyrite zone (77785D).

(F) Coarser grained marcasite euhedra replaced by a veinlet network of iron oxides with digenite and covellite; grains of pyrite are also visible (77785C).


A
Cp
S
Cp
C(s)
T.L.
2 mm
B
Cp
Cp/Bn
R.L
0.2 mm
C
Mc
R.L.
0.2 mm
D
Fe
Fe
Py
Sp
R.L.
0.2 mm
E
D
Py
R.L.
0.2 mm
F
Mc
R.L.
0.2 mm

GSWA 23530

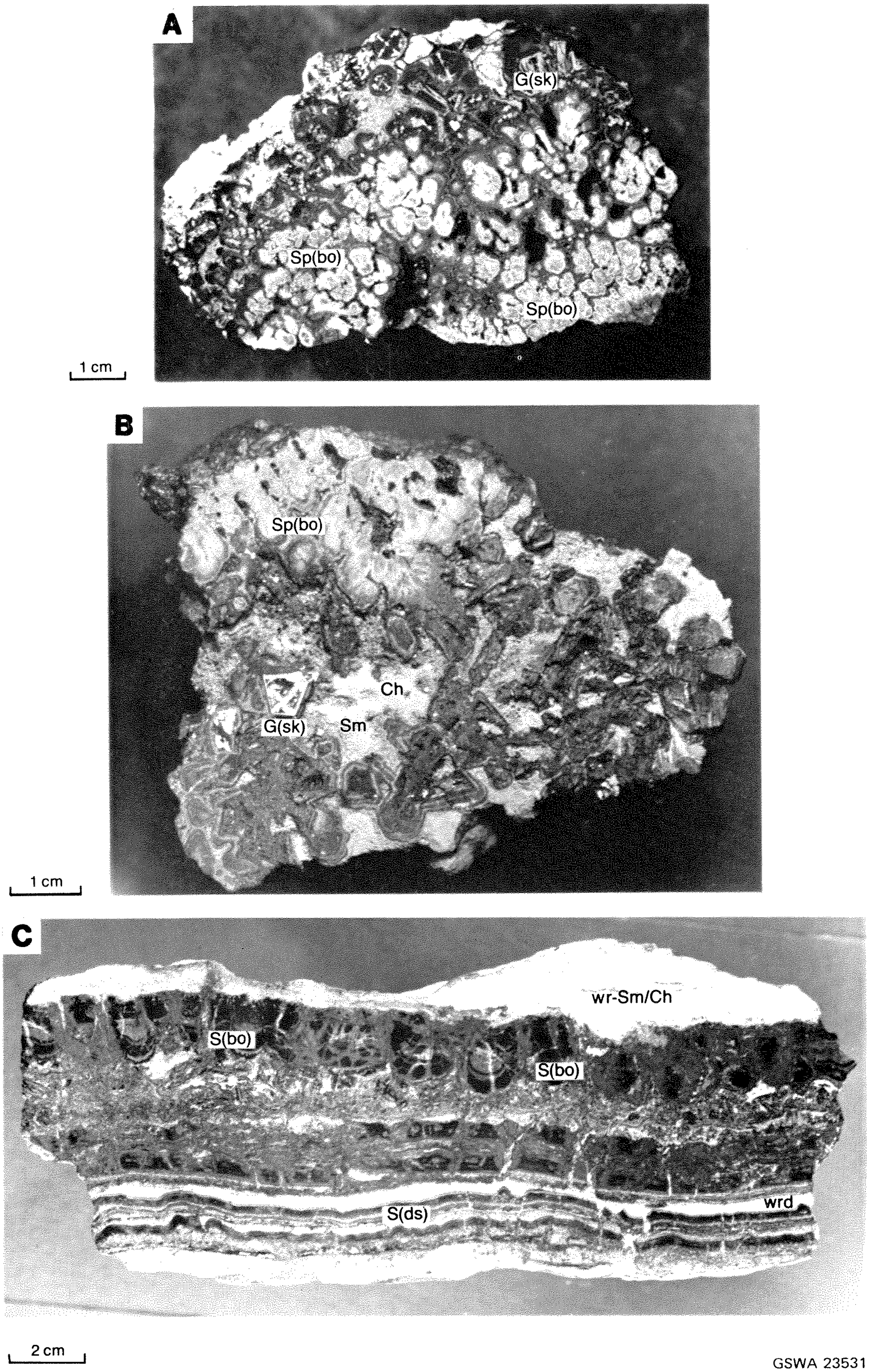
PLATE 6

Hand specimens illustrating Narlarla ore textures and mineralogy.

(A) Botryoidal-skeletal sphalerite-galena ore showing botryoids of sphalerite with oriented, intergrown laths and blebs of galena, skeletal galena cubes, and laths, also former 'gel' cores to dendrites. Interstitial smithsonite and pores are indicated (actual size).

(B) Botryoidal-skeletal sphalerite-galena ore showing growth banding in sphalerite botryoids, and included skeletal galena grains. Interstitial material is mixed chlorite and smithsonite (x 1.3).

(C) Bedded sphalerite-galena ore with wall-rock smithsonite-chlorite-siliciclastics. Laminae of botryoidal sphalerite and beds of disseminated sphalerite euhedra (some slumped and fractured) are interbedded with reworked wall-rock detritus (x 0.7).


A
G(sk)
Sp(bo)
Sp(bo)
1 cm
B
Sp(bo)
Ch
G(sk)
Sm
1 cm
C
wr-Sm/Ch
S(bo)
S(bo)
wrd
S(ds)
2 cm

GSWA 23531

PLATE 7

Microscopic textures of Narlarla ores.

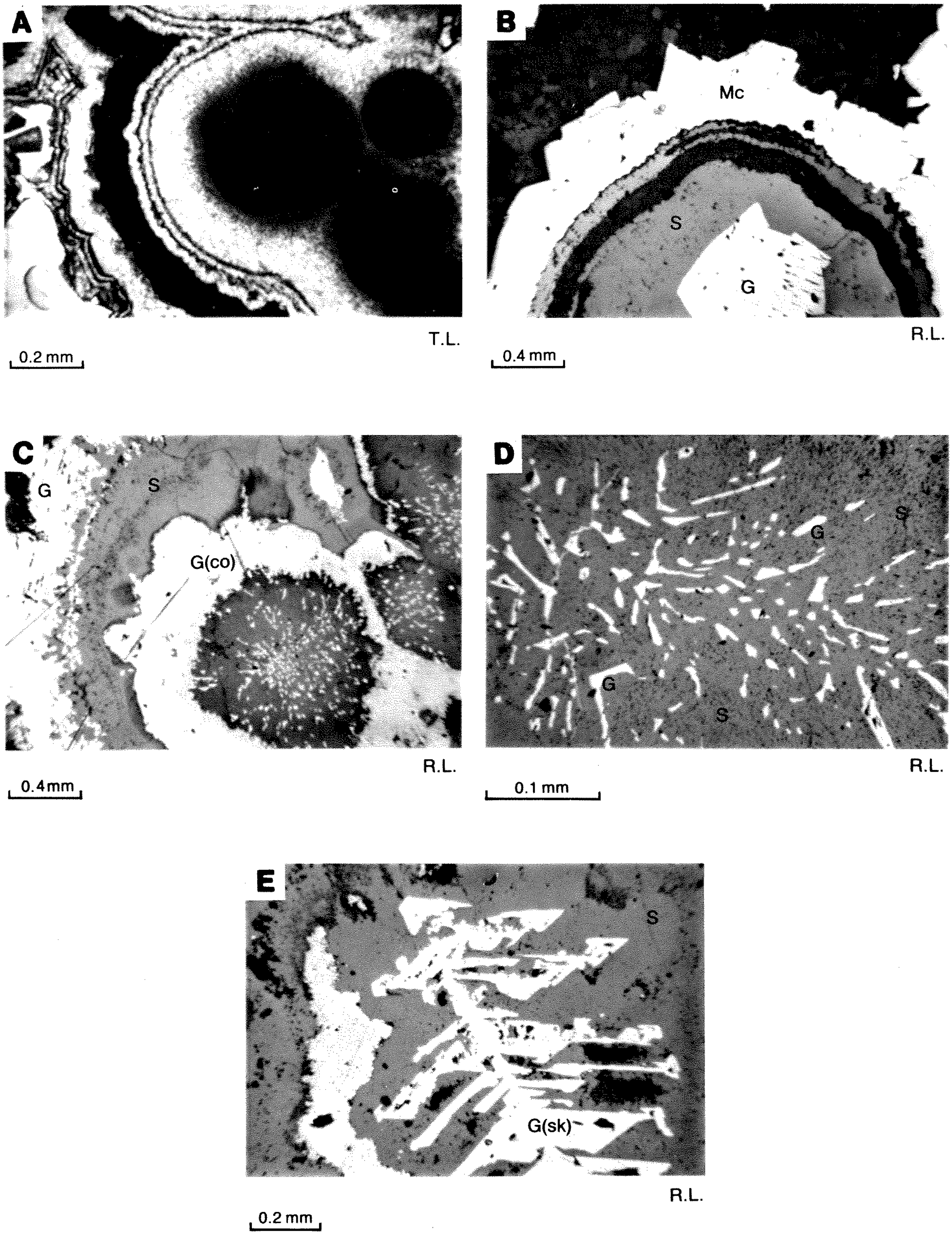
(A) Laminae of sphalerite growth zones, variously coloured, around an opaque, gel-like, circular core (80111B2).

(B) Sphalerite botryoid around a galena euhedron nucleus and rimmed by marcasite (78086B).

(C) Botryoid of sphalerite with laminae of 'colloform', 'spongy' galena and galena blebs, and rimmed by galena euhedra (80114).

(D) Detail of galena inclusions in botryoidal core of (C) (80114).

(E) Skeletal galena inclusion in sphalerite (80114).


A
T.L.
0.2 mm
B
Mc
S
G
R.L.
0.4 mm
C
G
S
G(co)
R.L.
0.4mm
D
G
S
G
S
R.L.
0.1 mm
E
S
G(sk)
R.L.
0.2 mm

GSWA 23532

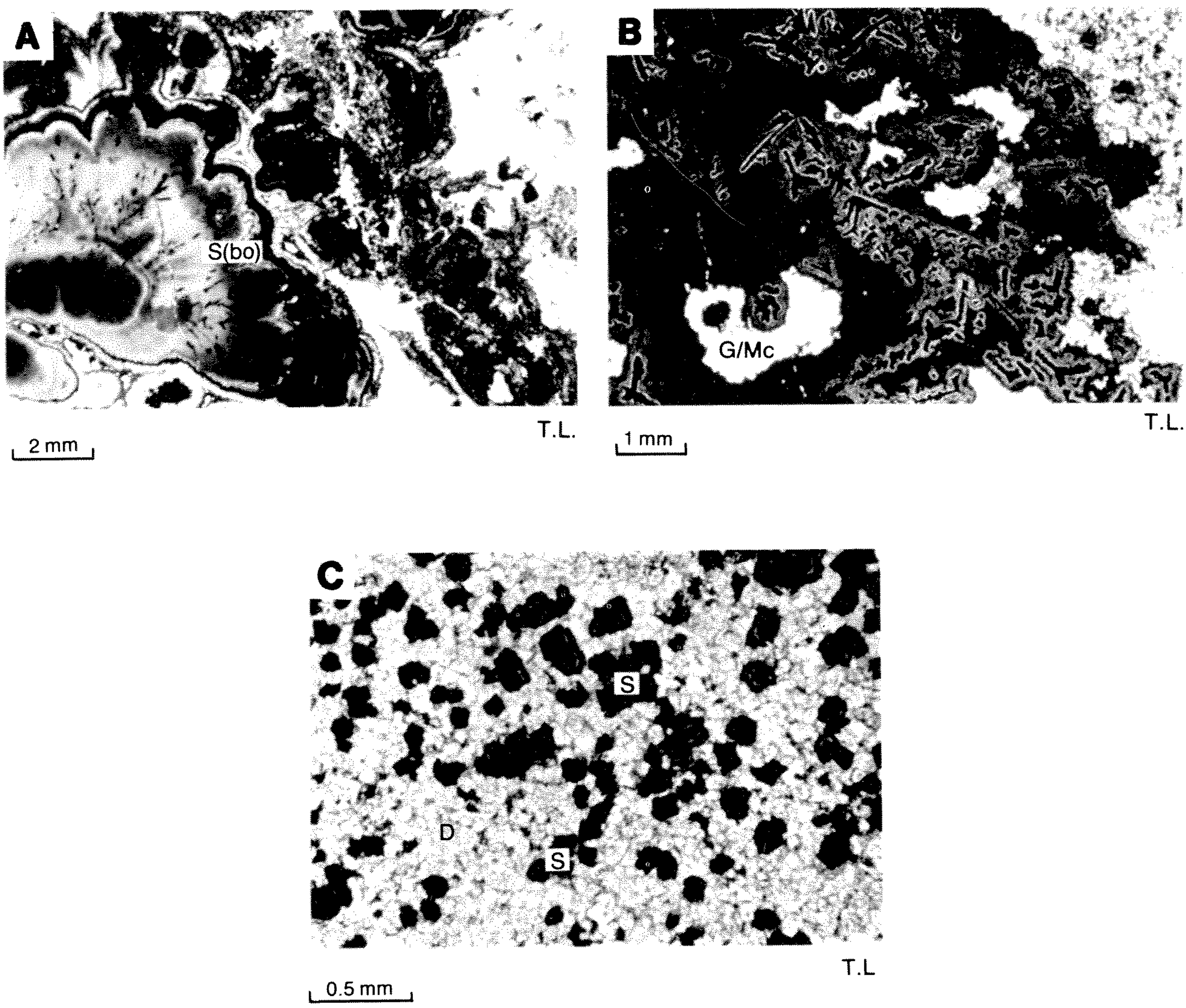
PLATE 8

Microscopic textures of Narlarla ores.

(A) View in transmitted light of 'gel-like' core to sphalerite botryoid (80115A).

(B) Dendritic sphalerite with primary porosity infilled by galena and marcasite (79053).

(C) Disseminated, zoned euhedra of sphalerite, interstitial to dolomitic limestone wall rock (79104).



GSWA 23533

PLATE 9

Styles of mineralization, Blendevale.

(A) Sinuous vein of sulphide (mainly sphalerite) which is paragenetically later than fibrous, turbid spar, and is post-dated by clear spar (76965).

(B) Irregular vein of sphalerite in stromatoporoid limestone (79908).

(C) Disseminated, fine-grained granules of sphalerite in fenestral, *Amphipora* limestone (79942).

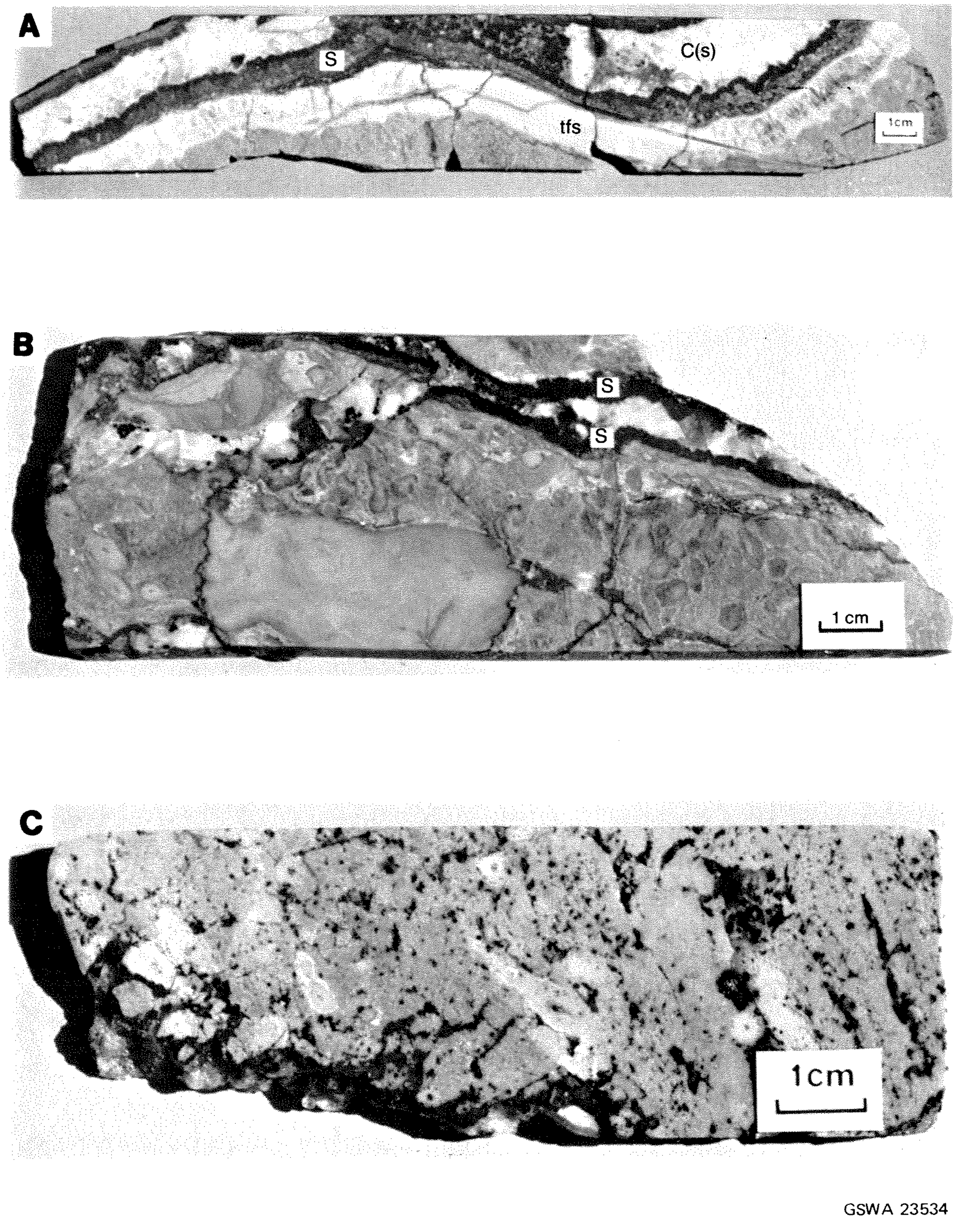
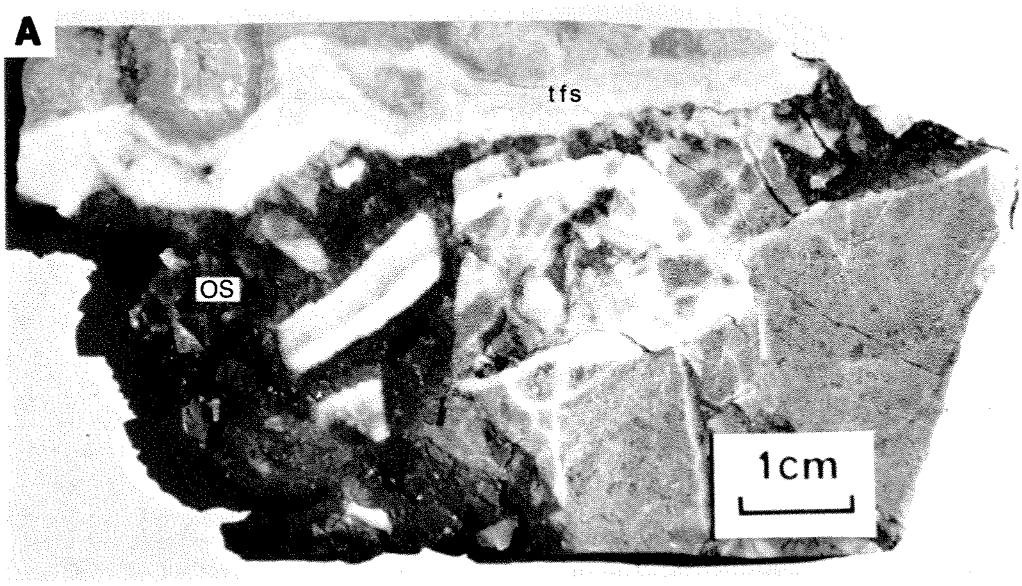

A
S
C(s)
tfs
1cm
B
S
S
1 cm
C
1cm
GSWA 23534

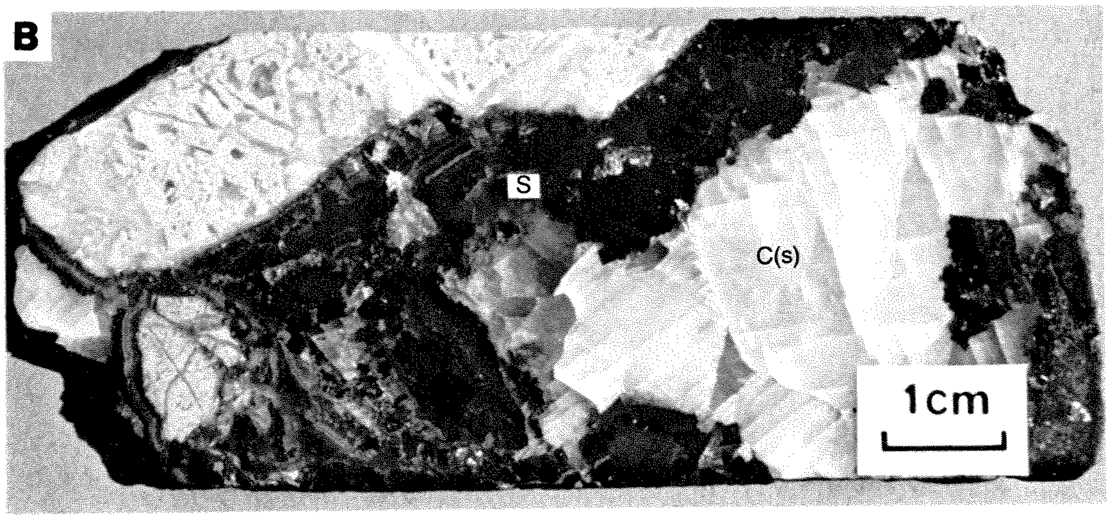
PLATE 10

Breccia-related styles of mineralization, Blendevale.

(A) Rims and open-space sulphide (mainly sphalerite), filling between breccia clasts (79914).

(B) Rimming of breccia clasts by banded, 'colloform' sphalerite, fractured and cemented by late-stage spar (79951).





GSWA 23535

PLATE 11

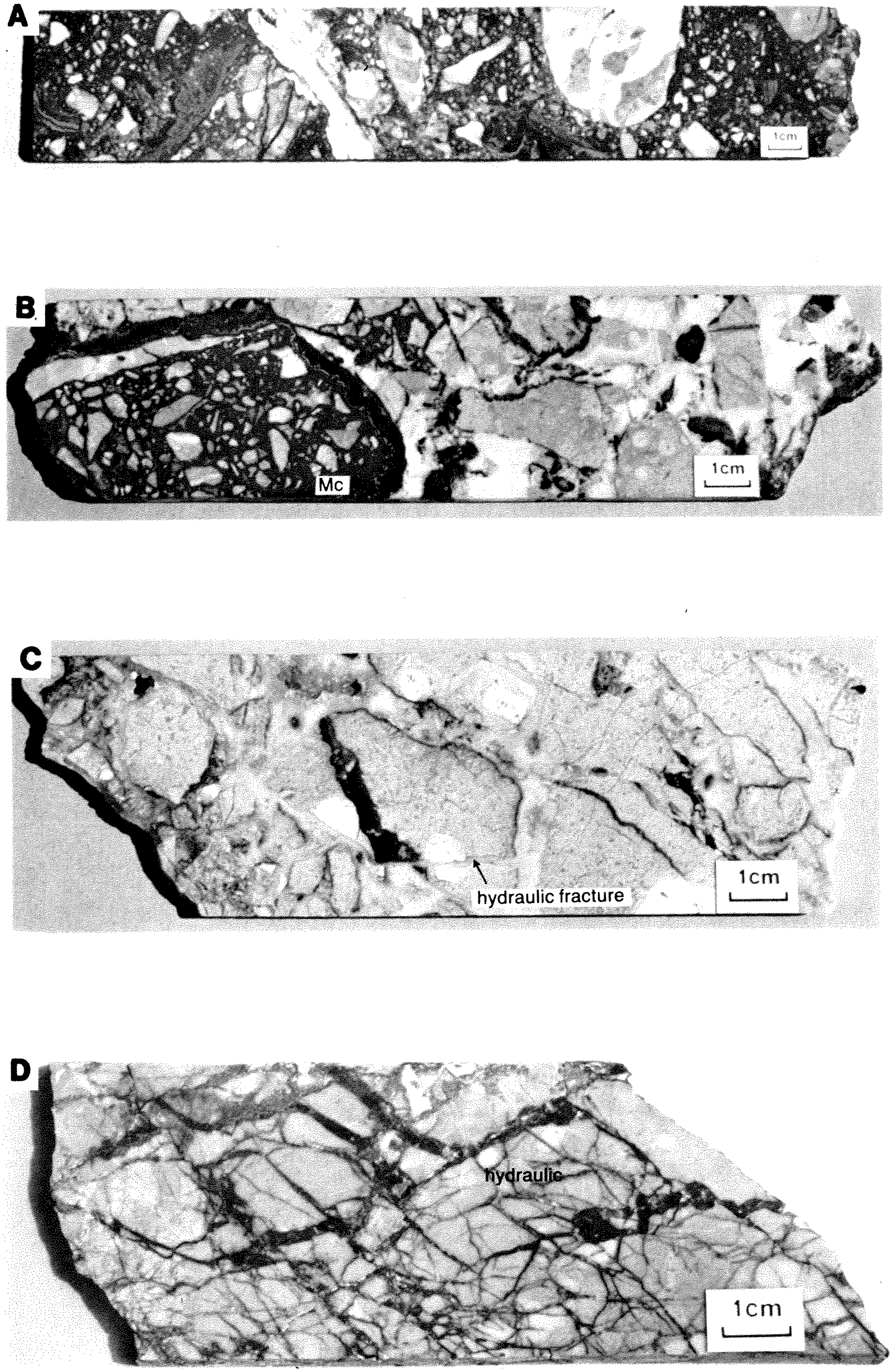
Breccia classification, Blendevale mineralization.

(A) Tectonic breccia showing rounded to angular fragments of variable size in a milled matrix (80032).

(B) Rubble breccia showing fragments of different lithologies, including a clast of marcasite-cemented tectonic breccia (far left), in chaotic arrangement (79906).

(C) Mosaic/rubble breccia showing fragments of fenestral limestone: note the hydraulic fracturing as indicated by vein-wall matching across clasts (BHP U3).

(D) Crackle breccia (79911).



GSWA 23536

PLATE 12

Mineralogy and texture of iron sulphides, Blendevale.

(A) and (B) Coarse grains of marcasite with overgrowths of botryoidal sphalerite. In (B) the polars are slightly uncrossed to illustrate the anisotropy of marcasite (76974).

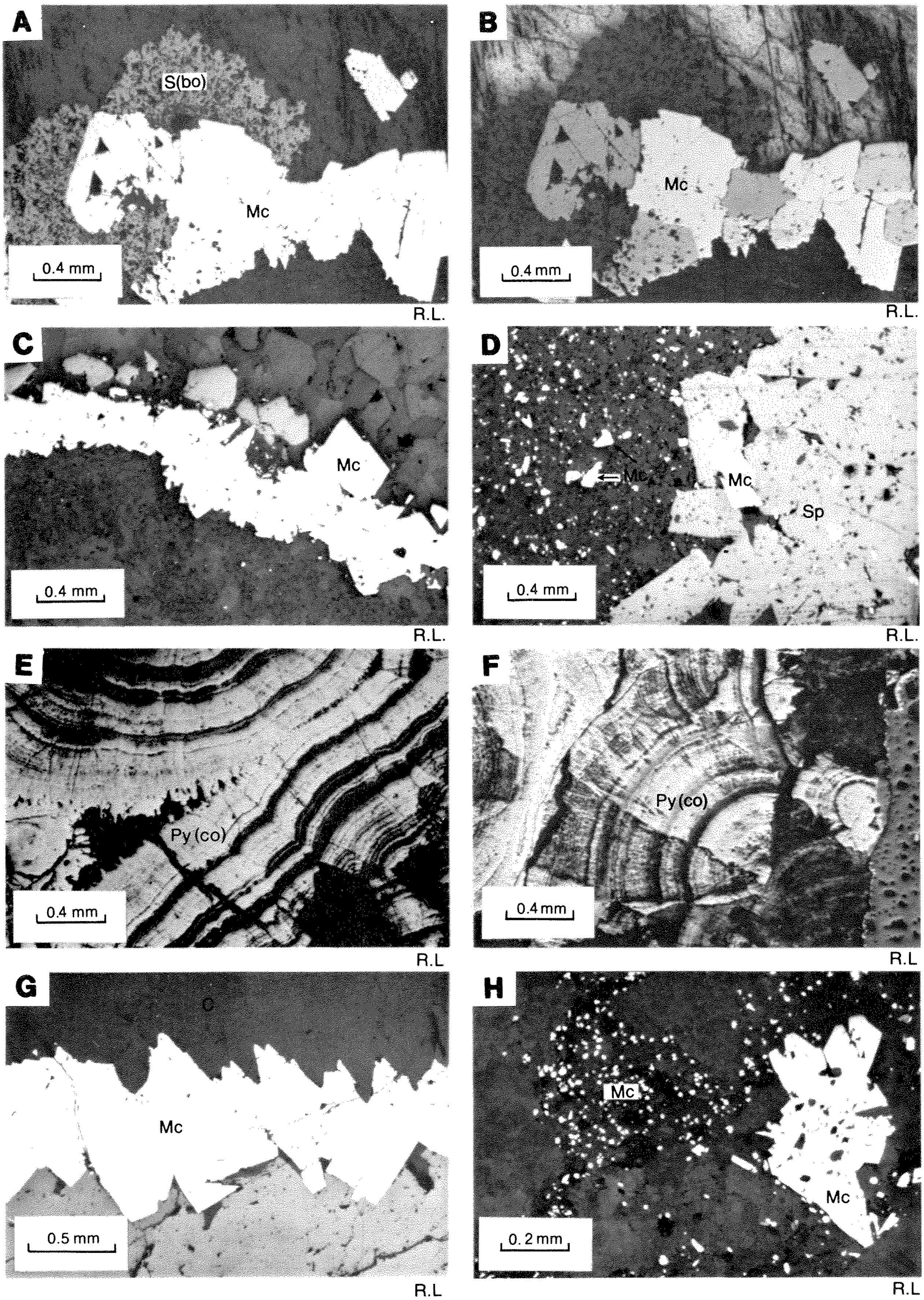
(C) A rind of rhomboidal marcasite grains upon a limestone-breccia clast (76903).

(D) Very fine-grained marcasite grains overgrown and included by sphalerite (76904).

(E) and (F) Botryoidal, 'colloform' pyrite composed of numerous very fine inclusion-rich laminae (inclusions of solid, ?carbonaceous matter) (80019).

(G) Euhedra of marcasite overgrown upon euhedral calcite (76919).

(H) Two size habits of marcasite – the finer grained material is preferentially developed in the matrix of the host breccia (76944).


A
S(bo)
Mc
0.4 mm
R.L.
B
Mc
0.4 mm
R.L.
C
Mc
0.4 mm
R.L.
D
Mc
Mc
Sp
0.4 mm
R.L.
E
Py (co)
0.4 mm
R.L
F
Py (co)
0.4 mm
R.L
G
C
Mc
0.5 mm
R.L
H
Mc
Mc
0.2 mm
R.L

GSWA 23537

PLATE 13

Illustrations of sphalerite mineralization, Blendevale.

(A) and (B) Banded and spherulitic growth of sphalerite upon a marcasite lamina in transmitted light (A) and in reflected light (B). Note the irregularly shaped inclusions of galena visible in reflected light (80018).

(C) Finely banded or 'colloform' sphalerite overgrown by coarsely banded sphalerite (79959).

(D) A single botryoid of sphalerite with numerous, dispersed inclusions of galena (80023).

(E) The right half of the frame shows fibrous calcite which is overgrown by marcasite and banded sphalerite. Two opaque granules of galena are enclosed and have been rimmed by later sphalerite growth (76926).

(F) A single, large, zoned euhedron of sphalerite growing in an open fracture (76926).

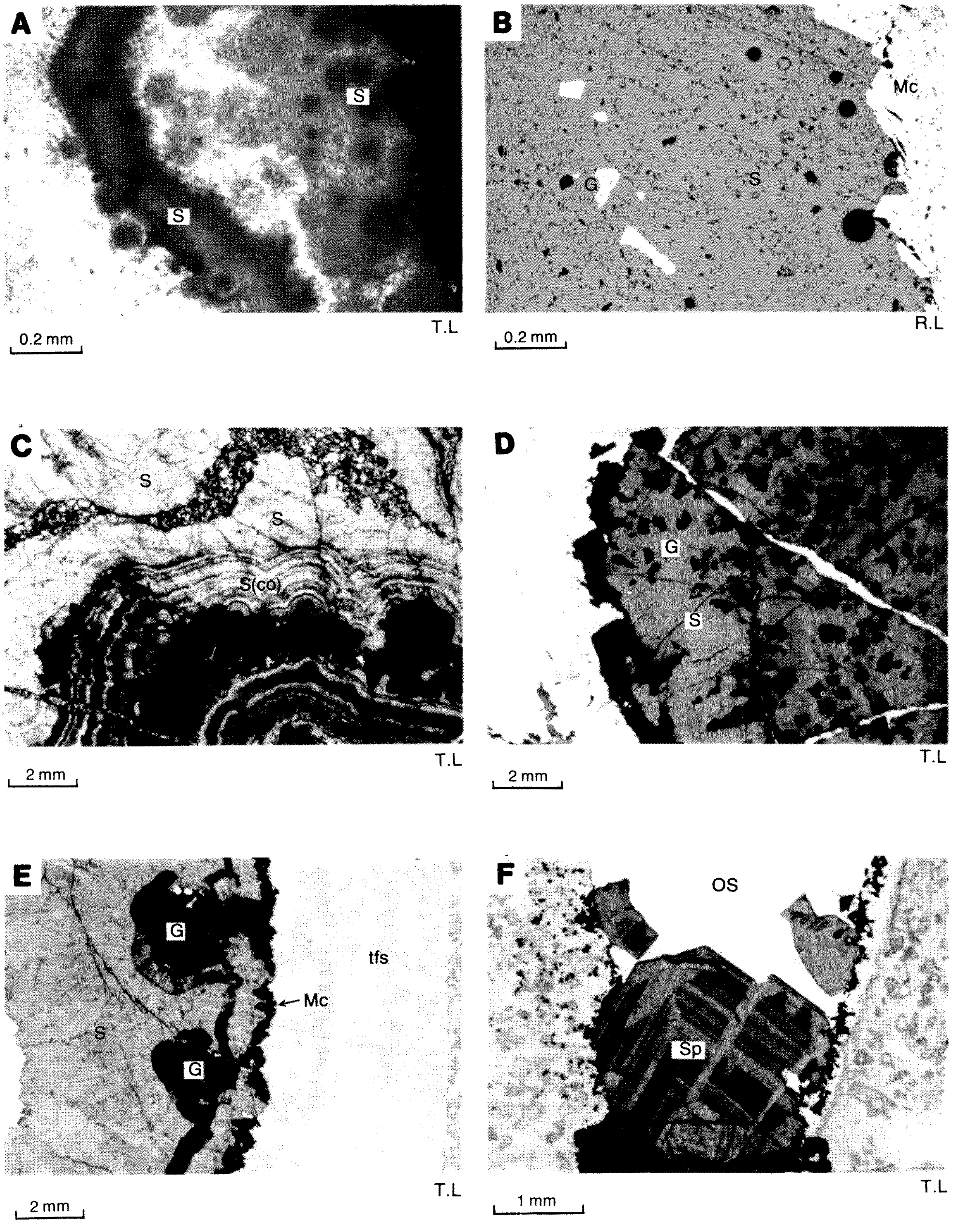

A
S
S
T.L
0.2 mm
B
Mc
G
S
R.L
0.2 mm
C
S
S
S(co)
T.L
2 mm
D
G
S
T.L
2 mm
E
G
Mc
S
G
tfs
T.L
2 mm
F
OS
Sp
T.L
1 mm
GSWA 23538

PLATE 14

Microscopic textures of mineralization, Sorby Hills.

(A) A vein of coarse-grained, saddle dolomite cross-cutting finer grained host dolomite. A euhedral grain of galena, which pre-dates saddle dolomite precipitation, is outlined (74849).

(B) Silicification of host sediments as indicated by euhedral overgrowths of quartz on detrital sand grains (74842B).

(C) Elongate, petal-shaped crystals (?pseudomorphs after gypsum) embedded in pervasive pyrite mineralization (74886).

(D) A large, single, bladed crystal of barite grown *in situ* in an argillaceous siltstone (77725).

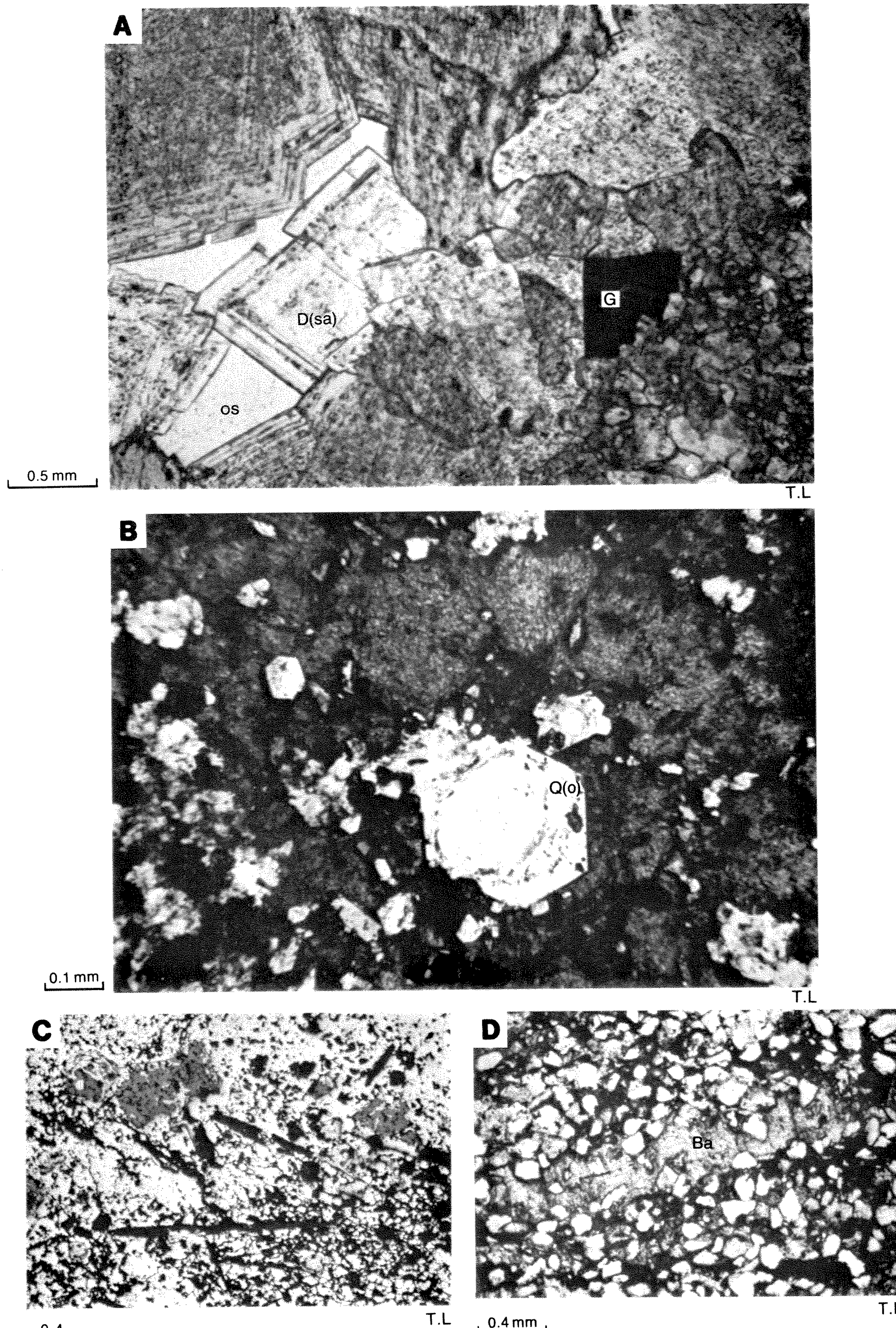
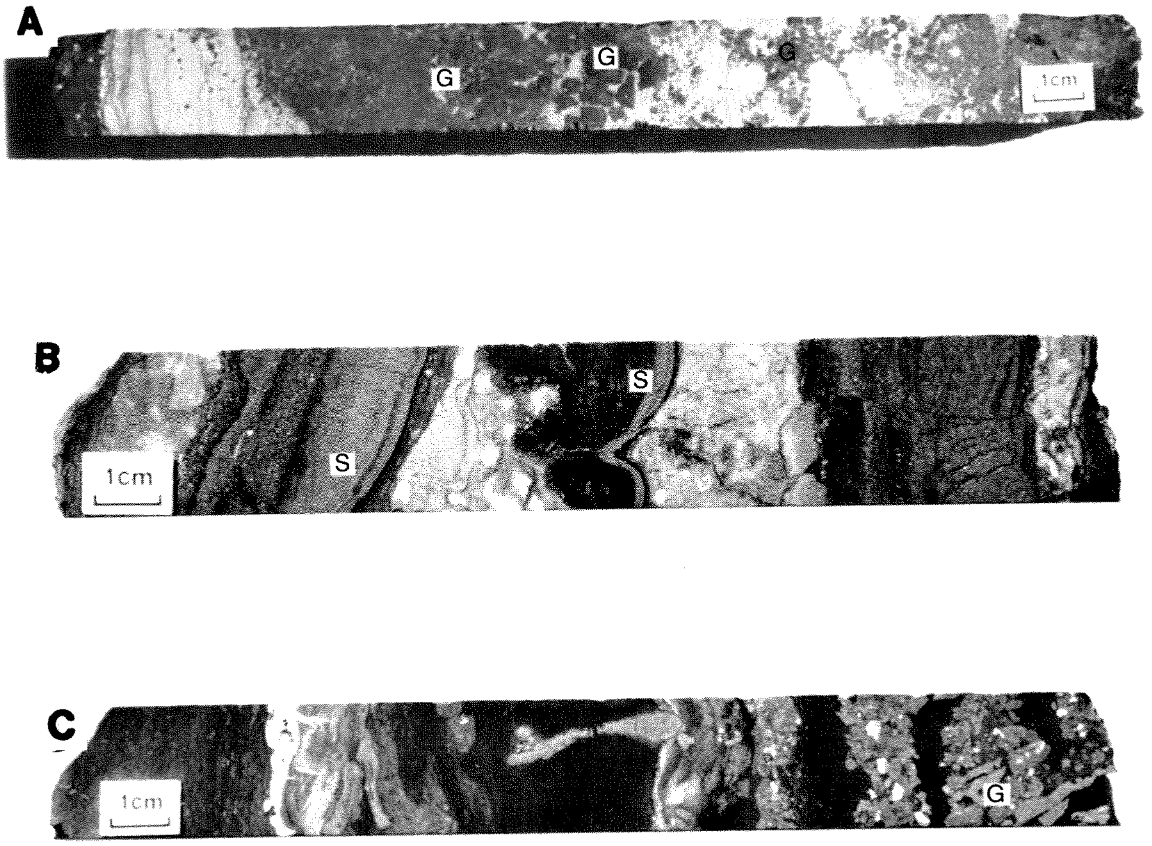

A
D(sa)
G
os
0.5 mm
T.L
B
Q(o)
0.1 mm
T.L
C
0.4
T.L
D
Ba
0.4 mm
T.L

PLATE 15

Hand specimens illustrating sulphide mineralization, Sorby Hills.

(A) Disseminated galena euhedra localized in the matrix of an intraformational breccia (outlining clasts) and coalesced to form a seam of pervasive 'stratiform' mineralization (80047).

(B) and (C) Patches and rich 'seams' of 'stratiform' sulphide mineralization including pyritic, sphalerite-rich and galena-rich horizons (80079).



GSWA 23540

PLATE 16

Galena and sphalerite mineralization, Sorby Hills.

(A) A large 'poikiloblastic' crystal of galena growing in a dolomitic siltstone (74858).

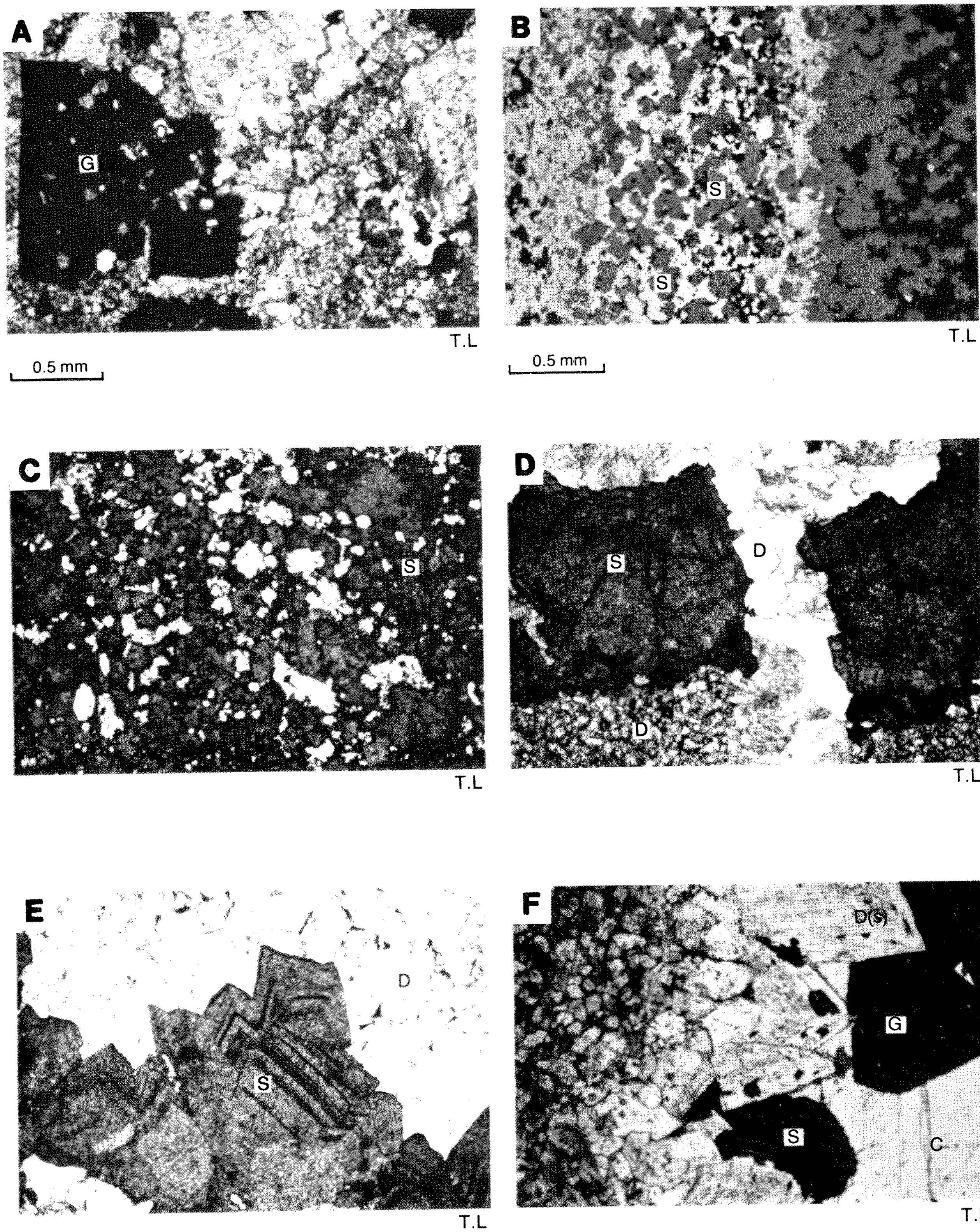
(B) Coalescing sphalerite grains cemented by pervasive pyrite mineralization and replaced in part by galena (74885).

(C) Pervasive sphalerite mineralization including euhedral quartz grains (74842B).

(D) A veinlet of dolomite cross-cutting sphalerite and finer-grained dolomite (74893).

(E) Coarse, euhedral, growth-zoned sphalerite crystals (77715).

(F) Overgrowth of sphalerite and galena on coarse saddle dolomite in a vein – the sulphides are post-dated by calcite and show a slight corrosive affect against dolomite (77735).



GSWA 23541

PLATE 17

Iron sulphide microscopic textures, Sorby Hills.

(A) Rounded framboids of pyrite in dolomitic siltstone (74835).

(B) Framboids of pyrite close to (but not recrystallized by) a coarse, galena crystal (74835).

(C) Pervasive pyrite mineralization, mostly interstitial to host-sediment grains but replacive in part (74839).

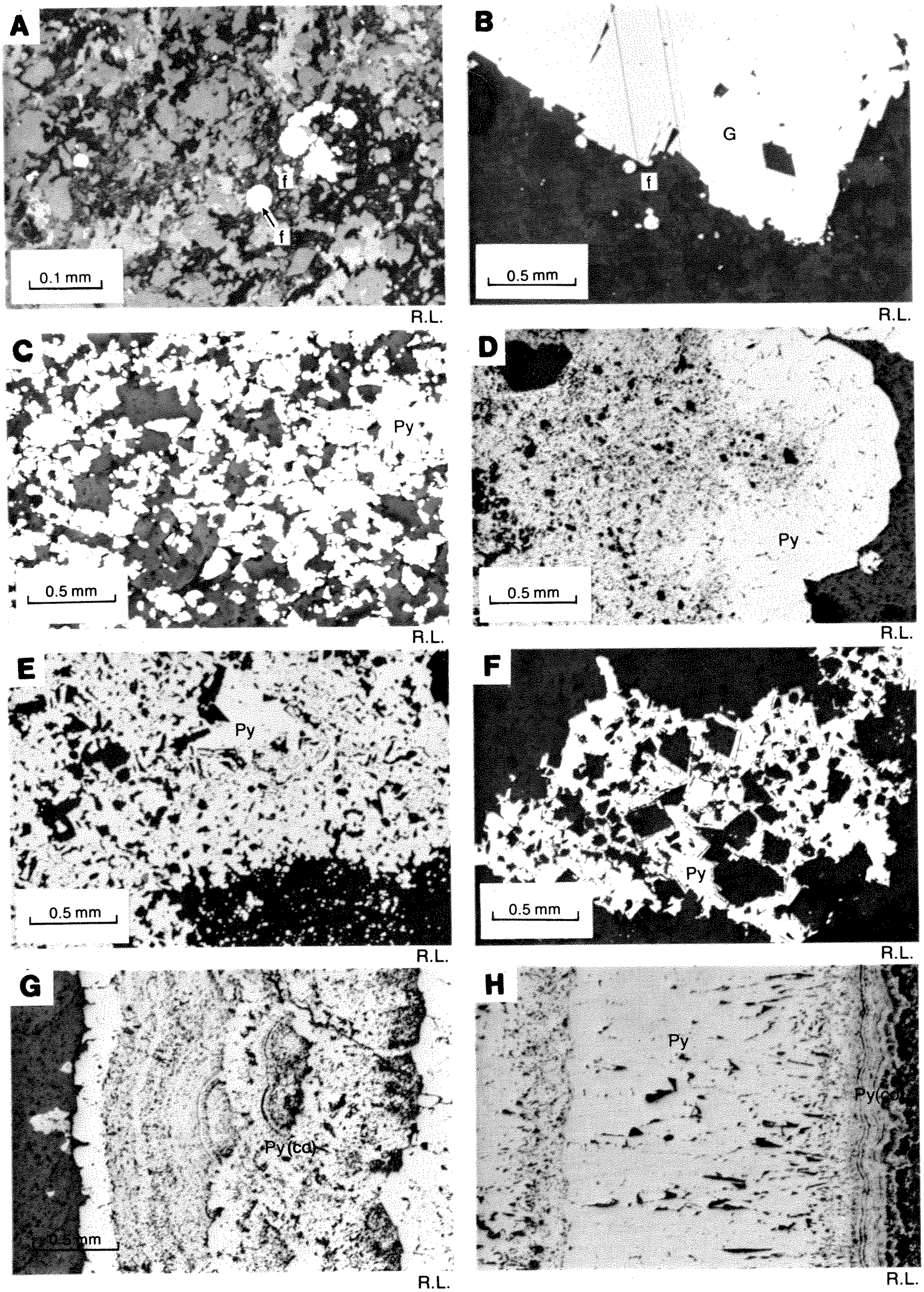
(D) Porous, pervasive iron sulphide mineralization overgrown by coarse-grained pyrite euhedra (77703).

(E) Replacement of dolomite by pervasive pyrite mineralization as shown by relic rhomboids of dolomite (77737).

(F) Replacement of dolomite with preferential iron sulphide growth along particular growth zones (?iron-rich units) (77721).

(G) 'Colloform' iron sulphide (74884).

(H) Detail of 'colloform' iron sulphide overgrown by pyrite showing a columnar crystal structure (74886).


A
0.1 mm
f
f
R.L.
B
G
f
0.5 mm
R.L.
C
Py
0.5 mm
R.L.
D
Py
0.5 mm
R.L.
E
Py
0.5 mm
R.L.
F
Py
0.5 mm
R.L.
G
Py(cd)
0.5 mm
R.L.
H
Py
Py(cd)
R.L.

GSWA 23542

PLATE 18

Copper, sulphosalt and silver sulphide mineralization, Sorby Hills.

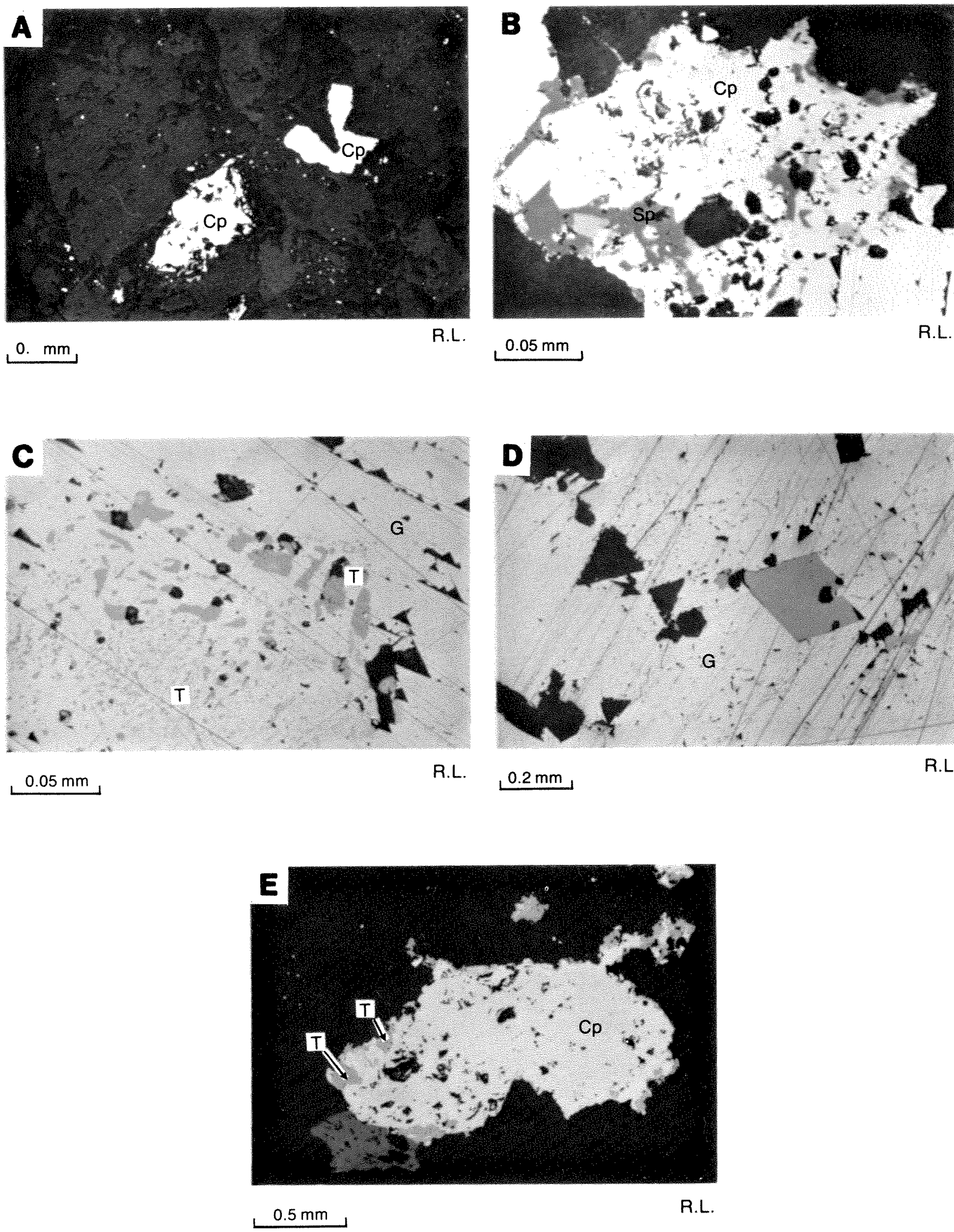
(A) Anhedral blebs of chalcopyrite interstitial to grains of the host sediment and overgrowing pyrite (74835).

(B) A complex bleb of sulphides including galena, sphalerite, pyrite, chalcopyrite, and tennantite-tetrahedrite (77752A).

(C) Irregularly shaped exsolutions of tennantite-tetrahedrite in galena (77712).

(D) A single crystal of pyrargyrite-proustite, forming an euhedral pseudomorph of a dolomite grain, included in galena (80087).

(E) A bleb of chalcopyrite with peripheral tennantite-tetrahedrite (74854A).


A
Cp
Cp
0. mm
R.L.
B
Cp
Sp
0.05 mm
R.L.
C
G
T
T
0.05 mm
R.L.
D
G
0.2 mm
R.L.
E
T
T
Cp
0.5 mm
R.L.

GSWA 23543

A61482/6/88-750-AL/604 GARRY L. DUFFIELD, Government Printer, Western Australia