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AN EVALUATION OF THE MINERAL POTENTIAL OF THE ONSHORE CARNARVON BASIN

by

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CONTENTS

	Page
Introduction	1
Geological and tectonic setting	1
Base metals	7
World significance of Phanerozoic sediment-hosted base-metal deposits ..	7
Models of base-metal deposits	7
Carbonate-hosted lead-zinc deposits ..	12
Gneudna Formation..	13
Moogooree Limestone	16
Callytharra Formation	19
Stratiform copper mineralization associated with shallow marine sediments and continental red beds	20
Stratiform, shale-hosted, lead-zinc and copper-lead(-silver) deposits ..	25
Shales of the Byro Group ..	26
Bentonitic and radiolarian shales of the Winning Group	28
Kimberlites and diamonds	32
Uranium	40
Provenance and source rocks	40
Potential and exploration for sandstone-hosted deposits	42
Roll-front deposits	42
Peneconcordant deposits	45
Tectono-lithologic or strucural-stack deposits	46
Other styles of uranium mineralization	47
Recommendations for further exploration ..	49
Cretaceous sands	49
Permian sand sequences	50
Carboniferous sandstones	51
Devonian sands	52
Devonian and Carboniferous carbonates	52

Page

Exploration methods	52
Airborne radiometric surveys ..	52
Ground radiometric surveys	53
Radon surveys	53
Hydrogeochemistry	53
Gravity surveys	54
Drilling	54
Downhole logging	54
Heavy-mineral sands	55
Provenance and theoretical considerations	55
Potential host sand sequences	58
Previous exploration	59
Potential for further exploration ..	62
Industrial minerals	64
Evaporite	64
Bentonite	67
Barite	68
Garnet	69
Phosphate	69
Fullers earth	70
Limestone	70
References	72
Appendix 1 Carnarvon Basin: base-metal exploration	80
Appendix 2 Carnarvon Basin: diamond exploration	81
Appendix 3 Carnarvon Basin: uranium exploration	83
Appendix 4 Carnarvon Basin: mineral-sands exploration	86

ILLUSTRATIONS

FIGURES Page

1.	Composite stratigraphic column onshore Carnarvon Basin.	2
2.	Diagrammatic section northern Carnarvon Basin.	5
3.	Diagrammatic representation of the stages of development of the Indian Ocean.	6
4.	Size-grade comparison of sediment-hosted and other major deposits of base metal.	8
5.	Lithostratigraphic relationships of the Silurian rocks of the southern Carnarvon Basin.	24
6.	Location of kimberlites at Wandagee.	33
7.	Major oxide (Wt%) variation diagrams for Wandagee kimberlites.	35
8.	Model of a West Australian kimberlite pipe. ..	36
9.	Potential diamond-exploration targets, onshore Carnarvon Basin.	38
10.	East-west cross section through Manyingee 1 mineralization.	44

TABLES

1.	Phanerozoic sediment-hosted base-metal deposits.	9
2.	Modes for the transportation and precipitation of base metals.	13
3.	Outline stratigraphy of Silurian Kalbarri Group.	22
4.	Gypsum production from Shark Bay	66

PLATES (in pocket)

1. Carnarvon Basin mineral occurrences with recommendations for exploration (scale 1:1 000 000)

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by P.H. Harrison

INTRODUCTION

This review has been prompted by the completion of the remapping of the Carnarvon Basin by officers of the Geological Survey.

All available data on mineral exploration from departmental files has been reviewed in the light of the revised stratigraphy and sedimentology which is to be published in a Bulletin on the Carnarvon Basin, (Hocking and Moors, in prep.), together with recent advances in the understanding of the control by plate tectonics of the development of the basin.

A number of 'models' for the development of mineralization are considered for their potential application within the basin. Particular consideration is given to the potential for base-metal mineralization as it is considered that this has so far been largely overlooked by exploration companies.

GEOLOGICAL AND TECTONIC SETTING

The Carnarvon Basin forms part of a continuous 4 000 km-long belt of sedimentary rocks extending, at least in the offshore, from the Perth Basin through to the Bonaparte and Arafura Basins.

The Carnarvon Basin section of this belt contains in excess of 500 000 km^3 of sediments with an aggregate thickness in excess of 20 km (Fig. 1). Sedimentation began in the Silurian with a thick, inter-

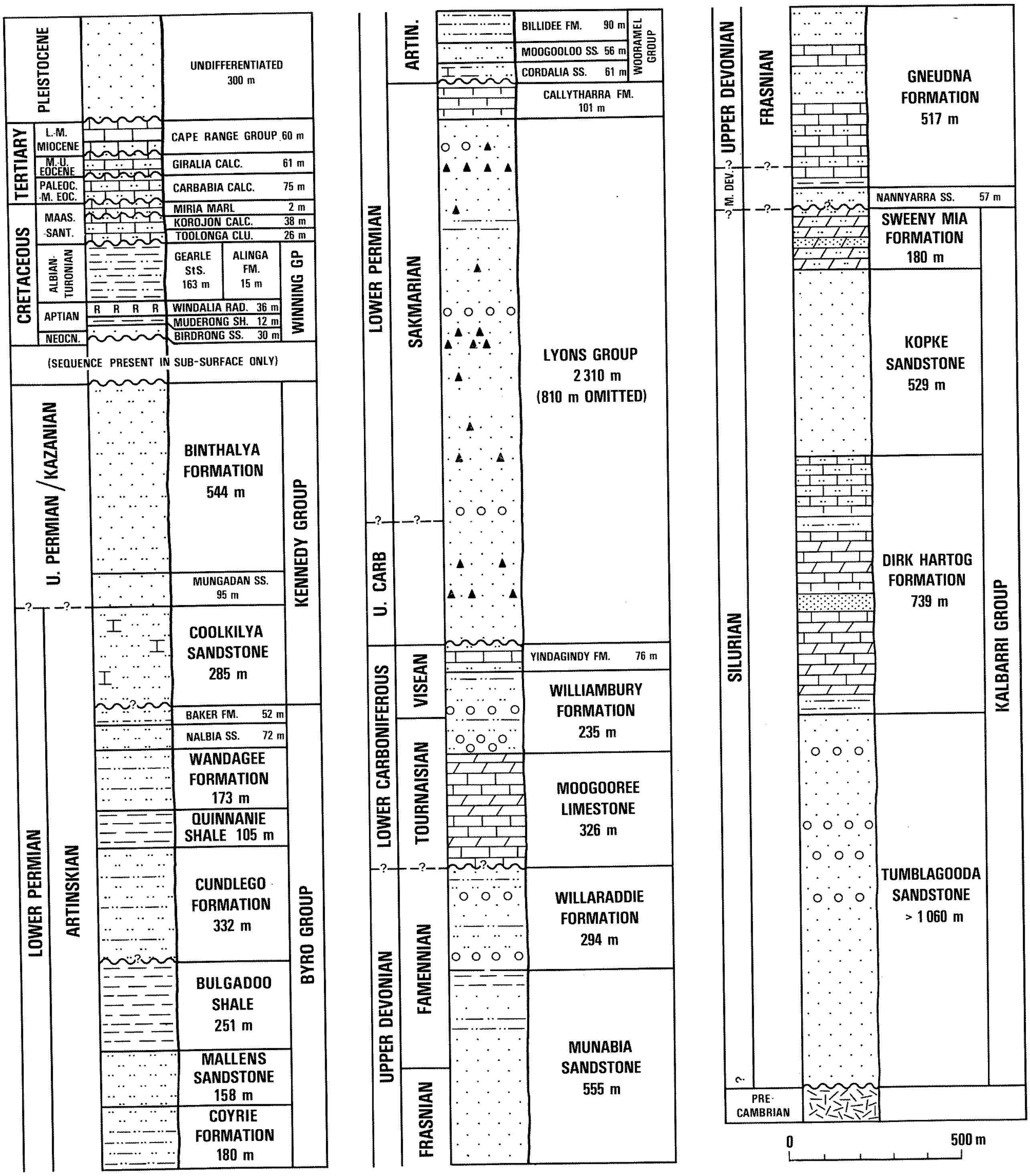

FIGURE 1: COMPOSITE STRATIGRAPHIC COLUMN ONSHORE CARNARVON BASIN (MAXIMUM THICKNESS SHOWN)

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digitating series of continental to marine red-bed sandstones, carbonates and evaporites (the Kalbarri Group, of Hocking and Moors, in prep.).

Veevers and others (1982) following Veevers (1976) and Veevers and Cotterill (1976, 1978), suggested that sedimentation within the Carnarvon Basin, prior to late Carboniferous times, took place in a 'Pre-Gondwanan' failed rift-arm or aulacogen, associated with the opening and growth of the Tethys. This Tethyan bay had previously been termed the 'Sinus Australis' by Dietz and Holden (1970).

The sediments of the Kalbarri Group appear to represent the early infilling of the aulacogen from the south and southeast, with periods of rapid sediment supply, possibly associated with the movements of a 'proto' Darling Fault system. Following the cessation of these movements, the partial infilling of the rift and subsequent sedimentation during a marine transgression through the Devonian and Carboniferous appear to have been largely under epeirogenic conditions. The basin at this time was probably a narrow, shallow, shelf-like bay of the Tethys ocean, situated in low latitudes, in which, on the margins of the basin, clearwater carbonate sedimentation interdigitated with fluvial-sand deposits, probably formed during periods of local faulting. Further into the basin this sequence grades into calcareous siltstones and shales. This Tethyan stage of the development of the basin was termed, by Veevers and others (1982), the Pre-Gondwanan tectonic regime. The final stages of this appear to have been marked by a short period of tectonism at the end of the Visean which saw rejuvenation of the proto-Darling Fault system (along the western side of the Weedarra and Carmandibby Inliers) which resulted in folding of the existing sedimentary sequence followed by the erosion of the Devonian, Carboniferous, and part of the Silurian, sequences in the southern part of the basin. By the Late Carboniferous Tethyan continental drift had carried the basin into high latitudes which resulted in the onset of glaciation of the Precambrian hinterland and the deposition of a thick (1-1.5 km) wedge of glacial and fluvio-glacial sediments, the Lyons Group.

Veevers and others (1982) have termed the next stage of tectonic development the Gondwanan regime. This comprised rifted-arch development between the Australian and Greater Indian continental plates and continued for a long period until continental break-up.

Pyritic and phosphatic carbonaceous shales in the Permian Byro Group appear to have been deposited in a deep-water euxinic environment. This environment was probably developed in rifts resulting from north-trending tensional faults. This faulting controlled sedimentation through the Triassic and Jurassic causing the accumulation of many kilometres of sediments in rift-controlled basins in the northern, offshore section of the basin. (The onshore section of the Carnarvon Basin was largely exposed and subject to erosion through the Triassic and Jurassic.)

This rift-controlled sedimentation ended abruptly in the Cretaceous with the onlap and deposition of the Aptian Winning Group following continental breakup. The resulting relationships of the various sequences is well illustrated by a section through the north central part of the basin (Fig. 2).

From a study of palaeomagnetic data Veevers and Hansen (1981), showed that the separation of the Australian and Indian plates took place near the beginning of the Cretaceous (123 m.y. B.P.) and that by Winning Group times the plates were separated by a land-locked gulf, at least 3 000 x 300 km, open to the north but joined between Ceylon, southern India, and

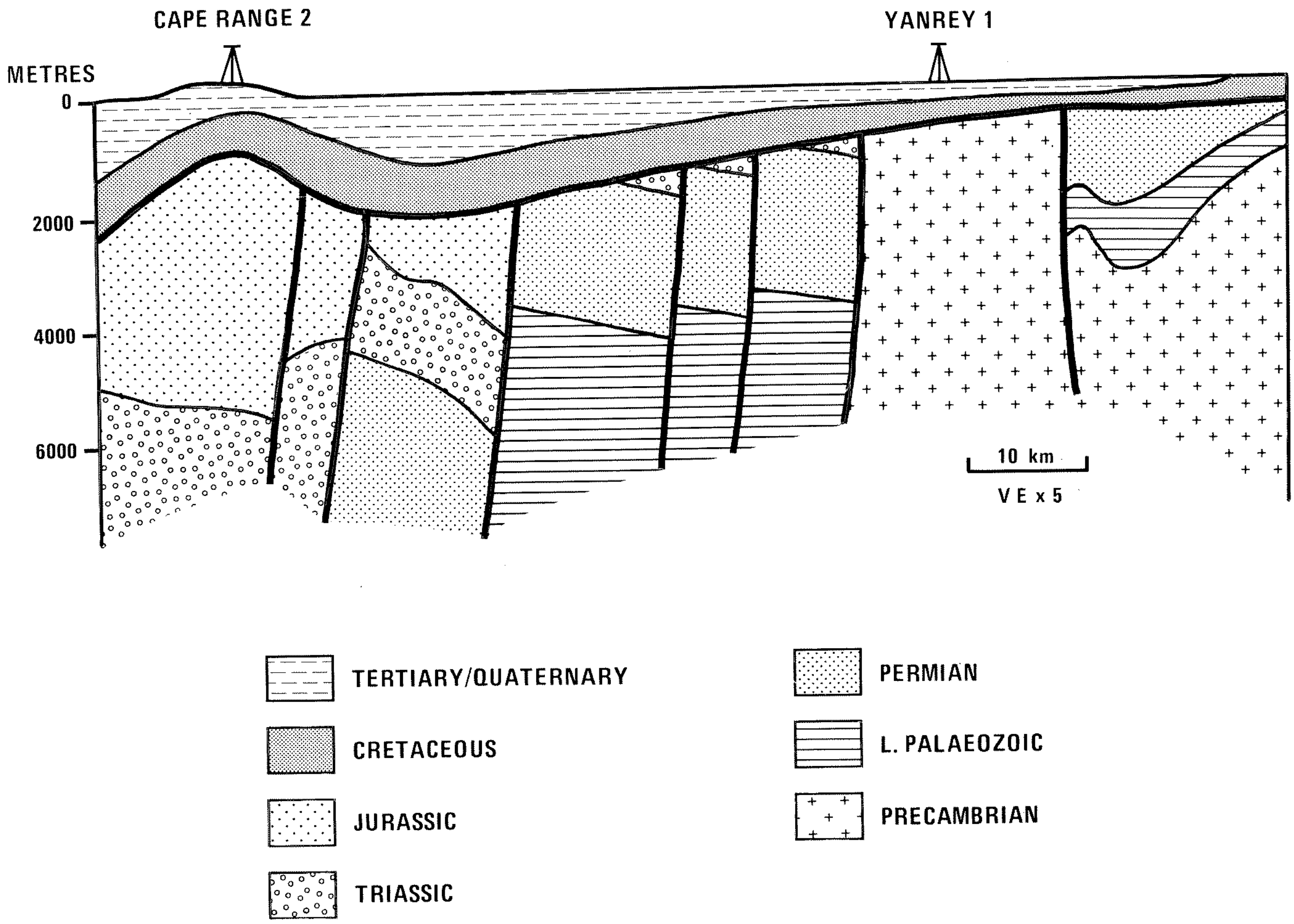

FIGURE 2 : DIAGRAMMATIC SECTION NORTHERN CARNARVON BASIN

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Enderby Land in the south - a situation not dissimilar to the present 2 200 x 250 km gulf of the Red Sea.

The possible tectonic development of the basin is illustrated in Figure 3.

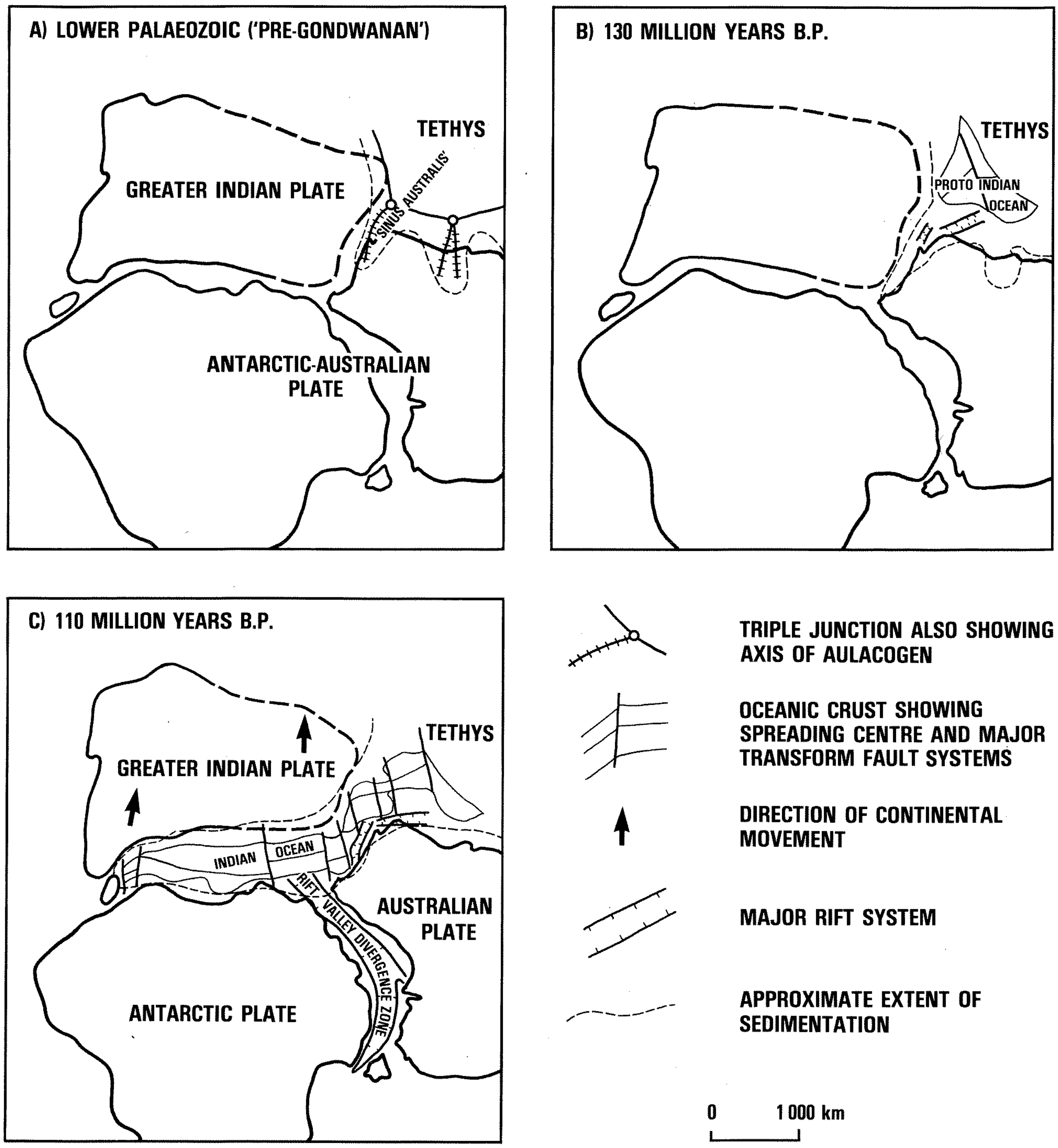

FIGURE 3: DIAGRAMMATIC REPRESENTATION OF THE STAGES OF DEVELOPMENT OF THE INDIAN OCEAN

CONSTRUCTED USING DATA FROM DIETZ AND HOLDEN [1970]
VEEVERS [1976]
EVANS [1981]
VEEVERS AND OTHERS [1982]

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BASE METALS

WORLD SIGNIFICANCE OF PHANEROZOIC SEDIMENT-HOSTED BASE-METALS DEPOSITS

Figure 4, modified after Gustafson and Williams (1981), attempts to put the importance of sediment hosted base-metal deposits in perspective when compared to various other major types of base-metal deposits. It can be seen that they are particularly attractive exploration targets in terms of both potential size and potential grade.

What is perhaps more significant is the fact that around the world, many major deposits of this type are found in Phanerozoic sedimentary sequences. Table 1, which excludes carbonate-hosted (Mississippi Valley type) deposits, and includes only those deposits with greater than 12 million tonnes reserves, illustrates this. The ages, tectonic setting, and host lithologies of many of these deposits are similar to many sequences in the Carnarvon Basin.

MODELS OF BASE-METAL DEPOSITS

Most models for the genesis of sediment-hosted base-metal sulphide deposits invoke the formation of metal-rich brines within the sedimentary pile, with the transport of metals taking place either as chloride complexes (Helgeson, 1964), or as sulphide complexes (Barnes and Czamanske 1967).

Carpenter (1978) has discussed the origin and chemical evolution of brines within sedimentary basins and suggests that most brines of commercial interest originate as interstitial fluids in halite rich rocks. Jackson and Beales (1967) have suggested that brines are expressed from large thicknesses of sediment during compaction, desorbing and dissolving base-metal ions which were

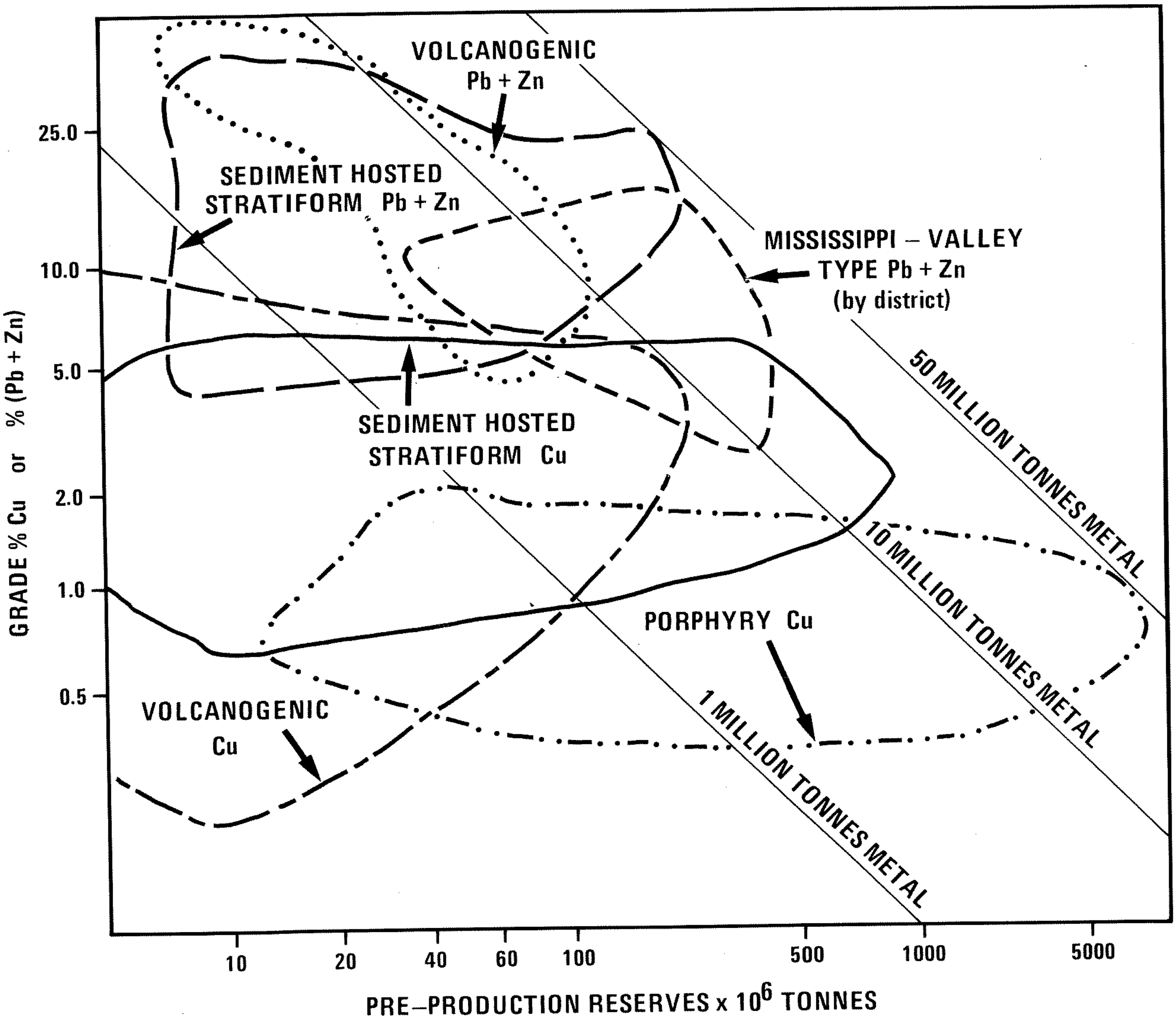

FIGURE 4 : SIZE–GRADE COMPARISON OF SEDIMENT HOSTED AND OTHER MAJOR DEPOSITS OF BASE METAL

MODIFIED AFTER GUSTAFSON AND WILLIAMS (1981)

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TABLE 1: PHANEROZOIC SEDIMENT-HOSTED BASE-METAL DEPOSITS

NAME	RESERVES (MILLION TONNES)	% Cu	% Pb	% Zn	AGE	LITHOLOGY	TECTONIC SETTING
BOLEO (MEXICO)	13.6 +	4.81	-	-	PLIOCENE	CONGLOMERATE & TUFF	RIFT
DZHEZKAZGAN (USSR)	100 +	1.5	1	-	CARBONIFEROUS	RED BED SAND/SHALE	INTRACRATONIC BASIN
MANSFELD (GERMANY)	75 +	2.9	-	1.8	PERMIAN	KUPFERSCHIEFER MARL & RED SAND	"
LUBIN (POLAND)	1000 +	2.0	-	-	PERMIAN	AS MANSFELD & RED CLASTICS	"
TYNAGH (IRELAND)	12.3 + *	0.4	4.9	4.5	CARBONIFEROUS	LIMESTONE	" (NEAR FAULT)
SILVERMINES (IRELAND)	18.4 + *	-	2.8	7.4	CARBONIFEROUS	DOLOMITE	"
RAMMELSBERG (GERMANY)	30 + *	1	9	19	DEVONIAN	BLACK SHALE	TROUGH IN INTRACRATONIC BASIN
MEGGEN (GERMANY)	60 *	0.2	1.3	10	DEVONIAN	CARBONACEOUS SLATE NEAR CARBONATE	"
HOWARDS PASS (CANADA)	100 *	-	1.5	6	SILURIAN	BLACK SHALE/ CHERT & CARBONATE	"
LAISUALL (SWEDEN)	80 + *	-	4.3	0.6	CAMBRIAN	QUARTZ SAND	LITTORAL SHELF

(Only deposits of over 12 million tonnes reserves are included; Mississippi Valley type deposits are excluded)

\+ Containing silver

* Containing barite

MODIFIED AFTER GUSTAFSON AND WILLIAMS (1981) previously absorbed onto organic matter, shales etc, during sedimentation. Such brines may then migrate, in a manner similar to hydrocarbons, up dip, or along suitable fault or unconformity structures, to sites of deposition.

The Carnarvon Basin, as discussed above contains in excess of 500 000 km^3 of sediments with a total aggregate thickness in excess of 20 km and a maximum interpreted thickness in one locality of about 12 km. Thick evaporite sequences are present in the Silurian succession within the basin while thick sequences of argillaceous sediments, including evaporite-bearing sabkha facies rocks are known from a number of sequences.

Various authors have suggested that the presence of distal volcanism may be significant in the generation of sedimentary base-metal deposits. Volcanic rocks have been intersected in three offshore oil exploration wells, Edel 1 (Permian), Enderby 1 (Permian) and Yardie (Neocomian). The presence of bentonitic siltstones in the lower Cretaceous rocks provides further evidence of distal volcanism while a tuffaceous horizon containing shards of devitrified glass and angular feldspar phenocrysts has been reported from the Gearle Siltstone of the Giralia Anticline.

Faulting was active during a number of periods of tectonism and could have provided a 'plumbing system' for the migration of any mineralizing brines which may have been generated within the Basin. Evidence that such brines were generated up to the late Carboniferous, is provided in the occurrence of veins carrying barite, galena and sphalerite cutting both Precambrian basement gneiss and overlying Lyons Group sediments in the basement inlier approximately 10 km south of Mount Sandiman homestead. These occurrences are described in Mines Department open-file item 11 and 'M' number 2702 (Appendix 1).

There is also indirect evidence for the generation of brines during a Silurian mineralizing event. In the Northampton Block, which forms the Southern boundary of the Carnarvon Basin (Plate 1), epigenetic lead-zinc mineralization, with quartz, barite and dolomite, occurs in veins parallel to dolerite dykes, cutting both the dolerite and the basement granulitic gneiss. Hydrothermal alteration associated with these veins has recently been dated at 430 million years by Rubidium/Strontium methods (Blockley, pers. comm.). Michael and Groves (1977) suggested that brines formed by the interaction of Silurian (probably sulphate rich) meteoric water with basement metasedimentary rocks, and the resulting mineralized brines, rose to the surface and flowed preferentially along the unconformity between the basement and the Tumblagooda Sandstone.

Moors (1980) from a study of borehole temperature measurements in the Carnarvon Basin has shown that several areas of anomalous geothermal gradient are related to faults and other basement structures. He has further suggested that a possible explanation of the excess heat could be due to the migration of hot formational fluids up dip and along fault planes.

A number of these faults, for example the Rough Range Fault, formed major growth faults during the Jurassic, remaining active through to the Cretaceous before suffering reversed movement during Miocene times. They thus could have formed suitable 'conduits' for mineralized brines during Cretaceous times. The present anomalous heat flow may well represent the waning phase of a former hydrothermal system.

As suitable mineralizing brines are likely to have been formed, potential may exist for a number of styles of base-metal mineralization within the basin.

CARBONATE-HOSTED LEAD-ZINC DEPOSITS

A review of this type of deposit (commonly known as Mississippi Valley-type) from around the world shows that epigenetic mineralization may occur in carbonate sequences in palaeokarstic weathering systems beneath unconformities and in fault and breccia zones. Mineralization is often in reef or fore-reef breccia sequences, commonly developed on the flanks of basement ridges or close to basement edges. There is a frequent association with (local) dolomitization and silicification of the host carbonate sequence. Unconformities may be significant both in producing suitable sites for deposition (through karstification), and in providing channelways and traps for mineralizing brines.

Over the years many models have been proposed for the transport and precipitation of base-metals and sulphur in Mississippi Valley-type deposits. The most significant of these are summarized in Table 2 taken from Sverjensky (1981).

It is considered probable that conditions for the precipitation of ore by most of these mechanisms would have existed in a number of the carbonate sequences in the Carnarvon Basin, and that the probability of mineralization having been formed is reasonably high.

A number of exploration programmes for carbonate-hosted lead-zinc deposits have been reported to the Mines Department. These have focused on three main carbonate sequences, each of which may form suitable host rocks for this type of mineralization. Each of these carbonate sequences has been exposed, at least in part, by unconformities and thus may have undergone karstic weathering. The two older sequences were subject to pre-Permian tectonism producing block faulting which could have acted as a 'plumbing system' for the mineralizing brines. The epigenetic mineralization south of Mount Sandiman homestead provides evidence for such a situation. (see above).

TABLE 2. MODEL FOR THE TRANSPORTATION AND PRECIPITATION OF BASE METALS AND SULPHUR IN MISSISSIPPI VALLEY-TYPE DEPOSITS

Transportation of ore-forming constituents	Mechanism of precipitation of ore
I. Base metals transported by solutions without significant sulphur content	a. Mixing with solutions containing H_2S b. Replacement of diagenetic iron disulphides c. Thermal degradation of organic compounds releasing reduced sulphur
II. Base metals transported together with sulphate in the same solutions	a. Reduction of sulphate by reaction with organic matter or methane b. Reduction of sulphate by reaction with iron-bearing minerals
III. Base metals transported together with reduced sulphur in the same solutions	a. Increase of pH b. Dilution c. Decrease of temperature

The Gneudna Formation (Devonian): The Gneudna Formation crops out in three fault-separated meridionally oriented belts, the most extensive of which extends north for approximately 100 km from Mount Sandiman homestead to northwest of Lyndon homestead. The formation extends in the subsurface over much of the northern part of the Carnarvon Basin.

The majority of the carbonates within the Gneudna Formation are limestone, however, local areas of dolomite occur and dolomitization becomes more pervasive in the upper part of the formation.

Hocking and Moors (in prep.) suggested that the bulk of the formation was deposited in an epeiric sea environment. No definite reef developments are known in the outcrop belts, although fossils suitable for the production of stromatoporoid/coral reefs are present, and offshore, a probable reefal sequence, the Point Maud Member, extends over a thickness of 320 metres in Pendock 1 (Geary 1970).

Sedimentological studies by Aquitaine Australia Minerals Pty Ltd (Aquitaine) reported in Mines Department open-file items 556 and 561 indicate that a possible back-reef facies is present in the northern part of the most westerly outcrop belt in the vicinity of Ebbra Wells. They therefore indicate that there may be reefal development in the subsurface, perhaps over a possible basement ridge extending south from the vicinity of the Pleiades Hills area. 'Patch' reefs or atolls could be present elsewhere in the subsurface.

Through most of its outcrop length the Gneudna Formation is conformably overlain, by either the Willaraddie Formation or the Munabia Sandstone, which are relatively poor traps for mineralizing fluids. However, in the southern part of the outcrop, and locally further north, the formation is overlain by glacigene rocks of the Late Carboniferous Lyons Group, which may have formed better traps. Lyons Group rocks probably overlie the Gneudna Formation in places in the subsurface, as the sequence was faulted prior to its deposition. In much of the central and northern parts of the basin, borehole information suggests that the Gneudna Formation is overlain by Cretaceous rocks.

Exploration by Aquitaine consisted of regional (helicopter) examination of the carbonates followed by more detailed exploration of a Temporary Reserve and a number of claim groups west and northwest of Lyndon Station.

Diamond drilling of one area with a strong geochemical lead anomaly in soil (to 3200 ppm) near Ebbra Well, approximately 17 km northwest of Lyndon, located minor galena mineralization in fractured, vuggy dolomite, associated with minor organic matter, possibly bitumen. Grab samples assayed up to 6500 ppm Pb and 1850 ppm Zn, while a 4 metre interval assayed 4000 Pb and 219 ppm Zn.

International Nickel Australia Ltd (Inco) carried out a helicopter reconnaissance survey of the entire outcrop length of the Gneudna Formation as part of a regional reconnaissance programme. In addition to the anomalous zone tested by Aquitaine possible gossanous material assaying over 1% Pb was located northeast of Woodcock Bore, on Mount Sandiman Station. This zone was not tested as infill sampling showed that it was of limited extent.

Drilling completed by various companies during uranium exploration located pyrite mineralization in several places within the Gneudna Formation. A number of base-metal anomalies have also been reported. Most of these data remain confidential.

It can be seen that exploration completed so far has shown that mineralizing brines passed through the Gneudna Formation. There is thus a reasonable possibility that significant mineralization could be developed in suitable depositional sites. Such situations could be present in the areas where the Gneudna is unconformably overlain by the Lyons Group; in zones of porosity associated with pre-Permian faulting; or with possible reef developments south of the Pleiades Hills as discussed above. Reef developments of the type located in Pendock 1 could be present in a number of fault blocks in the Gascoyne Sub-basin, north and northwest of Carnarvon. Unfortunately these cannot be regarded as potential exploration targets as they are covered by a minimum of 350 m of Cretaceous sedimentary rocks.

Devonian rocks present on the Wandagee Ridge are covered by as little as 100 metres of Cretaceous material near the Wandagee Fault. Petroleum exploration data, which are limited to the two wells Quail 1 and Wandagee 1 have so far provided no evidence of reefal developments on the Wandagee Ridge, which may not have been formed in Devonian times.

The Moogooree Limestone (Carboniferous): Exploration of the Moogooree Limestone has been carried out by two groups, Aquitaine (Mines Department open-file item 556) and Inco.

The main Moogooree Limestone outcrop extends over a length of 55 km from 20 km south of Moogooree homestead to 8 km north of Williambury homestead. A second, faulted, belt 20 km long is centred 4 km west of Williambury homestead while a third outcrop is present west of Harris Bore. While some siliclastic rocks are present (mainly at the base of the sequence) the bulk of the unit consists of fossiliferous and oolitic limestone which is commonly dolomitized.

Much of the Moogooree Limestone contains a high proportion of algal material and chemical precipitates suggesting that at least, in part, 'grazing' organisms were absent, perhaps as a result of hypersaline conditions (Lavaring, 1979). Possible evaporite nodules were described briefly by Radke and Nicoll (1981). A variety of echinoderm and brachiopod fossils are also known and brachiopod coquinas are formed in places. Colonial and rugose corals are present, especially in the western and southernmost outcrops. Detailed mapping by Inco showed the development of small patch reefs or coral mounds, possibly developed over irregularities in the basement, and flanked by limestone breccias, coquinas and oolitic layers.

A possible reconstruction would invoke the presence of hypersaline lagoonal conditions parallel to the shore line and separated from the main ocean by shell banks and coral patch reefs.

Although calcilutite is present within the sequence further out in the basin, carbonaceous shales, bituminous shales and chert are also known.

Throughout much of its outcrop the Moogooree Limestone is overlain conformably by a relatively poor trap rock, the sandstone of the Williambury Formation. In the southern 11 km of the outcrop, however, it is unconformably overlain by glacigene rocks of the Lyons Formation, which potentially form a much better trap.

Aquitaine, during helicopter sampling, collected rock chips assaying 1900 ppm Pb and 1% Zn. These were undercut by two diamond-drillholes and assays up to 1.1% Zn and 1400 ppm Pb over one metre were obtained from a porous oolitic limestone. Individual grab samples assayed up to 2.2% Zn.

This drilling was followed by a programme of photogeological mapping, chip and auger sampling and percussion drilling. A number of anomalous base-metal assays were recorded.

Inco, carried out a helicopter survey of the entire strike length of the Moogooree Limestone. Potentially gossanous or ferruginous outcrops were sampled and stream-sediment samples were taken where gullies and 'streams' were sufficiently well developed. The results showed that base-metal anomalies were essentially restricted to that portion of the limestone which is unconformably overlain by Permian rocks. North of the area previously examined by Aquitaine, a gossan assaying 1.27% Pb, 2020 ppm Zn and 6600 ppm Ba was located. Gully samples assaying up to 2563 ppm Pb were also obtained.

Inco then completed a programme of detailed grid-controlled geological mapping, soil sampling, and induced polarization (IP) surveying. A number of gossan outcrops, some containing hemimorphite, were located and several strongly anomalous lead and zinc soil anomalies were outlined, assaying up to 775 ppm Pb and 670 ppm Zn. The IP results were interpreted as indicating several potential sulphide conductors. Geological mapping showed that a palaeokarst system had been infilled by the Permian sediments.

An attempt was made to drill these anomalies by a combination of percussion, air core, and diamond drilling. As a result of severe problems of lost circulation, associated with numerous large cavities, most of the programme had to be abandoned and none of the holes drilled reached their target depth. No base-metal mineralization was intersected although one hole drilled a gossan zone assaying up to 1.3% Pb.

The work completed by Aquitaine and Inco is considered to indicate considerable potential for mineralization where the Moogooree Limestone is unconformably overlain by the Lyons Group. With Inco's withdrawal from exploration in Australia the anomalous sections outlined in the southern 11 km of the outcrop remain, largely, untested. Further potential could be present to the west, below the cover of Lyons Group sediments. Similar, unconformable, relationships are present west of Harris Well on Williambury Station.

As with the Gneudna Formation, there is evidence of pre-Permian faulting, particularly in the vicinity of

Williambury homestead. Breccia zones associated with this faulting are also possible target zones for mineralization.

The Callytharra Formation (Permian): The Callytharra Formation has a very extensive outcrop in the Carnarvon Basin, extending for some 390 km from the Lyndon River, to south of the Wooramel River.

The unit consists of two main facies: a lower calcareous siltstone, deposited in quiet marine conditions below wave base; and an upper calcarenite facies, formed after the shallowing of the basin under more agitated shoaling conditions (Hocking and Moors, in prep.). Both are richly fossiliferous and Condon (1967) has suggested that organic banks or reefs could be developed over shoal ridges. No evidence for this is seen in outcrop.

The Callytharra Formation is overlain unconformably by the Moogooloo Sandstone, a relatively poor trap rock. Karstification, which is a feature of this unconformity, is especially well developed in an area of over 1 000 km^2 between Coonantha Well (Bidgemia), Red Ochre Well (Dairy Creek) and the southern end of the Pells Range (Hocking and Moors, in prep). Well-developed tower and corridor karstification is present, with a relief of up to 30 m.

The Callytharra Formation has been the subject of reconnaissance exploration for Mississippi Valley-type mineralization by a number of groups, although no detailed exploration programmes have been reported to the Mines Department.

During regional exploration by Inco the majority of the strike length was flown by helicopter in a search for gossans. Although a number of ferruginous units were located, only very slightly anomalous base-metal values were returned. These were from north of Mount Sandiman woolshed (where they were interpreted as resulting from manganese scavenging) and northeast of Bidgemia homestead.

In the latter locality gossans are developed in 'corridor' karst features; textures in the gossans, however, indicate that they are derived from pyrite and marcasite with no evidence of base-metal sulphides.

As a result of this sampling it was concluded that the main Permian mineralizing event preceeded the deposition of the Callytharra Formation. In view of the very extensive carbonate development however, further evaluation may be warranted.

Stratiform copper mineralization associated with shallow marine sediments and continental red beds

Stratiform metalliferous deposits, commonly hosted in reduced shales or stromatolitic dolomites underlain by continental red beds and overlain by evaporites, account for 26.9% of the world's copper reserves (COMRATE 1975).

Important deposits of this type are those of the Copper Belt of Zambia and Zaire (late Proterozoic), the Kupferschiefer of Germany and Poland (Permian), Udecon (Early Proterozoic) and Dzhezkazgan (Carboniferous) of the USSR. Many other smaller deposits are known throughout the geological record, some, like the Layo deposit of Mexico, being as young as Palaeocene.

Numerous hypotheses have been proposed to explain the origin of these deposits but more recent ideas have tended to emphasize an association with sabkha sedimentation. Renfro (1974) proposed that mineralization resulted from the interaction between relatively fresh metal-bearing seaward-flowing groundwater and marine water in algal mats. Rose (1976) demonstrated that copper was not sufficiently soluble to be transported in this way. He showed, however, that the mineralization had been introduced at temperatures of less than 75°C and suggested that the copper had been introduced into a reducing environment (e.g. in sabkhas) as chloride complexes. He envisaged that brines derived from evaporite units within the sedimentary sequence would leach copper from oxidized red beds, pointing out that these are uniquely suited to maintaining an appropriate oxidation state in sufficiently large volumes of rock.

It seems probable that, for significant mineral deposits to be formed, 'anomalous' background amounts of copper would still need to be present in the system. These could be derived from oxidative alteration of basalts (Haynes, 1972), propylitically altered basic rocks within the basin, or from red beds which have been derived from a hinterland containing copper mineralization or suitably altered rocks.

Annels (1984) has suggested that the sediments of the Zambian Copper Belt, formed as an infilling of an ancient aulacogen, with metals being derived from the seepage of magmatically enriched hydrothermal solutions along Precambrian rift systems and associated fractures.

A geological situation which may have potential for mineral deposits of this type could be present within the Carnarvon basin in the rocks of the Silurian Kalbarri Group (Hocking and Moors, in prep.) which, as pointed out above, were probably deposited in an aulacogen. The Kalbarri Group consists of two 'couplets' of distinct lithotypes which can be related to a broad depositional setting in which siliclastic sediments of braided fluvial origin prograded out into an epeiric basin in which evaporite deposits and dolomitic sequences formed. An outline of the stratigraphy of the group is given in Table 3.

TABLE 3: OUTLINE STRATIGRAPHY OF SILURIAN KALBARRI GROUP

UNIT	DESCRIPTION
Sweeny Mia Formation	Uppermost unit of group, consists of evaporites, dominantly anhydrite, interbedded with dolomite. Kendall (1979) suggested that these may be shallow-water subaqueous deposits rather than sabkha deposits, but it seems probable that sabkhas would have been present further south and east, on the margins of the basin. The formation is known at present from wells in the Shark Bay area.
Kopke Sandstone	This formation has been newly defined by Hocking and Moors (in prep.). It marks a temporary return to depositional conditions similar to those which prevailed during the deposition of the Tumblagooda Sandstone.
Dirk Hartog Formation	This unit is known only from drill information. It consists mainly of dolomite, limestone and shale deposited on a wide tidal basin margin.
Yaringa Evaporite Member	This prominant evaporite unit occurs within the Dirk Hartog Formation. Hocking and Moors (in prep.) have intepreted it as having formed in a dessicating or barred basin environment.
Tumblagooda Sandstone	Hocking (1981) showed that this red-bed sequence consists predominantly of a braided fluvial facies in the east which grades westwards into coastal marine sediments. It is probable that sabkha deposits were developed between the lobes of fluvial fans, however, these have not yet been identified.

The relationships of the various formations are illustrated in Figure 5 after Hocking and Moors (in prep.). It can be seen that the overall relationships are not dissimilar to those described from many 'red bed' copper deposits.

Palaeocurrent data indicate that the provenance of the sedimentation for the Tumblagooda Sandstone was from the southeast (Hocking, 1981). Clasts of Archaean and Proterozoic rocks, including Coomberdale Chert from the Moora Group, have been identified. This suggests that sediments could also have been derived from the Yandanooka Group, in which copper mineralization is present in the Arrowsmith Sandstone and Arrino Siltstone; and from the Billeranga Group, in which copper mineralization is known in the remnants of the previously more extensive Morawa Lavas.

The evidence for a Silurian mineralizing event in the age of hydrothermal alteration in epigenetic mineralization of the Northampton Block (Blockley pers. comm.) has been discussed earlier. It is therefore suggested that there may be potential for copper mineralization in coastal sabkhas of the Dirk Hartog Formation and Sweeney Mia Formation. These are probably developed east and southeast of the present drill intersections, in the area between the Murchison and Wooramel Rivers. Possible indications of sulphide mineralization are given by the presence of pyrite in the Dirk Hartog Formation in Tamala 1 and in the Sweeney Mia Formation in Yaringa 1 and Hamelin Pool 2. Pyrite was also noted in possible Silurian red beds which were intersected in coal exploration bores near Meadow homestead. None of these intersections appear to have been assayed for base metals or associated indicator trace elements.

These potential target sequences, while they do not crop out, are present at a shallow depth (as little as 25 metres) below Cretaceous, Tertiary and Quaternary

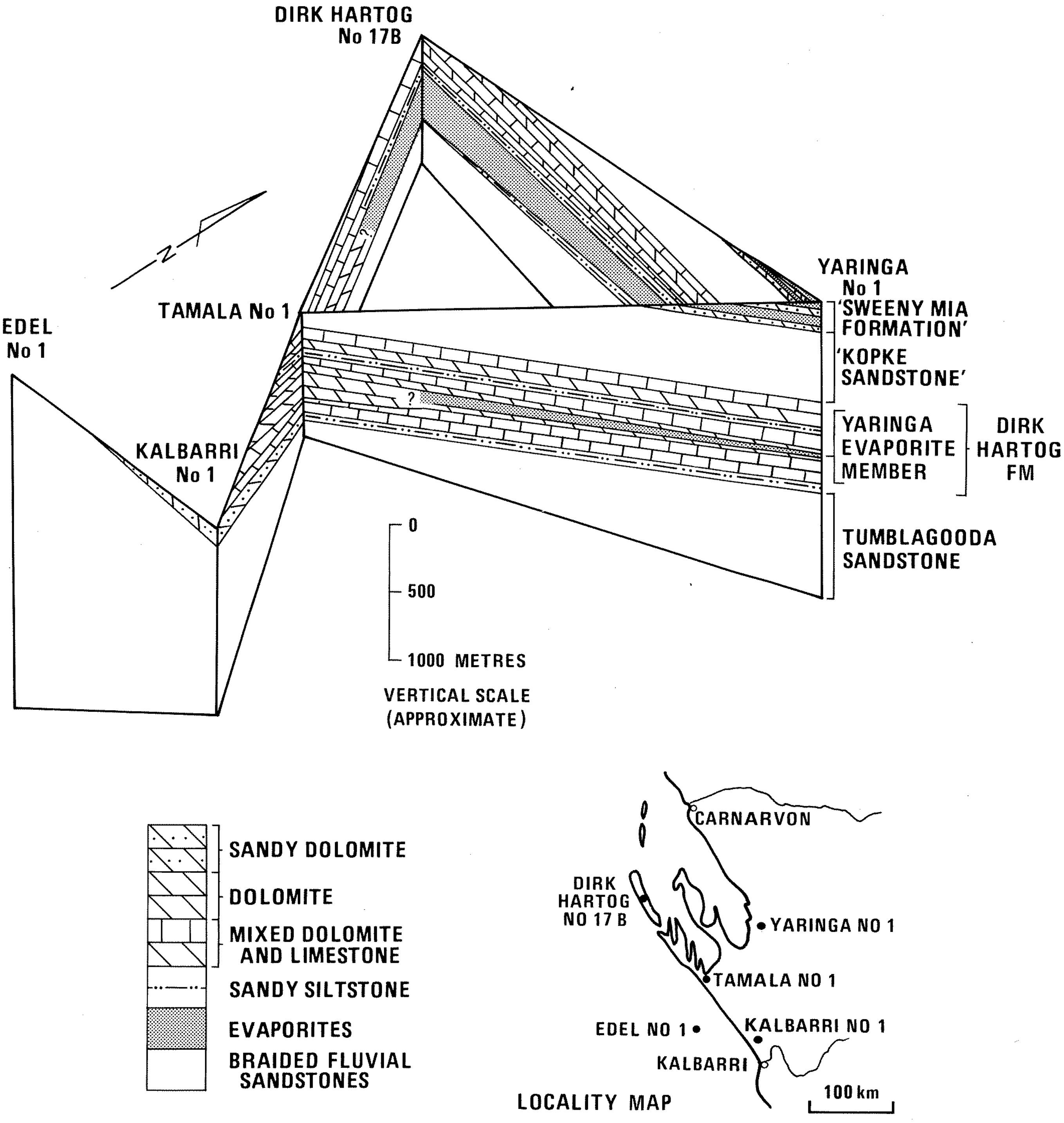

FIGURE 5 : LITHOSTRATIGRAPHIC RELATIONSHIPS OF THE SILURIAN ROCKS IN THE SOUTHERN CARNARVON BASIN

MODIFIED AFTER HOCKING AND MOORE (in prep.)

GSWA 21304

sedimentary rocks in much of the area described, and thus could represent a potential exploration target. The area of possible exploration potential is indicated on Plate 1.

Stratiform, shale-hosted, lead-zinc and copper-lead (-silver) deposits

Sediment-hosted, stratiform, deposits of lead-zinc and copper-lead form a very important part of the World's base-metal reserves. Gustafson and Williams (1981) have shown that of the ten largest lead-zinc deposits, five are of this category.

A particular feature of deposits of this type is the 'bedded' nature of the sulphides, at even the finest scale. A variety of theories have been proposed to explain their genesis, more recent ones tending to regard the mineralization as being syn-sedimentary or early diagenetic in origin. Gustafson and Williams (1981), suggested that lead-zinc deposits result from the evolution, heating and chemical reduction of brines deep within the basin. These then form mineralization diagenetically or in some cases by exhalation of dense brines on the sea floor - the so called 'sedimentary exhalative deposits'.

Important occurrences of mineralization of this type are present throughout the geological record from the Proterozoic to the recent. Important examples are Broken Hill (Early Proterozoic); Mount Isa (Middle Proterozoic); Sullivan, Canada (Middle Proterozoic); Howards Pass, Canada (Silurian); and Rammelsberg and Meggen, Germany (Devonian).

The best known of the recent examples, and perhaps the only documented base-metal deposits presently forming, are in the brine pools of the Red Sea. (The 'black-smokers' of the East Pacific Rise are not forming mineral deposits as their products are rapidly oxidized and dispersed.)

Within the Red Sea brine-pads, gel-like sediments containing between 20 and 100 metres of sulphides are saturated by hypersaline, hot, brines believed to be of hydrothermal origin. (Rona, 1973). They occur as local ocean-floor basins within a 250 km x 10 km rift which formed at a divergent plate boundary, and may have significant parallels in the Carnarvon Basin.

A feature of this class of lead-zinc deposit is the almost ubiquitous presence of highly anomalous silver values and a frequent association with stratiform 'bedded' barite. Within the Carnarvon Basin two sequences are considered to warrant exploration for mineralization of this type.

Shales of the Byro Group (Permian): The Artinskian Byro Group consists of two main 'facies associations' (Moore, Denman and Hocking, 1980): a fine-grained facies association; and a sandstone facies association.

Some of the rocks of the fine-grained facies association may have potential for stratiform base-metal mineralization. The association comprises two facies, a grey siltstone facies and a black-shale facies, which may represent a potential host to mineralization. The black-shale facies is developed mainly in the Bulgadoo and Quinnanie Shale sequences, but is also present in the Baker Formation and Wandagee Formation. It appears to have formed offshore in deep euxinic or anoxic water. Condon (1967) and Thomas and Smith (1976) suggested that topographic silling had resulted in local restricted environments, although Moore, Denman and Hocking saw no need for a silled basin.

The black-shale facies is characterized by laminated black shales and fine siltstone with a restricted fauna.

It contains significant amounts of pyrite, as disseminations and fine bands, and, in outcrop, secondary gypsum. Phosphate may be present (up to 1.25 % has been recorded) indicating slow deposition.

If mineralized brines were debouched into the basin during sedimentation, or saturated the sediments soon after deposition, conditions would have been ideal for the formation of base-metal mineralization. The presence of barite-galena-sphalerite veins cutting the basal Lyons Group in the Mount Sandiman area has been discussed previously. These indicate that at least some mineralizing fluids were generated during or after Late Carboniferous times and suggest that further evaluation of the Byro Group could be justified.

The shale sequences are generally poorly exposed being seen mainly in river and creek sections (e.g. the Lyndon and Minilya rivers). Away from these drainages a thin cover of soil, sand or wash effectively blankets the sequence. The sequence has, however, been intersected in several drillholes put down for phosphate or potash exploration. Although considerable quantities of pyrite have frequently been logged in many holes, no assays for base metals or indicator elements have been reported to the Mines Department. The most effective method of exploration of this sequence would seem to be by broad-spaced (several kilometres) stratigraphic drilling, with sulphide-rich sections being analysed for base metals and silver. Williams and others (1982) have shown that pyrite in shales 10 to 20 kilometers from the McArthur base-metal deposit gives values in excess of 2000 ppm Zn, while Roberts (1982) showed that anomalous silver, in the range 6 ppm to 300 ppm was significant in distinguishing pyrite from sequences containing base-metal deposits from 'barren' pyrite.

Bentonitic and radiolarian shales of the Winning Group (Cretaceous): The geological setting for the deposition of the Cretaceous sediments within the Carnarvon Basin has been described previously. The setting is considered to be geologically and tectonically similar to the present Red Sea rift which marks the geologically recent separation of the Arabian and African plates. Evidence of presently forming mineral deposits in the brine pools of the Red Sea has been discussed previously and it is suggested that possible analogues of these could be present in the sediments deposited in this Australian-Indian 'Red Sea'. In the Carnarvon Basin these are represented by the sediments of the Winning Group.

The Winning Group outcrops in many parts of the basin and occurs in the subsurface over most of the western part of the basin. Onshore members of the group are summarised in the following table:

Gearle Siltstone/ Alinga Formation	- bentonitic and radiolarian siltstone.
Windalia Radiolarite	- radiolarian siltstone and chert.
Muderong Shale	- shale, claystone, siltstone, greensand.
Birdrong Sandstone	- quartz sandstone, commonly glauconitic.

The group is unusual in that 'pelagic type' sediments were apparently deposited at less than 1 000 m depth.

Several of the shale and siltstone sequences are considered to be potential hosts for base-metal mineralization.

The Muderong Shale varies from dark grey-brown and black, to grey-green. It is commonly silty and may contain interbeds and lenses of fine sandstone. In the shallower, eastern part of the basin it is commonly glauconitic but further west, in the Giralia Anticline, drill intersections are frequently found to be bentonitic and to contain nodules, stringers and fine beds of pyrite. Pyrite has also been reported as a cement in sandy layers. Thin beds of fine-grained dolomitized limestone have been recorded.

The Windalia Radiolarite is usually silicified in outcrop and has a characteristic white or yellow opaline appearance with purplish red banding or blotching. In the subsurface it is similar in appearance to the Muderong Shale or Gearle Siltstone but is characterized by the presence of up to 70% radiolaria and is best described as a radiolarian siltstone. It is usually dark grey to brown but in places contains glauconitic or chamositic (in the west) interbeds. Siderite-cemented interbeds occur locally. Carbonaceous sequences are present in places. In the Giralia Anticline drilling has shown that these occur as local thickenings which may represent deepenings of the sedimentary basin.

In bores around the Shark Bay area, 70 cm thick beds of black, conchoidally fracturing chert are present in the sequence. Once again pyrite is common as disseminated nodules and fine interbeds.

The unusually high silica content strongly suggests that there was an anomalous silica content in oceanic waters (Condon, 1968). Special weathering processes have been invoked to account for this but a more probable cause is considered to be fumerolic and hydrothermal activity associated with the development, offshore, of the volcanic spreading centre. It is interesting to note that the gel-like sediments in the Red Sea brine-pools are characterized by a high proportion of amorphous silica, together with sulphides, iron oxides and carbonate.

The Gearle Siltstone conformably overlies the Windalia Radiolarite. The main lithology of the unit is a dark grey-brown to black bentonitic siltstone grading into silty claystone. Radiolaria-rich siltstones are present near the base of the formation; and in the Giralia Anticline, tuffaceous horizons containing shards of devitrified glass and angular feldspar phenocrysts, have been described in mineral exploration reports.

A feature of the siltstone is the presence, near the middle of the sequence, of a number of beds of stratiform, sedimentary barite, up to 40 cm in thickness. Drilling suggests that these are lenticular in nature. In outcrop nodules of barite are frequently scattered across the surface. The Gearle Siltstone is commonly pyritic. Stratiform pyrite is known from a number of sections (including some of the barite-rich intervals) while disseminated pyrite together with nodules and tube-like aggregates of marcasite-pyrite are also common.

The Winning Group has been subject to a number of low-key exploration programmes for phosphate, bentonite and barite but only one exploration programme for base metals has been reported to the Mines Department. This programme, by Inco in 1978-79, was over two Temporary Reserves in the Giralia Anticline. Exploration started after the identification of anomalous silver values in sulphide nodules and microgossans in the Gearle Siltstone Sequence, near the occurrences of bedded barite. It consisted of geological mapping, stream and rock chip sampling, auger and air-core drilling and trial input-EM surveys.

A number of highly anomalous silver values, up to 352 ppm, were returned from sulphide and goethite nodules, and microgossan chips, with values over 30 ppm Ag being mainly restricted to the upper part of the Windalia Radiolorite and the lower part of the Gearle Siltstone in the north of the structure. A number of anomalous zinc values in excess of 1 000 ppm were also recorded from these surface samples, with values to 1 250 ppm Zn and 120 ppm Pb. Microgossan chips collected from water-bore sludge assayed over 2% Zn. Mineragraphic examination suggested the presence of sphalerite textures in this material. There is some possibility that these chips could have been derived from the Permian Byro Group which forms the basement for the Cretaceous in much of the Giralia Anticline but this was considered to be unlikely in view of the oxidized nature of the samples.

No significant base-metal or silver values were obtained in the deep drilling programme and it was concluded that any mineralization was too sparsely distributed to be economically significant. The presence of saline groundwater and carbonaceous horizons caused continuous activity on all EM channels.

The presence of anomalous silver and base-metal values together with base-metal microgossans is considered to provide further evidence of the metaliferous potential of the Winning Group sequence, although there is a strong possibility that any significant mineralization could be basinward of the Giralia area, or even offshore and thus outside the range of economic exploration.

The anomalous heat flow associated with the Rough Range Fault, to the northwest of the Giralia Anticline has been discussed earlier. A second area of anomalous heat flow occurs to the South of the anticline (Moors, 1980) in the area of the Gnaraloo 1 and Chargoo 1 wells possibly resulting from the movement of formational fluids associated with a horst block in the Palaeozoic 'basement' in this area.

The Winning Group sediments over and adjacent to both of these structures may well have significant potential for 'sedimentary exhalative' base-metal mineralization. Another area of anomalous heat flow in the Robe River area (Moors, 1980) should also be evaluated.

KIMBERLITES AND DIAMONDS

Reconnaissance exploration for kimberlites commenced in the Carnarvon Basin in the mid 1970s and culminated in the discovery by CRA Exploration Pty Ltd in 1978, of kimberlitic dykes and pipes in the Wandagee area. The pipes were found as a result of sampling stream gravel for indicator minerals. The work located kimberlitic pyrope garnet and chrome diopside. Subsequent airborne magnetic surveys delineated further pipes under as much as 160 m of sediments. Details of the discovery have been given by Atkinson, Hughes and Smith (1984) from whose paper the following details are taken.

The Wandagee kimberlite province consists of 16 separate kimberlite occurrences in an elongate north-south zone some 50 km long. The cluster is situated along the fault-bound eastern edge of the northerly trending Wandagee Ridge, in the major fault zone which separates the ridge from the Merlinleigh Sub-basin (Fig. 6.).

Both magmatic rocks and tuffs are present within the Wandagee cluster. Magmatic rocks are described as porphyritic peridotites having much in common with kimberlites. They contain 45% olivine, 45% clinopyroxene and minor matrix material. In unweathered rock the porphyritic olivine occurs as large subhedral to euhedral phenocrysts from 0.4 - 2.0 mm in diameter. Rare large rounded xenocrysts of granular olivine are also present. The groundmass consists of a plexus of stubby prisms of greenish to faint purplish brown clinopyroxene together with minor brown mica and devitrified glass.

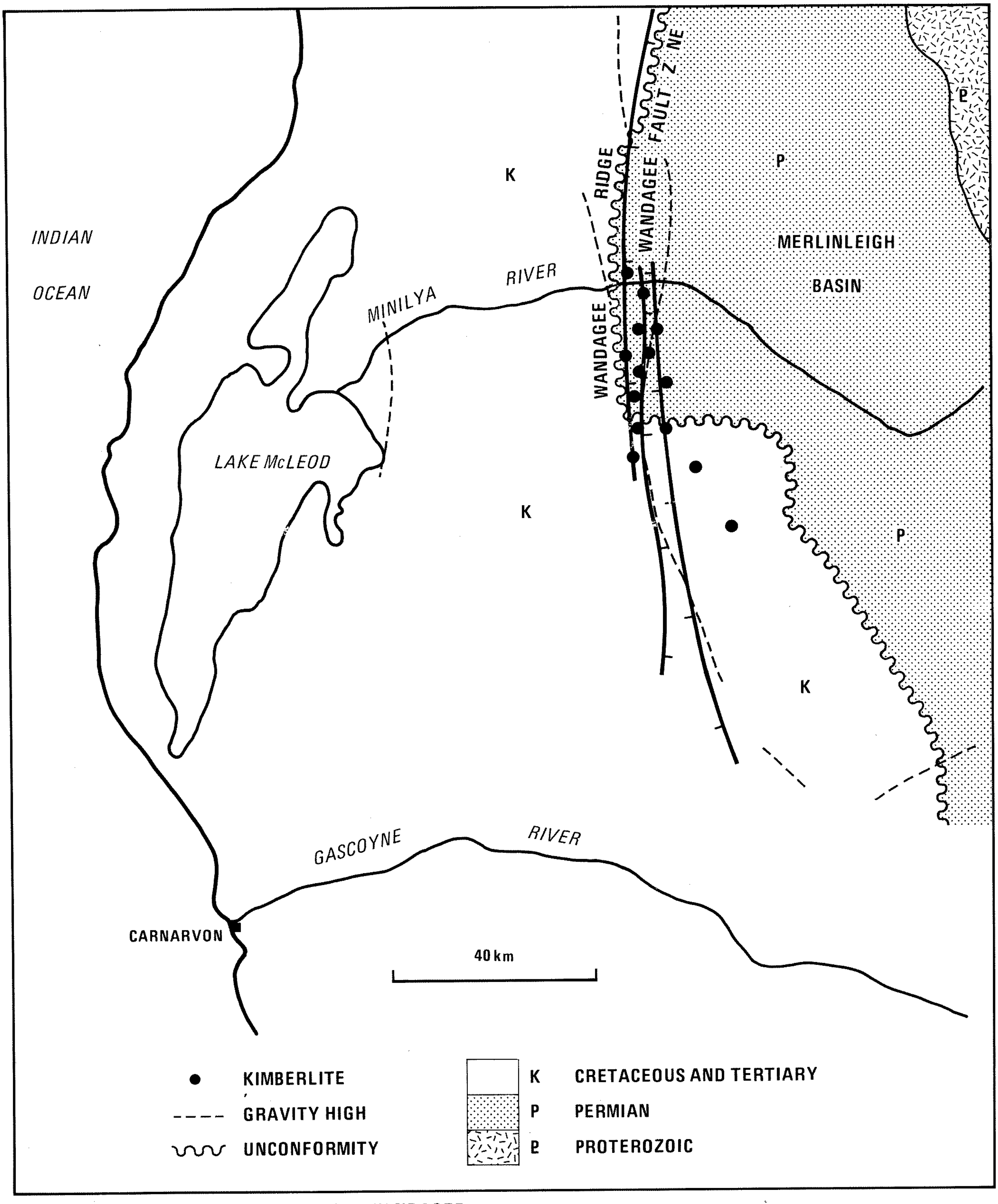

FIGURE 6: LOCATION OF KIMBERLITES AT WANDAGEE

MODIFIED AFTER ATKINSON et al (1984)

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The Wandagee tuffs are extensively weathered where seen in trench exposures and show considerable alteration in drill core. They are clast supported with well-rounded phenocrysts of olivine, now pseudomorphed by talc, carbonate and chlorite, forming 15-25%. The remainder of the clasts are predominantly subrounded porphyritic igneous types. Minor clasts of pyritic shale and micaceous siltstone are also present.

While the magmatic rocks have major element geochemistry resembling 'classic' kimberlite, they are abnormally soda rich and therefore constitute a separate Western Australian type. They also occur in the higher parts of the kimberlitic fields of Al_2O_3 and SiO_2 and at the lower end of the the scales for MgO, TiO_2, K_2O and K/Na (Fig. 7). The tuffaceous diatremes are more aluminous and less magnesian; this may be due to contamination by country rock xenolithic material. Heavy-mineral concentrates from the Wandagee kimberlites contain coarse pyrope, chrome-diopside, magnesian chromite, magnetite, picro-ilmenite, zircon, and rare diamonds.

Ten diatremes, ranging up in size to a maximum of 14 hectares, occur in the cluster. These are thought to be within the pipe zone of the kimberlite volcano because of the absence of bedding and the steep contacts with country rock. The material within these pipes consists mainly of kimberlite tuff with abundant spherical, nucleated, kimberlite autoliths indicative of gaseous emplacement. The remainder of the Wandagee kimberlite bodies are thin (up to 3 m), westerly dipping sills intruding Permian micaceous siltstones. The sills, which consist of magmatic kimberlite, are dense, dark grey and fresh, in contrast to the extensively weathered and altered tuffs. The postulated relationship of the Wandagee pipes to the idealized kimberlite volcano is illustrated in Figure 8.

Four of the Wandagee diatremes are overlain by 70 m

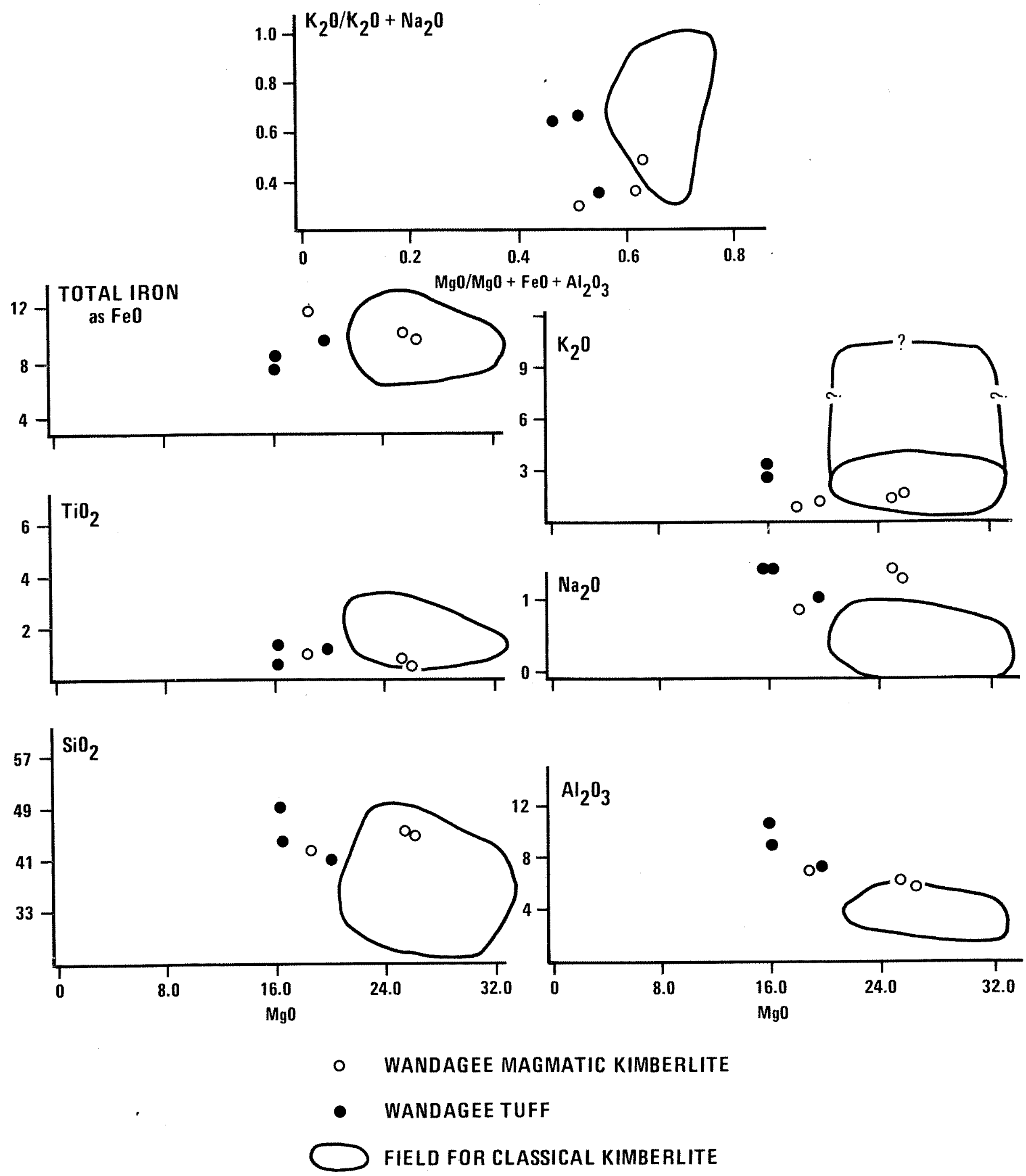

FIGURE 7: MAJOR OXIDE (WT %) VARIATION DIAGRAMS FOR WANDAGEE KIMBERLITES.

MODIFIED AFTER ATKINSON et al (1984)

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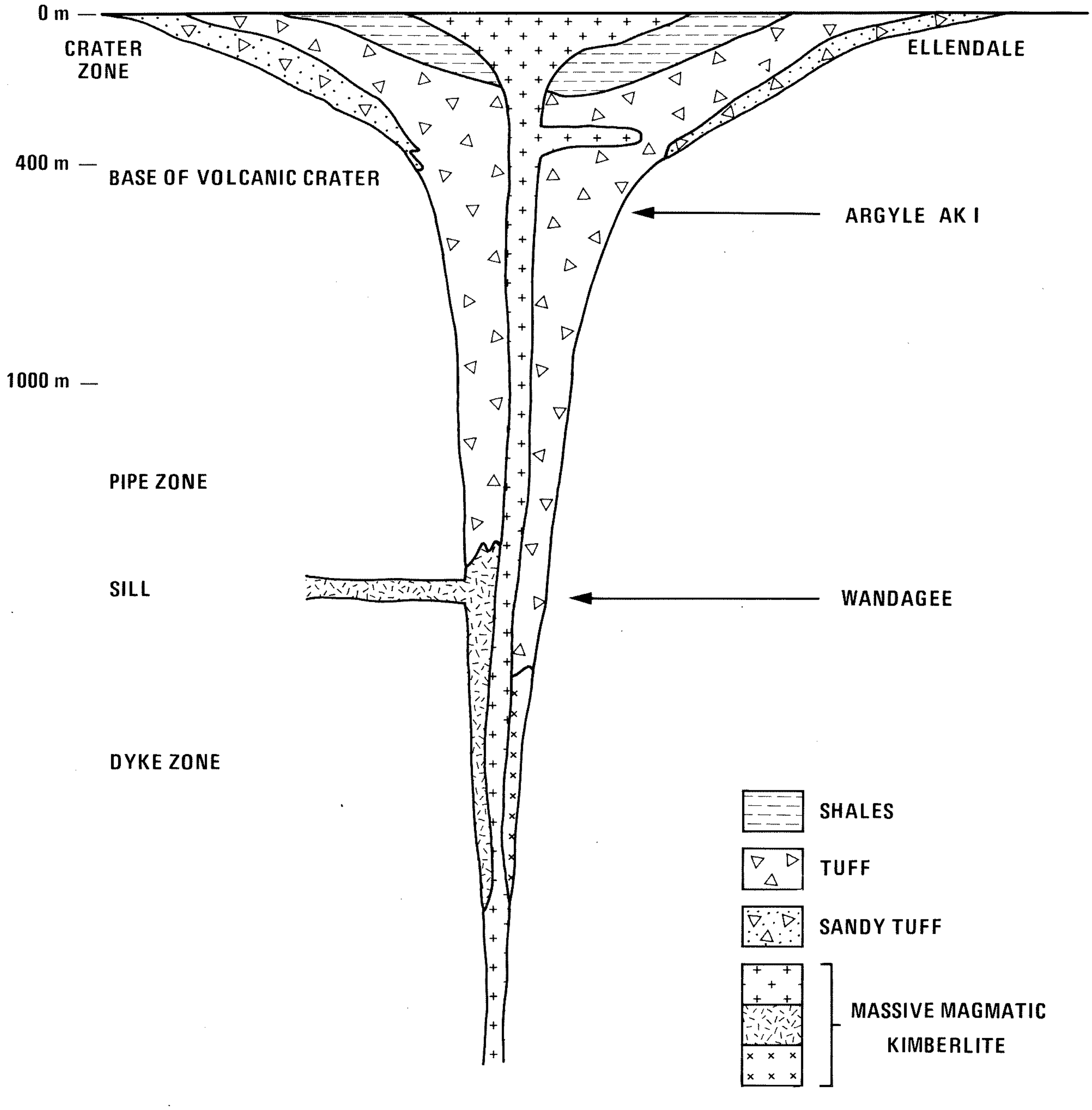

FIGURE 8: MODEL OF A WEST AUSTRALIAN KIMBERLITE PIPE

MODIFIED AFTER ATKINSON et al (1984)
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of Cretaceous Winning Group sediments and one has been dated using U-Pb methods on xenocrystal zircon at 160 ± 10 my. The kimberlites are thus thought to be Jurrasic in age. Their emplacement is probably due to tensional crustal fracturing during the embryonic separation of the Australian and Indian continental plates, prior to final separation.

This apparent relationship of the kimberlites to major fault systems raises interesting possibilities for further exploration. Several other major faults marking the boundary between major horsts-and-grabens are present within the Carnarvon Basin. The western boundary of the Wandagee Ridge is marked by the major Marrilla Fault, while in the south of the basin, the Coolcalalaya Sub-basin represents a major rift system which is separated from the Ajana ridge to the west by the Hardabut/Ajana Fault system. The eastern margin of the Coolcalalaya Sub-basin is marked by Western Australia's most fundamental fault, the Darling Fault which to the north resolves itself into the Woodrarrung Fault and the Darling splay fault. (Fig. 9).

All of the faults mentioned above probably represent major tensional crustal fractures and are therefore potential sites for kimberlite intrusion. In many places, particularly in the western part of the basin, these faults are covered by younger Cretaceous sediments, however, the experience of CRA Exploration Pty Ltd indicates that detailed airborne magnetic surveys can locate buried kimberlite pipes beneath this cover.

In spite of fairly intensive exploration within the basin following CRA's initial successes there have been few indications giving further encouragement. No additional kimberlites have been located although a number of occurrences of possible kimberlitic indicator minerals have been reported. Stockdale Prospecting Ltd, in work

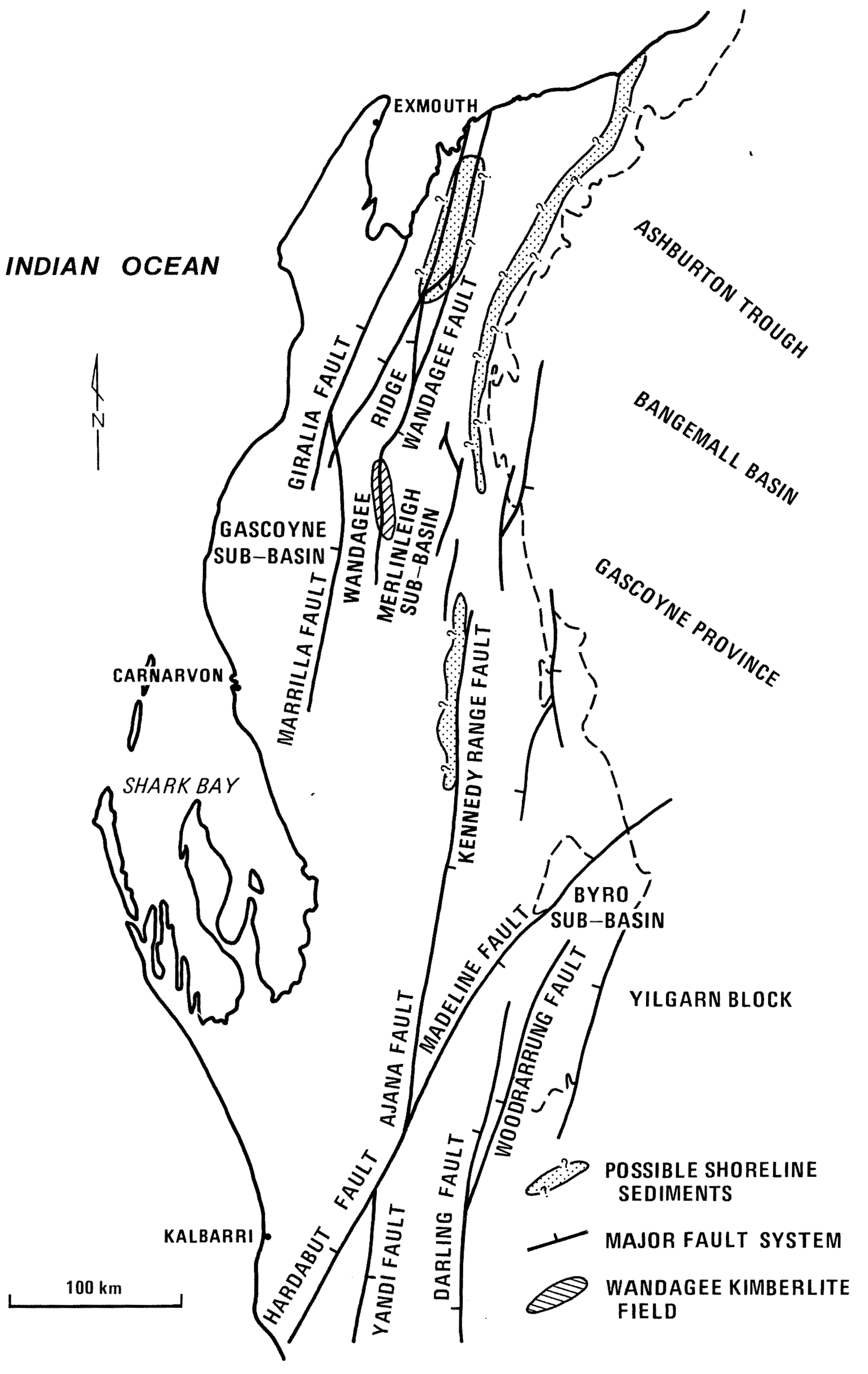

FIGURE 9 : POTENTIAL DIAMOND EXPLORATION TARGETS ONSHORE CARNARVON BASIN

GSWA 21308

described in open-file item 1034, reported the discovery of chromium diopside and microdiamonds, on the Byro 1:250 000 geological sheet, in the area between the Darling Fault and Meeberrie Fault systems. Follow-up work, including airborne magnetic surveys and loaming, failed to locate the source of these minerals which were concluded to be derived from Permian tillites. Later information suggests the possibility that these minerals may have been derived as a result of laboratory contamination.

Broken Hill Propriety Co Ltd (BHP), in exploration near Dairy Creek on the Glenburgh 1:250 000 geological sheet, described in Mines Department open-file item 1319, reported the discovery of three kimberlitic chromite grains. These minerals however, were not confirmed by follow-up sampling.

In the Lyons River area, on the Kennedy Range and the Mount Phillips 1:250 000 map sheets, CRA, in reconnaissance work described in Mines Department open-file item 1288, reported the location of kimberlitic chromites and microdiamonds in sediment sampling. Follow-up bulk sampling failed to locate the source of the indicator minerals, which were regarded as having been derived from Phanerozoic sediments. The microdiamonds were regarded as having derived from laboratory contamination.

Stockdale Prospecting, in item 1038 of the open file describing exploration on the Winning Pool 1:250 000 map sheet north of the Kennedy Range, report the presence of trains of indicator minerals which appear to be derived from Cretaceous sediments. As CRA's work has demonstrated that the Wandagee kimberlites are pre-Cretaceous in age this raises an interesting exploration possibility. It must be assumed that a considerable volume of kimberlitic material, representing the upper part of the kimberlitic volcanoes, was eroded prior to the deposition of the

Cretaceous sedimentary sequence. Although much of this material is probably incorporated in Jurassic sediments in the offshore parts of the basin, there is a possibility that some has been included in the Birdrong Sandstone sequence of the Cretaceous Winning Group. There is thus a possibility that alluvial diamonds may be present in any heavy-mineral concentrations within this sequence. In the area of the Kennedy Range possible shoreline facies have been recognized in the Birdrong Sandstone. It is considered that these should be further examined for possible alluvial diamond concentrations. Shoreline facies are also present near the northeastern margin of the basin (Hocking and van de Graaff, 1978), however a large number of fluvial channels were shown to be present in this area by drilling completed during uranium exploration, and the sediment supply from these probably swamped any kimberlite derived material. A number of Quaternary alluvial sequences have been, and are being, examined as potential diamond-source areas but no work has been reported which examined the potential of the Cretaceous sequence. Areas of possible potential have been indicated in Figure 9.

URANIUM

PROVENANCE AND SOURCE ROCKS

The provenance for the sedimentation in most of the central part of the Carnarvon Basin has been the Proterozoic rocks of the Gascoyne Province. The main elements of the geology of this tectonic unit are discussed by Daniels (1975), Gee (1979), and Williams and others (1983a, 1983b). Minor uranium occurrences are a feature of much of the central and northern parts of the Gascoyne Province and have been the subject of fairly intensive exploration, some of which was itemized by Butt and others (1977) and Carter (1981). The majority of these occurrences are plotted on Plate 1. It will be seen that most are associated with certain of the granitic intrusives, either with pegmatites and veins associated with these, or with calcreted drainages derived from them.

The particular granites and pegmatites which contain anomalous mineralization are muscovite (and tourmaline) - bearing, syn- and post-tectonic batholiths and plutons, together with their 'late-stage' products. Williams and others (1983a) suggested that these were derived by anatexis from the metasedimentary rocks of the Morrissey Metamorphic Suite, as opposed to generally early-phase biotite-bearing granites which are believed to be derived from Archaean and Proterozoic 'basement' and which generally do not carry anomalous uranium. These authors further suggested that uranium was pre-concentrated in the sedimentation, metamorphism and migmatization of the Morrissey Metamorphic Suite and further scavenged and enriched during hydrothermal processes associated with the emplacement of the muscovite-bearing granitoids. Evidence for the high uranium content of the granites is given by Valsardieu and others (1981) who reported the presence of secondary uranium minerals associated with exfoliation surfaces in the granites and Mines Department open-file items 366 and 145 which report assays of 80 ppm U_3O_8 in granite and record 580 ppm from granite pegmatites respectively. Uranium is further concentrated in (fossil) calcretes within present-day drainage systems. Butt and others (1977) showed that west of the 'Meckering Line', regional uplift produced rejuvenation of the drainages and erosion of the calcretes into terraces. The uranium has thus once again been released into the drainages which flow over the rocks of the Carnarvon Basin. These various factors combine to define an area of the basin in which suitable host rocks, under the right physical and chemical conditions, are considered to have potential for the development of a number of types of sedimentary uranium deposits. This area has been shown on Plate 1. Outside this area the provenance of sedimentation is much lower in uranium content and potential for mineralization is probably greatly reduced.

POTENTIAL AND EXPLORATION FOR SANDSTONE-HOSTED DEPOSITS

The main types of uranium deposits have been classified by Dahlkamp (1978). Of the six types of deposits which Dahlkamp regards as having potential economic significance, the sandstone types are considered most likely to occur within the Carnarvon Basin. Dahlkamp has subdivided sandstone-hosted deposits into three main types, the conditions of formation for which had been further discussed by Stanton (1972) and Adler (1974).

Dahlkamp has pointed out that while individual deposits may be small, the potential for a district as a whole is considerable and may be up to 150 000 tonnes of contained uranium, indeed about 95% of uranium reserves in the United States are in deposits of the sandstone type.

Roll-front deposits

In this type of deposit, uranium mineralization follows the contact between oxidized and reduced sandstone, this being the furthest down-dip penetration of oxidizing groundwater. Under oxidizing conditions uranium becomes soluble as uranyl ions ($U^{6}+$), and these ions may react in a number of ways to form uranium minerals. In particular their reaction with hydrogen sulphide resulting from the breakdown of coalified plant and humate remains, or associated with 'down basin' oil and gas deposits, leads to the formation of the two most important ore minerals, uraninite and coffinite.

A continuing process of re-working with the advance of the redox front is probably important in the formation of significant ore-deposits. If ions such as vanadate, phosphate, arsenate, or carbonate are present within the system in significant quanity this recycling may be interrupted by the formation of relatively insoluble uranyl compounds such as carnotite, tyuyamunite, phosphuranylite, and meta-autunite. (The presence of the latter two minerals in the oxidized zone of some of the deposits discovered so far in the Carnarvon Basin may account for the relatively small reserves of the individual deposits.) A particular characteristic of roll-front deposits is the interbedding of the permeable (mineralized) layer within impermeable horizons such as clay and siltstone. In cross section, roll-front deposits are frequently seen to be crescent-like, while in plan they have been described as being like an irregularly laid pipe. Deposits form best in areas with shallow dip (less than 5°) and are best developed in palaeochannels in fluvial deposits, probably because of the channelling of groundwater flow. Such conditions occur in several units in the Carnarvon Basin, and these are considered below.

The roll-front type of deposit has been the target of most of the uranium exploration conducted in the basin. This exploration has resulted in the discovery of a number of occurrences of uranium mineralization, at least one of which has the potential to become an economic deposit. This deposit was described by Valsardieu and others (1981). It is located near Manyingee Hill, 50 km northeast of the Barradale Roadhouse and occurs within a fluvial and deltaic facies of the Cretaceous Birdrong Sandstone, which is developed within palaeochannels incised into basement granitoids and 'sealed' by siltstones of the Muderong Shale. The deposit, which is associated with a redox front, is in many ways typical of the roll-front style of mineralization (Fig. 10). One unusual feature, is the presence of brannerite [(U Ca Fe Th)(Ti Fe)$_2$O$_6$], together with minor rutile and ilmenite, in the reduced zone. The preservation of this mineral suggests that the source of the uranium must be of very local origin, probably from

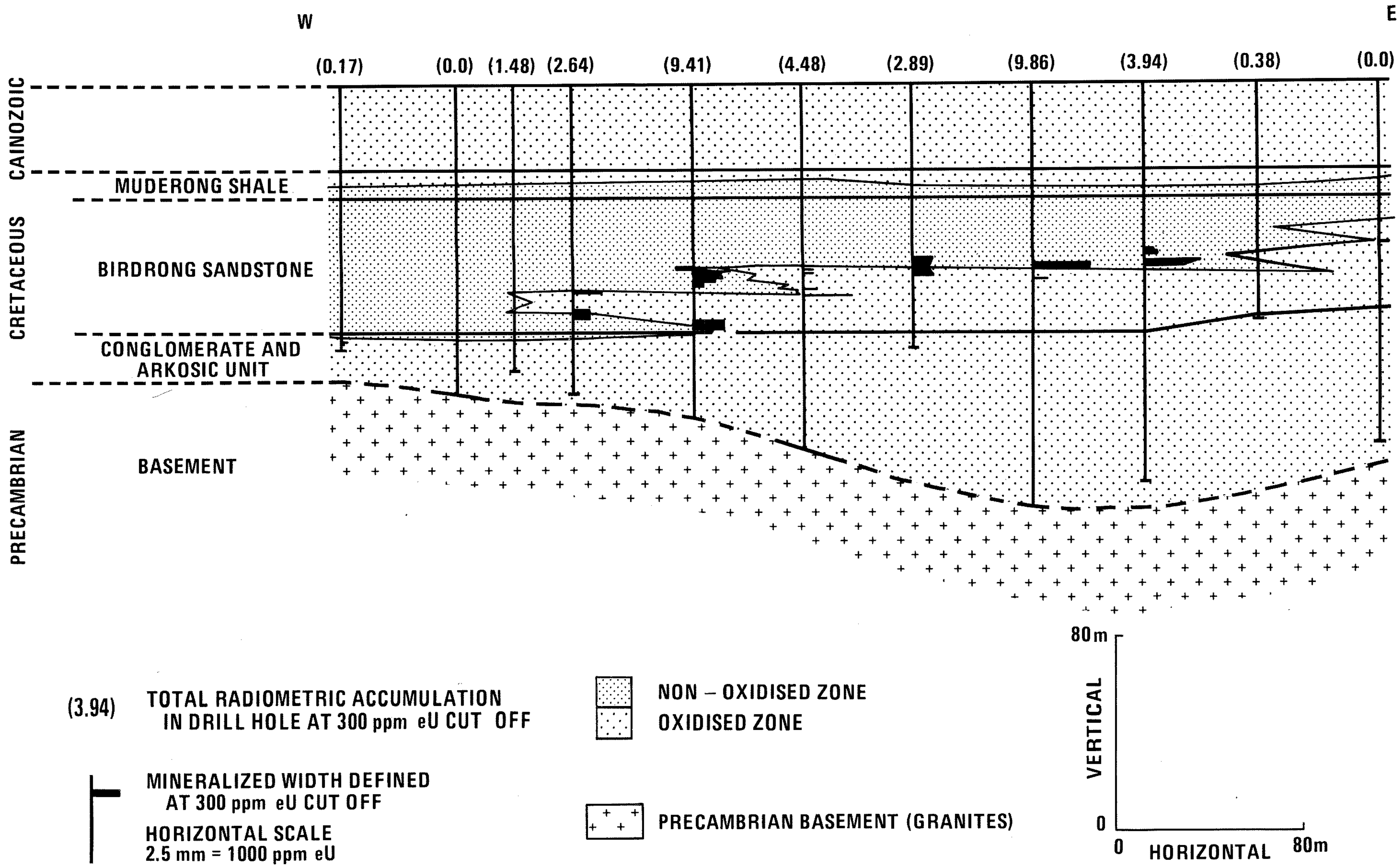

FIGURE 10 : EAST–WEST CROSS SECTION THROUGH MANYINGEE 1 MINERALIZATION

(AFTER VALSARDIEU et al 1981)

GSWA 21309

granitoids which outcrop just southeast of the mineralization.

The Manyingee mineralization is, at present, the subject of studies with a view to future solution-mining of the deposit.

Fairly extensive exploration, completed in the Cretaceous sequence in the northern part of the Basin, has resulted in the discovery of numerous palaeochannels, and several occurrences of mineralization associated with redox fronts. Much of the detail of this mineralization remains confidential, however, the locations of several of the more significant uranium occurrences are shown in simplified form on Plate 1 and details of Mines Department open-file reports describing exploration for roll-front deposits are summarized in Appendix 3.

Peneconcordant deposits

While these deposits are, in many ways, similar to roll-front deposits, they show several very important differences. The deposits form flat-lying or gently dipping bodies which are essentially parallel to the enclosing strata. In plan they are usually amoeboid or lenticular-oblong in shape. The mineralization occurs in sandstones or sandy siltstones which have been deposited in fluviatile, deltaic, or lagoonal environments. Evidence available suggests that they are of very early epigenetic origin, the mineralization being introduced as uranyl, in either oxygenated or weakly reduced groundwater, into areas which were strongly reducing with high H_2S accumulations. These usually appear to be derived from accumulations of plant 'trash' or from bogs or swamps incorporated in the sedimentary sequence. There is thus a frequent association with lignite or coal-bearing horizons.

A number of the World's most economically important uranium deposits are of this type, including the deposits of the Agades Region of Niger and many of the deposits of the Colorado Plateau of the United States.

An examination of exploration reported to the Mines Department suggests that there have not been any exploration programmes mounted specifically to look for this type of mineralization within the Carnarvon Basin. It is considered, however, that there is considerable potential for mineralization to be developed in a number of sequences, particularly in the Permian succession.

One major exploration programme for roll-front mineralization which was carried out in the Pells Range area in the Permian Moogooloo Sandstone, appears to have intersected mineralization akin to the peneconcordant type and is considered to indicate considerable potential within the Moogooloo Sandstone. This exploration is described in Mines Department open-file item 1179 and details, together with results of other exploration programmes in the Moogooloo Sandstone, are summarized in Appendix 3.

Tectono-lithologic or structural-stack deposits

Deposits of this type form, through epigenetic redox processes, by the percolation of uraniferous groundwaters along permeable fault zones. Mineralization, consisting largely of pitchblende, uraninite and coffinite, is deposited both in the fault zone and in linguiform impregnations into adjacent clastic (reduced) sediments. A number of important deposits of this type are mined around the World, including those of the Franceville Basin of Gabon, and several deposits in New Mexico, USA. One exploration programme for this type of deposit in the Carnarvon Basin has been reported to the Mines Department. This programme, which was unsuccessful possibly because the area explored was situated too far west of the basement 'source area' is described in Mines Department open-file item 806. It is considered that there may be considerable potential for mineralization of this type associated with major faults along the eastern margin of the Merlinleigh Sub-basin and northern margin of the Byro Sub-basin, especially where these faults cut both the basement granitoids and Palaeozoic fluvial or deltaic sand sequences. Sequences with particular potential are the Devonian Munabia and Willaraddie Formation, the Carboniferous Williambury Formation and Harris Sandstone, and several sandy sequences in the Permian, especially the Moogooloo Sandstone and sandy sequences of the Byro Group. There may also be potential for mineralization where faults cut the Devonian Gneudna Formation and Carboniferous Moogooree Limestones.

Other styles of uranium mineralization

Adler (1974) described an unusual style of uranium mineralization, from an interbedded sandstone and limestone sequence at Grants in New Mexico, in which ore occurs where limestone is locally deformed and intensively fractured by intraformational folding. The limestone, which is fetid,was presumably rich in H_2S which acted as a reductant to uranyl-rich groundwaters transported in an underlying sandstone sequence. Minable uranium accumulations occur both in the limestone and the adjacent sandstone. A very similar geological situation is present within the Carnarvon Basin, both in the Devonian Gneudna Formation and in the Carboniferous Moogooree Limestone. Minor occurrences of uranium minerals have been reported from the Gneudna Formation from two localities, one of which is described in Mines Department open-file item 864.

Although both of these occurrences appear to be related to the recent circulation of near-surface uraniferous groundwaters, and to be of limited extent, they suggest that conditions suitable for the formation of uranium mineralization are present in the limestone, which may warrant further exploration.

Dahlkamp (1978) suggested that large-tonnage, low-grade deposits associated with black shale and phosphorite sequences could be a possible future source of uranium (although, given present market and price trends this seems unlikely for a considerable period of time). Rock units which may potentially host such deposits are present in the Carnarvon Basin, notably in the Lyons and Byro Groups in the Merlinleigh Sub-basin, and the Byro Group of the Byro Sub-basin. One minor occurrence of carnotite and tyuyamunite in siltstones and claystones of the Lyons Group (Harris Sandstone) has been reported in Mines Department open-file item 11.

A number of calcrete occurrences are present within drainages on the eastern margin of the Carnarvon Basin. As discussed above this area is west of the Meckering Line and rejuvenation of the drainages has resulted in the better developed bodies being actively eroded into a series of terraces. Consequently it is considered unlikely that significant tonnages of mineralization are preserved in these 'fossil' calcretes. More recent and currently forming calcretes, where they are present, appear to form only a sporadic, thin veneer.

One occurrence of uranium mineralization in calcrete has been located within the confines of the Carnarvon Basin; at Quail Springs, west of Lyndon Station. This occurrence is described in open-file item 366. Minor carnotite was found to occur, spottily, in a thin veneer of calcrete developed over a highly uraniferous granite.

The locations of these various occurrences is shown on Plate 1 and details of the exploration programmes are summarized in Appendix 3.

RECOMMENDATIONS FOR FURTHER EXPLORATION

A number of general and specific targets recognized during the preparation of this review are considered to warrant further exploration for uranium. These are discussed below.

Cretaceous sands

While the main area of the Cretaceous sediments on the margin of the northern part of the basin has been, and is being, intensively explored, it is considered that a number of areas warrant further testing.

Exploration described in Mines Department open-file item 863 has shown that palaeochannels infilled by probable fluvio-deltaic sands, are developed to the east of Mount Forrest (south of Barradale Roadhouse), on the margin of the basin. These channels, together with a redox front, may extend into the area covered by former Temporary Reserves 6795H and 6796H, where they have not been tested. As these channels drain an area of highly uraniferous Proterozoic granite, they are considered to warrant drill testing.

Hocking and others (1983) showed that Cretaceous sands, assigned to the Birdrong Sandstone and Nanutarra Formation, are present in the area northwest of Williambury homestead. There is a good possibility that Cretaceous palaeochannels are developed in this poorly exposed area. Exploration to the northwest (item 863) has shown that the groundwater in the overlying Quaternary sediments is highly uraniferous. If this oxidizing groundwater comes in contact with these buried palaeochannels there is an excellent possibility that redox related uranium mineralization may have formed.

Away from the margins of the basin, drilling completed in a number of petroleum exploration wells, and, more recently in exploration for kimberlite, together with interpretation of geophysical data, has shown the presence of Proterozoic granitoids, beneath Cretaceous cover, in parts of the Wandagee Ridge. The areas in which these are believed to occur has been shown on Plate 1. In Yanrey 1 Windalia Radiolarite rests directly on this basement granite suggesting that it formed an exposed positive feature during the deposition of the Birdrong Sandstone. If this is the case, fluvial and/or deltaic channel-fill sands derived from it could have potential for roll-front or peneconcordant uranium mineralization. The presence of interbedded lignite and glauconitic sands in East Marrilla 1 and the presence of pyritized fossil wood, in a Cretaceous greywacke, in a bore hole just west of Mia Mia Station, suggest that suitable sand facies may be developed.

Permian sand sequences

As discussed previously, several of the Permian sand sequences, especially those of the Wooramel Group, are considered to be particularly prospective targets for uranium exploration.

The Billidee and Keogh Formations in the northern part of the Byro Sub-basin contain extensive wood fragments and coaly horizons and could be prospective for peneconcordant uranium mineralization, although they are probably south of the best source area. The Moogooloo Sandstone has been shown to be prospective in the Pells Range area (item 1179) and certainly warrants further exploration. In the Pells Range area peneconcordant mineralization appears to have formed in a deltaic environment. To the east in the Congo and Bush Creek Synclines, closer to the basement source area, a predominantly fluviatile facies of the Moogooloo Sandstone is present which could be prospective for roll-front or peneconcordant mineralization. Reports received by the Mines Department suggest that only scanty exploration has been carried out in this section. Further north, in the section between the Pells Range and Lyons River Station, exploration described in Mines Department open-file item 805 suggests that a less prospective intertidal facies of the Moogooloo Sandstone is present. Still further north there is again a development of fluvial and limited deltaic conditions, and the sequence appears to warrant further exploration. Areas close to the more uraniferous granite occurrences in the basement, such as along the east side of the Weedarra Ridge, may be most prospective.

Carboniferous sandstones

There does not appear to have been any specific exploration for uranium aimed at the Carboniferous sequence, although parts of the succession have been covered by regional airborne radiometric surveys. The Harris Sandstone, the basal unit of the Lyons Group, contains extensive lycopod plant remains and was deposited under fluvial and, in part, glacial outwash conditions. The sequence could be prospective for redox-related uranium mineralization, although it formed under relatively cold conditions with less potential for oxidation in the source area.

The Williambury Formation, shows some evidence of oxidation in outcrop. The unit was deposited as an alluvial-fan complex, and in part of its outcrop, is in direct contact with anomalously uraniferous basement granitoids. As much of the unit is poorly exposed or obscured by laterite, airborne radiometry would probably have been ineffective and it is thus considered to represent a prospective exploration target. Channelling is present and locally exposed claystones with plant rootlets may represent inter-lobe swamp deposits. These could represent prospective host rocks for peneconcordant mineralization of the Niger type.

Devonian sands

The Munabia Sandstone and Willaraddie Formation sequence were interpreted by Moors (1981) as an alluvial-fan/fluvial-plain depositional sequence. This sequence, which was shed largely from tectonically uplifted basement granites (probably under oxidizing conditions) must be considered to be prospective for uranium. Limited exploration completed southeast of Williambury homestead is described in Mines Department open-file item 11, but there does not appear to have been any systematic exploration of the sequence.

Devonian and Carboniferous carbonates

The potential for the development of mineralization similar to the Grants (New Mexico) type has been discussed above. The Devonian and Carboniferous carbonate sequences remain, essentially, unexplored for uranium of this type. The presently outcropping rocks of these units have probably been situated close to exposed granitic basement rocks through much of their geological history and thus are considered to warrant further exploration for uranium mineralization.

EXPLORATION METHODS

The study of very extensive company exploration data has provided an excellent opportunity to study the effectiveness of various exploration methods used in the Carnarvon Basin, and the following comments may be pertinent.

Airborne radiometric surveys

These have been largely ineffective as the majority of mineralized occurrences in the Phanerozoic rocks are masked by non-mineralized cover rocks. Most anomalies detected by airborne surveys are related to basement granitic rocks.

Ground radiometric surveys

Similar comments apply as to airborne surveys although in a number of cases small, sub-economic ocurrences have been located during ground traversing. Because of the broader line spacing, these were not detected by airborne surveys. (e.g. item number 11).

Radon surveys

Surveys for radon released as a daughter element by the radioactive decay of uranium have been carried out as part of several exploration programmes using either alphameters or 'track etch' cups. The surveys were carried out over Cretaceous and Permian rocks and were largely unsuccessful. In the Cretaceous rocks the Muderong Shale caps the occurrences of mineralization, and largely seals the passage of the radon. Surveys carried out over Permian rocks may have been more successful. An orientation survey using alphameters described in Mines Department open-file item 1179, returned anomalous alpha-radiation counts, albeit not with a direct relationship to underlying mineralization. Radon surveys would probably be particularly suited to exploration for structural-stack deposits related to fault lines.

Similar constraints will probably apply to helium surveys, a number of which are currently being carried out experimentally by the CSIRO, in conjunction with various exploration companies.

Hydrogeochemistry

Most of the exploration programmes carried out to date have included sampling and analysis of groundwater from bores, wells and springs for uranium, acidity, etc. uranium concentrations in groundwater; either related to 'fossil' deposits, presently forming roll fronts; or in waters being currently derived from granitic basement rocks. Although many areas have been intensively sampled it appears, from data reported to the Mines Department, that little or no hydrogeochemical sampling has been carried out in the area between Lyons River and Williambury homesteads (an area containing several potentially prospective units) or in the Congo and Bush Creek Synclines where potentially prospective facies of the Moogooloo Sandstone are present.

Gravity surveys

Several companies have carried out detailed gravity surveys as part of their exploration programmes over the Cretaceous and Permian sand sequences. In many cases these have been highly successful in aiding the recognition of palaeochannels and the siting of exploration drilling.

Drilling

Stratigraphic and anomaly drilling, using rotary-mud techniques, or various reverse circulation methods is ultimately the most effective exploration approach. The most successful exploration programmes have been those which have combined hydrogeochemical surveys, gravity surveys, geological mapping, and systematic stratigraphic drilling to locate palaeochanels and redox fronts. Diamond core drilling has generally been restricted to the later stages of exploration once mineralization has been located and specific information is required from drill core.

Downhole logging

Downhole geophysical logging, using techniques such as natural gamma, SP and resistivity surveying, has generally been carried out in conjunction with drilling programmes and appears to enhance considerably the effectiveness of such programmes. One particular problem, which has become apparent from a number of programmes, is the occurrence of disequilibrium phenomena in a number of the younger deposits in the Cretaceous sequence which can lead to spurious results in gamma logging. Particular care is needed in interpreting estimated uranium assays from such logs and only limited reliance can be placed on such 'assays' which should be regularly checked by laboratory determinations.

HEAVY MINERAL SANDS

PROVENANCE AND THEORETICAL CONSIDERATIONS

The effects of variations in provenance on the composition and, thus, economic potential of heavy-mineral suites was discussed by McPherson and Fander (1976). They pointed out that the 'ultimate source' of the majority of heavy minerals are the igneous and metamorphic rocks of the ancient shield areas, variations in the geology of which may result in considerable changes in the derived heavy-mineral assemblage.

In the case of the Carnarvon Basin the provenance in the south (i.e. the granites and greenstone belts of the Yilgarn Block, and the gneisses and pegmatites of the southern part of the Gascoyne Province) might be expected to yield a mineral suite dominated by ilmenite, derived from the basic igneous and metamorphic rocks, but with a high proportion of zircon, derived from granites, and rutile, derived from basic igneous rocks, 'reworked granites' and pegmatites. In the central part of the basin the influence of the rocks of the Morrissey Metamorphic Belt on the provenance might be expected to dilute the value of the heavy mineral suite by providing differing quantities of 'light' heavy minerals of metamorphic origin, such as garnet, kyanite, staurolite and epidote. The provenance of the sediments in the northern part of the Carnarvon Basin is mainly the magnetite-rich rocks of the Hamersley Basin and the intrusive complexes of the western part of the Pilbara Block. This being the case, it is considered probable that the heavy-mineral suite would be swamped by large quantities of magnetite and titano-magnetite.

An examination of the data from the limited number of exploration programmes for mineral sands completed to date suggests that the results reported fit in well with this broad, theoretical prediction. It is therefore considered that areas with the most favourable potential mineralogy are those in the south, in the drainages of the Murchison and Wooramel Rivers, and, to a lesser extent, those in the central part of the basin drained by the Gascoyne, Minilya and Wooramel Rivers.

One exception to these broad zonations is to be found in the southernmost part of the coastal section of the basin, south of the Murchison River. In this section a high proportion of garnet, derived from the Northampton Block, has been incorporated in the heavy-mineral suite. In the vicinity of the Hutt Lagoon, near Port Gregory, the garnet is in sufficient quantity and quality to be of economic interest. This occurrence is further discussed below in the section on industrial minerals.

A significant factor in the formation of heavy-mineral deposits is the pre-concentration of the minerals in sedimentary sequences (McPherson and Fander, 1976). Weathering and erosion of the sediments, especially under lateritic regimes, can release, relatively rapidly, significant quantities of minerals for concentration into economic deposits. This means that shorelines which back onto major sedimentary basins are particularly favourable for the formation of mineral-sand deposits.

The sand fraction of the sediment load of river systems mainly reaches the ocean in times of flood. It follows therefore that rivers such as those in the Carnarvon Basin with a significant flood regime associated with cyclonic storms are especially favourable for the formation of mineral-sand deposits. Marine concentration processes also appear to operate most effectively during such storms which are probably a significant factor in the development of economic heavy-mineral deposits.

Upon reaching the ocean the sand fraction of the sediment load remains in the surf zone. It is transported from there by longshore currents. A particular feature of much of the coastal Cainozoic sequence of the Carnarvon Basin has been the dominance of carbonate sedimentary processes. It is apparent that potential mineral-sands deposits can only form where the supply of siliclastic material substantially exceeds the supply of carbonate from these processes. This situation is found adjacent to present or ancient river mouths, in the direction of the prevailing longshore drift, or where a sandstone unit is being eroded locally. In much of the basin the prevailing direction of longshore drift is from south to north, as shown, for example by the dune sequences developed north of the Gascoyne delta, but it appears that at least locally, in the area northeast of Exmouth Gulf, there may be a southerly drift.

Dunes form as the result of prevailing onshore winds, and, where there is significant pre-concentration in the beach environment, they may be the repository of significant low-grade mineral deposits. The prevailing westerly winds in the Carnarvon Basin have led to the formation of major systems of sand dunes and beach ridges associated with the Gascoyne, Ashburton, Robe and Cane Rivers.

POTENTIAL HOST SAND SEQUENCES

Eustatic changes of sea level during Pleistocene to Holecene times, in response to glacial and interglacial periods, have resulted in the formation of raised shorelines in a number of places within the basin. Van de Graaff and others (1976) and Denman and van de Graaff (1977) have described Pleistocene marine terraces in the Cape Range and Lake Macleod areas. The sediments of these terraces, the Exmouth Sandstone and Bundera Calcarenite, include both shoreline and dune deposits.

Van de Graaff and others (1980, 1982) and Hocking and others (1983) have shown that this sequence extends north to the Onslow and Long Island areas, and south at least as far as Lake Macleod. In the north and in the Cape Range area conglomeratic sequences contain clasts of banded iron-formation suggesting that the source of the terriginous material was from the Ashburton and Robe Rivers and thus from an unfavourable provenance area. South of the Cape Range, however, material was probably supplied by the ancestral Lyndon and Minilya Rivers. These areas do not appear to have been explored but probably warrent prospecting in view of the more favourable provenance.

Johnson (1974) described possible Pleistocene sand ridges (the Bejaling and Brown Beach ridges) associated with an ancient delta of the Gascoyne River.

Logan and others (1976) summarized Pleistocene sedimentation in the Shark Bay area. Here the main sand unit, the Peron Sandstone is a predominantly dunal sand, possibly derived from sand from the ancestral Wooramel River and from a former more southerly outlet of the Gascoyne River.

Southwards from Shark Bay the morphology of the coastline changes dramatically with the development of the prominant Zuytdorp Cliffs. These together with the major incision of the Murchison River upstream of Kalbarri suggest a relatively recent uplift of the southern part of the Carnarvon Basin. This was probably caused by a fault just offshore and parallel to the Zuytdorp Cliffs. North of the Murchison River in this uplifted area, a number of features indicative of fossil shorelines were described by Inco in Mines Department open-file item 477. Although no evidence has been found of their absolute age they appear, at least in part, to predate the formation of the Murchison gorges, and are considered to be probably Pleistocene.

Tertiary sediments although they are generally more indurated, contain a number of possible shoreline sand sequences and may warrant consideration as targets for mineral-sand exploration. The Lower Eocene Merlinleigh Sandstone, which outcrops mainly on the top of the Kennedy Ranges, but extends as far west as Mardathuna homestead and as far north as Moogooloo Hill and the Lyndon River, includes both fluviatile and marine sands (Hocking and others, 1983) and parts of the succession were probably deposited under shoreline conditions. In the Cape Range Group the Middle Miocene Lamont Sandstone and Pilgramunna Formation are probably shoreline deposits while the Miocene Vlaming Sandstone appears to be a predominantly shoreline/dune deposit (van de Graaff and others, 1980). These sequences, which may have received their terrigenous input from an ancestral Lyndon River, could warrant further evaluation for mineral-sand potential. They are generally well indurated and commonly strongly silicified.

PREVIOUS EXPLORATION

Most exploration for mineral sands completed to date appears to have been concerned with sequences of recent origin. Only one operator has concentrated on searching for raised shorelines.

Ashburton Sands Pty Ltd and Ferrovanadium Corporation NL carried out exploration, from 1967-72, in coastal dune sequences associated with the mouth of the Ashburton River. This exploration, described in open-file item 1515, consisted of mapping, magnetic and resistivity surveys and auger drilling. Two lines of dunes were tested. The first, behind the present tidal beach, contains in excess of 15% heavy minerals (H.M.) over a length of 11 km and a width of 300 m. The base of this deposit is 1 m or less above high tide.

A second, older deposit, occurs in a partly eroded dune series some 2 km inland from the present coast, with the base of the mineralization being some 3 m above present sea level. Mineralization, grading between 8 and 11% H.M. has been traced over a total length of 24.3 km. These deposits, collectively known as the Onslow prospect, reportedly contain a total of 5.84 Mt of contained H.M., at an average grade of 10.4% H.M. using a cut-off grade of 5% H.M. Unfortunately between 60% and 70% of the heavy minerals are iron oxides (mainly hematite, martite, and goethite) and the presence of a high proportion of iron-stained quartz precludes the preparation of an iron-ore product. Further details of these deposits were given by Baxter (1977).

Robertson Research, working for Bamboo Creek Gold Mines NL, supervised reconnaissance exploration of the coastal sequences near the Robe and Fortescue Rivers. Although considerable quantities of heavy minerals were present, sampling showed that they were between 35% and 85% iron oxides with the remainder comprising mainly ilmenite and ferromagnesian minerals, with very minor zircon and garnet.

At the mouth of the Cane River on Yardie Creek Station (Onslow and Yarraloola 1:250 000 sheets), Vam Ltd completed a programme of prospecting and auger drilling between 1968 and 1971. Reserves of 22.5 million cubic metres, at 4.7% contained H.M., were reported. Once again the heavy-mineral suite was dominated by magnetite, goethite and martite. This exploration is described in Mines Department open-file item 1007.

Reconaissance exploration was also carried out in this northern coastal strip by Coastal Titanium Pty Ltd but the area was down-graded because of the high proportion of iron oxides.

A number of companies carried out exploration for mineral sands on the Peron Peninsula in the Shark Bay area. Deposits here occur on presently forming beaches and in the mobile foredunes behind them. The deposits appear, in part, to be derived from the re-working of the Peron Sandstone and in part to originate from the Wooramel River. A strong, local southwesterly tidal rip transports sediment from this river and concentrates the heavy minerals which are gradually transported shorewards by wave action. Local concentrations of up to 80% contained H.M. have been reported. Post-holing by Coastal Titanium* defined 26 700 tonnes of contained H.M. in ore grading 8.9% H.M. with an inferred potential for an additional 80 000 tonnes of contained H.M. The concentrate contained 25-60% ilmenite, 4-11% leucoxene, 20% zircon, 0.5% rutile and 13% garnet, with the remainder being mainly iron oxides. From 1979-1980 Allied Eneabba Ltd* carried out a programme of vacuum drilling concentrating on the dune deposits. Only minor concentrations were located, to a maximum of 2% H.M., forming a thin veneer over topographic features. It was concluded that there was no economic potential. The area is currently subject to exploration by Southern Goldfields Ltd.

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* Report currently being processed for Mines Department "M" series open-file system.

As discussed above, one programme designed to search for raised shorelines in the area north of the Murchison River, was carried out in 1976 and 1977 by Inco. This work is described in Mines Department open-file item 477. Exploration was initiated following the recognition, (on air photos and poor quality early-generation Landstat imagery) of the course of a possible 'proto-Murchison River', with a mouth in the area southwest of the Billabong Roadhouse. Work completed included photo-mapping, airborne radiometric and magnetic surveys, and auger drilling. A Quaternary sand plain was located in which possible coastal notches were identified at 125 m 145 m, 160 m, 168 m, and 175 m above sea level. Only a low heavy-mineral content (up to 2%) was present although this had a favourable mineralogy including 40-42% ilmenite, 4-5% leucoxene, 10-11% rutile, 26-27% zircon, 1-1.5% monazite and 4-5% kyanite.

POTENTIAL FOR FURTHER EXPLORATION

As discussed above, because of the variations in the provenance of the source rocks, it is considered that potential for economic mineralization is restricted to the central and southern parts of the basin.

One area which appears to have been largely neglected by previous explorers is the Recent (Bejaling) and Pleistocene (Brown) beach ridges associated with the mouth of the Gascoyne River, near Carnarvon, and extending for 45 km north of the town. Sampling of mineral slicks on present beaches near Carnarvon by Coastal Titanium returned a mineral concentrate containing 43% ilmenite, 13% zircon, 2% rutile and 1% monazite with the remainder being mainly iron oxides and garnet. A similar mineralogy was obtained from samples collected from the beach ridges, by the writer, although silicate 'light heavies' rather than iron oxides formed the 'gangue' component. In view of the very large untested sequence and the relatively favourable infrastructure further evaluation and drilling of this sequence is considered to be justified.

The Peron Sandstone has itself not been explored for mineral sands, but in the Cape Peron area north of Denham it appears to be in part the immediate source for mineralization developed on recent beaches and dunes. Sampling of the Peron Sandstone here gave assays up to 0.5% H.M. In view of the favourable mineralogy in the recent strandlines, exploration of the older eolian deposits contained in the Peron Sandstone appears justified. Much of this unit is unconsolidated.

The favourable mineralogy found in concentrates north of the Murchison River makes this area particularly interesting. An examination of recently generated computer-enhanced false-colour Landsat images indicates that there may be a number of ancient courses of the Murchison River draining into this area, together with a number of features which could represent former shorelines. An area to the southwest of the Billabong Roadhouse is considered to be of particular interest. Although apparent 'desert'-type dunes are present it is possible that these could be obscuring (or reworking?) Pleistocene coastal sequences deposited in the vicinity of the ancient river mouths. The location of the former river courses and areas of potential interest have been included on Plate 1.

As discussed above, lower priority exploration targets could be present in Pleistocene and Tertiary sand sequences deposited close to the ancestral Lyndon and Minilya Rivers. Unfortunately many of these sequences are largely indurated or silicified.

INDUSTRIAL MINERALS

EVAPORITES

The most significant mining project currently in operation in the Carnarvon Basin is that owned by Dampier Salt Ltd (CRA) at Lake Macleod on Special Agreement Area ML 245 S.A. The operation was initially proposed to produce langbeinite- $K_2Mg_2(SO_4)_3$ -from potash-rich lake brines, and a 200 000 tonnes per annum potassium-sulphate plant was installed. Production from this plant has been restricted, due to economic factors, and the main product has been solar salt, this being part of the World's second largest solar-salt operation.

Annual production, normally between 1.1 and 1.6 million tonnes is shipped from a jetty at Cape Cuvier. Production for 1982 was 681,567 tonnes.

The Lake Macleod basin includes an evaporite sequence at least 12 m thick, containing salt, gypsum and sylvite. Salt production is from evaporating pans which are filled by pumping from ditches which tap seepages of near-saturated brines from a thick halite bed.

Shark Bay Salt Pty Ltd operates a solar-salt plant at Useless Loop on the Freycinet Estuary at Shark Bay. Sea water is concentrated in a system of evaporation and crystallizer ponds which are lined by plastic sheeting. Production for 1982 was 526 734 tonnes.

Evaporites are present within the Silurian sequence, in the Yaringa Evaporite Member of the Dirk Hartog Formation, and in the Sweeney Mia Formation. The latter was previously referred to as Unknown Formation Unit A by Henderson and Shannon (1966). Anhydrite was first found in a Wapet deep test-bore, Dirk Hartog 17B in 1957, while halite was discovered in Yaringa 1, drilled by

Continental Oil Company. This discovery prompted the drilling of two holes, Hamelin Pool 1 and 2, specifically to test the potential of the evaporites. These were drilled under a farm-out agreement between Magellan Petroleum Pty Ltd, Continental Oil Co., and Australia Sun Oil Co. Ltd.

Details of these programmes are given in BMR Bulletin 198 (Wells, 1980). Yaringa 1 intersected 36.2 m of halite in eight beds; Hamelin Pool 1 drilled 22.9 m of salt in seven beds; while Hamelin Pool 2 intersected 5.2 m of salt in 3 beds. Sylvite is present in small amounts in the salt beds of Yaringa 1 suggesting some potential for economic potash mineralization. The marked thinning in Hamelin Pool 2 has been taken as indicating that this is near the margin of the basin (Wells, 1980), but at the depth at which they were intersected (greater than 1000 m) variations in thickness could result from plastic flowage of the halite.

Simple geometry suggests that the Yaringa Evaporite Member should occur closer to the surface in the area north of Kalbarri 1 well and thus be a potential target for potash exploration (Fig. 6). A recent study of the hydrogeology of the basin (Allen, pers. comm.) has shown zones of greatly increased salinity, in this general area, in both the confined (Birdrong Sandstone) and unconfined groundwater. Allen has suggested that these may result from evaporites in the (Silurian) basement rocks.

A second evaporite-carbonate suite, the Sweeney Mia Formation (Hocking and Moors, in prep.) is present in the upper part of the Yaringa and Hamelin Pool wells. Although no halite was intersected, extensive beds of anhydrite or gypsum interbedded with dolomite, are present, from 174 m to 230 m in Yaringa 1, 241 m to 262 m in Hamelin Pool 1, and 235 m and 268 m in Hamelin Pool 2. These suggest that evaporite minerals of potential economic interest could occur elsewhere within the basin.

The Sweeney Mia Formation probably sub-crops at a shallow depth beneath a thin cover of Cainozoic and Cretaceous sediments in the area south of Shark Bay (Fig. 6).

Gypsum is another evaporite mineral of considerable economic significance within the Carnarvon Basin. A major mining project is operated by Agnew Clough Limited in an area 6 km south of Useless Loop. In this area a number of isolated bedded deposits of gypsum have formed as a result of the evaporation of sea water in minor barred basins at the heads of relic inlets. Production from the Shark Bay project is exported entirely and is sold mainly to Japan and S.E. Asia. A specification of 95% minimum $Ca\ SO_4.2H_2O$ is achieved by allowing the mined material to drain in stockpile and by crushing, screening and washing, to reduce the level of $CaCO_3$. Production reported to the Mines Department since 1974 is as follows.

TABLE 4. GYPSUM PRODUCTION FROM SHARK BAY

Year	Tonnes
1974	74 609
1975	49 293
1976	40 220
1977	25 281
1978	86 077
1979	165 960
1980	207 112
1981	267 034
1982	311 941
Total	1 227 527

A number of very significant deposits of gypsum are present in the Lake Macleod basin, where drilling completed by Texada Mines Pty Ltd, during the initial investigation of the evaporite deposits, revealed thick beds of gypsum below the lake surface. Difficulty of extraction makes these reserves uneconomic at present. The area of potential interest is largely covered by Dampier Salt (Operations) Pty Ltd's Special Agreement Area (M.L. 245 S.A.).

Extensive reserves are also present in a flat basin extending for some 15 km north of Lake Macleod, in the vicinity of the mouth of the Lyndon River. These were designated as Qg on the Winning Pool-Minilya 1:250 000 map sheet, where they are exposed or very close to the surface (Hocking and others, 1983).

In 1971, Great Boulder Gold Mines Ltd (now part of W.M.C.) announced that deposits estimated to contain 100 000 000 tons of gypsum at a grade in excess of 90% $CaSO_4.2H_2O$ had been located in the basin north of Lake Macleod. The bulk of these deposits are covered by mineral tenements and are being evaluated by a number of exploration groups.

Further deposits of gypsum both in bedded and 'seed' or 'kopai' form are present to the east of Lake Macleod just north of the boundary between Boolathana and Boologooro pastoral leases. These were evaluated by the Geological Survey and were described by Connolly (1960). Reserves were conservatively estimated to contain approximately 9.5 million tons of bedded gypsum of variable grade (aproximately 82% to >97% $CaSO_42H_2O$).

Although many of the deposits in the vicinity of Lake Macleod are currently held under mineral tenements a number of areas of bedded gypsum located during the regional mapping programme appear to be open and may warrant further evaluation, especially those in the vicinity of the mouth of the Lyndon River.

BENTONITE

As has been discussed previously, bentonitic sequences are present in the Cretaceous Winning Group in both the Muderong Shale and Gearle Siltstone sequences. The Gearle Siltstone sequence in the Giralia Anticline was investigated by Garrick Agnew Pty Ltd in 1963-66 as a source of bentonite for use in processing Robe River iron ore. This work, described in open-file item 56, consisted mainly of reconaissance mapping and surface sampling. The clay was found to consist of saponite mixed with kaolinite and illite. Potential reserves were estimated to be about 300 Mt. The following table gives a representative analysis of various oxide components of the bentonite.

Oxide	%
SiO_2	53.5
Al_2O_3	17.7
Fe_2O_3	8.38
MgO	2.22
CaO	0.18
Na_2O	1.53
K_2O	1.29
TiO_2	0.67

BARITE

Barite, in the form of large septarian nodules, is present over much of the outcrop area of the Gearle Siltstone in the Giralia Anticline. Mapping and reverse-circulation drilling completed during an exploration programme for base metals completed by Inco and reported in Mines Department open-file item 1571, showed that these are the surface expression of stratiform, bedded deposits, up to 40 cm thick, apparently deposited in a series of local basins. Although the deposits are mostly friable and low grade, very extensive tonnages are present and could be of potential interest in view of the proximity of the North West Shelf drilling operations.

Mention has previously been made of veins carrying barite, with minor galena and sphalerite, occurring in both the basement gneiss and overlying Lyons Group sediments in a basement inlier, approximately 10 km south of Mount Sandiman homestead. The veins appear to be localized over structural highs in the basement. A number of the veins have been opened up by shallow prospect pits, however several do not appear to have been systematically sampled.

GARNET

A significant deposit of garnet sands is situated near Port Gregory in the south of the Carnarvon Basin. The deposit, on the 'Lynton Claims' is being mined by Target Minerals NL in one of the few mines in the World in which garnet is the main commercial product.

The deposit is situated on a probable Late Pleistocene shore line on the northeast side of the Hutt Lagoon. It contains an indicated reserve of 6.1 million tonnes contained H.M. at an average grade of 22.8% H.M. Garnet represents 83% of the H.M. content. Within the mine development-area a zone containing prime 'clean' coarse sand averaging 42% H.M. has been delineated. The sand is mined by scrapers, dozers and front-end loaders and is beneficiated by wet gravity-separation on site, and is further processed at Geraldton. The garnet is currently marketed mainly for sand blasting and filtration purposes but Target is currently investigating the possibility of producing a product for high technology applications such as coating, grinding and polishing, and in the electronics industry.

PHOSPHATE

A number of companies have carried out broad regional surveys for phosphate within the Carnarvon Basin, concentrating on the Cretaceous and Permian successions. These programmes are described in Mines Department open-file items 49 (Ocean Mining NL),66 (Electrolytic Zinc Co of Aust), 70 (Cyanamid Australia Pty Ltd) and 71 (IMC Development Corporation). Although a number of drilling programmes were undertaken no significant deposits were discovered.

Thin and discontinuous deposits of phosphate as nodules and phosphatized wood occur in the Cretaceous Alinga Greensand and Toolonga Calcilutite on the Ajana 1:250 000 sheet. Thin phosphatic beds are also present in the Miria Marl and Boongerooda Greensand sequences. These occurrences are apparently of no economic significance. A number of siltstone sequences in the Permian Byro Group contain phosphate networks and assays up to 1.25% P_2O_5 have been reported. It is considered that there could be some potential for the development of economic deposits within these sequences, especially within the Bulgadoo Shale and Quinnanie Shale sequences.

FULLERS EARTH

Deposits of attapulgite clay, a variety of fullers earth, of apparently good quality, are being evaluated from the Lake Nerramyne area on the Ajana 1:250 000 sheet.

LIMESTONE

Vast quantities of limestone are present within the basin, both in the Palaeozoic and more especially in Tertiary and Quaternary sequences. Minor local use has been made of the Palaeozoic limestones, especially the Carboniferous Moogooree Limestone and Callytharra Formation, as building stones, while various of the younger sequences have been used in road building.

Tertiary or Quarternary limestones have been investigated for their use as fluxes in a possible Pilbara steel industry.

The limestone of the Cape Range area was investigated by the Broken Hill Proprietary Co. Ltd (BHP) in 1961, 1962, and 1964 (McEwen, 1964). The Lewis, Tomich, Hammond Syndicate, who hold mineral claims near Exmouth, carried out limited testing in 1973-74. The BHP work indicated that much of the Trealla and Tulki Limestones tested are of good quality, and potentially suitable for the manufacture of steel. From BHP analyses, a typical good quality limestone from the Cape Range area contains 0.83 % SiO_2, 54.66% CaO, and 0.23% MgO, whereas a typical sample of poorer quality dolomitic limestone from this area contains 0.75% SiO_2, 34.4% CaO, and 17.2% MgO. Phosphorus content is commonly below 0.02% and no sample tested was above 0.074%. Inferred reserves, in a 1.6 km square block with a mean depth of 30 m above base-creek level, were estimated to be 80 to 90 million tonnes of limestone. Much of the area is presently covered by a Ministerial Reserve created to conserve the limestone for industrial use. Part of the limestone reserves are now within the Cape Range National Park.

Limestones on the Quobba 1:250 000 sheet were found by BHP to have deleterious amounts of silica, precluding their use as a flux. Limited testing of these deposits was also completed by the Hancock and Wright group.

During 1967, Ocean Mining A.G. tested the offshore coral sand deposits between Exmouth Gulf and Cape Preston. Although large deposits of promising grade were discovered off the Onslow coast, the cost of mining them could not compete with other sources and the project was abandoned. A typical analysis of the sand was 47.5% CaO and 87.8% (Ca, Fe, Mg)CO_3. The best quality recorded was 50.5% CaO, 93.6% (Ca, Fe, Mg) CO_3 and 89.9% $CaCO_3$.

REFERENCES

Annels, A.E., 1984, The geotectonic environment of Zambian copper-cobalt mineralization: Geol. Soc. London Jour. 141, p. 279-290.

Adler, H.H., 1974, Concepts of uranium-ore formation in reducing environments in sandstones and other sediments, in Formation of Uranium Ore Deposits: I.A.E.A. Symposium Vienna 1974.

Atkinson, W.J., Hughes, F.E., and Smith, C.B., 1984, A review of kimberlitic rocks of Western Australia Kimberlites. I: Kimberlites and Related Rocks, J. Kornprobst (ed.): Amsterdam, Elsevier, p. 195-224.

Barnes, H.L., and Czamanske, G.K., 1967, Solubilities and transport of ore minerals, in H.L. Barnes, (ed.), Geochemistry of hydrothermal ore deposits, 1st Edn: New York, Holt, Rinehart and Winston, p. 334-381.

Baxter, J.L., 1977, Heavy mineral sand deposits of Western Australia: West. Australia Geol. Survey Mineral Resources Bull. 10.

Butt, C.R.M., Horwitz, R.C., and Mann, A.W., 1977, Uranium occurrences in calcrete and associated sediments in Western Australia: CSIRO Miner. Res. Lab. Aust. Rept FP16.

Button, A., and Tyler, N., 1979, Precambrian palaeoweathering and erosion surfaces in southern Africa: Review of their character and economic significance: Inf. Circ. 135, Econ. Geol. Res. Unit, Univ. of the Witwatersrand, Johannesburg.

Carter, J.D., 1981, Uranium exploration in Western Australia: West. Australia Geol. Survey Rec. 1981/6.

Carpenter, A.B., 1978, Origin and chemical evolution of brines in sedimentary basins: Oklahoma Geol. Survey Circ. 79, p. 60-77.

COMRATE, 1975, Mineral resources and the environment: Washington, Natl. Acad. Sci.

Condon, M.A., 1967, The geology of the Carnarvon Basin, Western Australia: Australia Bur. Mineral Resources Bull. 77, Part 2.

________ 1968, The geology of the Carnarvon Basin, Western Australia: Australia Bur. Mineral Resources Bull. 77, Part 3.

Connolly, R.R., 1960, Report on inspection of Temporary Reserve 1632H and others for gypsum, Boologooro, N.W. Division: West. Australia Geol. Survey Ann. Rept for 1958, p. 23-24.

Dahlkamp, F.J., 1978, A classification of uranium deposits: Mineralium Deposita, v. 13, p. 83-104.

Daniels, J.L., 1975, Gascoyne Province in Geology of Western Australia: West. Australia Geol. Survey Mem. 2, p. 107-114.

Denman, P.D., and van de Graaff, W.J.E., 1977, Emergent Quaternary marine deposits in the Lake Macleod area, W.A.: West. Australia Geol. Survey Ann. Rept 1976, p. 32-37.

________, 1982, Quobba, Western Australia: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

Dietz, R.S., and Holden, J.C., 1970, The breakup of Pangaea: Scientific American, October, 1970.

Evans, P.R., 1981, The petroleum potential of Australia: Journal of Petroleum Geology, 4(2), p. 123-146.

Geary,J.K., 1970, Offshore exploration of the southern Carnarvon Basin: Australia Petroleum Expl. Assoc. Jour. v. 10, pt 2, p. 9-15.

Gee, R.D., 1979, Structure and tectonic style of the Western Australian Shield: Tectonophysics, v. 59, p. 327-369.

Gustafson, L.C., and Williams, N., 1981, Sediment-hosted stratiform deposits of copper, lead, and zinc: Economic Geology 75th Anniversary Volume 1981, p. 139-178.

Haynes, D.W., 1972, Geochemistry of altered basalts and associated copper deposits: Canberra, Australian Nat. Univ. Science Ph.D. thesis (unpublished).

Helgeson, A.C., 1964, Complexing and hydrothermal ore deposition: New York, Pergamon.

Henderson, S.W., and Shannon, P.H., 1966, Yaringa No. 1 well, Western Australia, Stratigraphic drilling project, well completion report: Continental Oil Company (unpublished).

Hocking, R.M., and van de Graff, W.J.E., 1978, Cretaceous stratigraphy and sedimentology, northeastern margin of the Carnarvon Basin, Western Australia: West. Australia Geol. Survey Ann. Rept 1977, p. 36-41.

Hocking, R.M., 1981, The Tumblagooda Sandstone, Western Australia: its type section and sedimentology: West. Australia Geol. Survey Ann. Rept 1980, p. 53-61 .

Hocking, R.M., Williams, S.J., Lavaring, I.H., and Moore, P.S., 1983, Explanatory notes on the Winning Pool-Minilya 1:250 000 Geological Sheet: West. Australia Geol. Survey Rec. 1982/9.

Hocking, R.M., and Moors, H.T., in prep. Geology of the Carnarvon Basin, Western Australia: West. Australia Geol. Survey Bulletin (in prep.).

Jackson, S.A., and Beales, F.W., 1967, An aspect of sedimentary basin evolution - The concentration of Mississippi Valley-type ores during late stages of diagenesis: Bull. Canadian Petroleum Geology, v. 15, no. 4, p. 383-433.

Johnson, D., 1974, Sedimentation in the Gascoyne River delta Western Australia: Univ. West. Australia Science Ph.D. thesis (unpublished).

Johnson, D.P., 1982, Sedimentary facies of an arid zone delta: Gascoyne Delta, Western Australia: Jour. Sed. Petrology, v. 52, 2, p. 547-563.

Kendall, A.C., 1979, Continental and supratidal (sabkha) evaporites, in R.G. Walker (ed.), Facies models: Geoscience Canada Reprint Series 1.

Logan, B.W., Brown, R.G., and Quilty, P.G., 1973, Carbonate sediments of the west coast of Western Australia: International geological congress, 25th., Sydney, 1976. Guide to excursion no. 37H.

Lavaring, I.H., 1979, Palaeocological and palaeogeographic implications of Rhipidomella michelini? (Leveille) in the Carboniferous of the Carnarvon Basin: West. Australia Geol. Survey Ann. Rept 1978, p. 89-92.

McEwen, R.C., 1964, Results of the 1964 testing programme at Cape Range, Western Australia: The Broken Hill Proprietary Co. Ltd. (unpublished).

McPherson, M.A., and Fander, A.W., 1976, Heavy mineral sands: Notes for workshop course: Australian Mineral Foundation Incorporated.

Michael, S.S., and Groves, D.I., 1977, The origin of the Northampton hydrothermal lead-zinc deposits, in Recent geological research relating low-temperature aqueous geochemistry to weathering, ore genesis and exploration, (J.E. Glover and D.I. Groves, eds): West. Australian Univ. Geology Dept and Extension Service, Publ. No. 1.

Moors, H.T., 1980, A formation temperature study of the Carnarvon Basin: West. Australia Geol. Survey Ann. Rept 1979, p. 89-95.

Moors, H.T., 1981, An alluvial fan - fluvial plain depositional model for the Devonian Willaraddie Formation and Munabia Sandstone of the Carnarvon Basin, W.A.: West. Australia Geol. Survey Ann. Rept 1980, p. 114-118.

Moore, P.S., Denman, P.D., and Hocking, R.M., 1980, Sedimentology of the Byro Group (Lower Permian), Carnarvon Basin, Western Australia: West. Australia Geol. Survey Ann. Rept 1979, p. 99-108.

Radke, W.D.G., and Nicoll, R.S., 1981, Evidence for former evaporites in the Carboniferous Moogooree Limestone, Carnarvon Basin, Western Australia: BMR Jour. Australian Geology and Geophysics, v. 6, p. 106-108.

Renfro, A.R., 1974, Genesis of evaporite-associated stratiform metalliferous deposits - a sabkha process: Econ. Geol., v. 69, p. 33-45.

Roberts, F.I., 1982, Trace element chemistry of pyrite: A useful guide to the occurrence of sulphide base-metal mineralization: Journal of Geochemical Exploration, v. 17, p. 49-62.

Rona, R.A., 1973, Plate tectonics and mineral resources: Scientific American, July, 1973.

Rose, A.W., 1976, The effect of cuprous chloride complexes in the origin of red-bed copper and related deposits: Econ. Geol., v. 71, p. 1036-1048.

Stanton, R.L., 1972, Ore petrology: McGraw-Hill, Inc.

Sverjensky, D.A., 1981, The origin of a Mississippi Valley-type deposit in the Viburnum Trend, Southeast Missouri: Econ. Geol., v. 76, no. 7, p. 1848-1872.

Thomas, B.M., and Smith, D.N., 1978, Carnarvon Basin, in Economic geology of Australia and Papua New Guinea-3. Petroleum, R.B. Leslie, H.J. Evans, and C.L. Knight, (eds), Australasian Inst. Mining Metall. Mon. 7, p. 126-155.

Valsardieu, C.A., Harrop, D.W., and Morabito, J., 1981, Discovery of uranium mineralization in the Manyingee Channel, Onslow Region of Western Australia: Australasian Inst. Mining Metall. Proc., No. 279, p. 5-17.

van de Graaff, W.J.E., Denman, P.D., and Hocking, R.M., 1976, Emerged Pleistocene marine terraces on Cape Range, Western Australia: West. Australia Geol. Survey Ann. Rept 1975, p. 106-114.

van de Graaff, W.J.E., Denman, P.D., Hocking, R.M., and Baxter, J.L., 1980, Yanrey - Ningaloo, Western Australia: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

van de Graaff, W.J.E., Denman, P.D., and Hocking, R.M., 1982, Onslow, Western Australia: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

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

Veevers, J.J., and Cotterill, D., 1978, Western margin of Australia: evolution of a rifted system: Geological Soc. Amer. Bull., v. 89, p. 387-355.

Veevers, J.J., and Hansen, L., 1981, Volcanism in the rift-valley system that evolved into the western margin of Australia: Geol. Soc. Australia Jour., v. 28, p. 377-384.

Veevers, J.J., Jones, J.G., and Powell, C. McA., 1982, Tectonic framework of Australia's sedimentary basins: A.P.E.A. Journal, v. 22 (1), p. 283-300.

Wells, A.T., 1980, Evaporites in Australia: Australia Bur. Mineral Resources Bull. 198.

Williams, N. (rapporteur); Cohen, Y., Haack, U., Hallberg, R.O., Kaplan, Isaac R., Nielsen, H., Sangster, D.F., Trudinger, P.A., Truper, H.G., and von Gehlen, K., 1982, Stratified sulphide deposits; state of the art report, in H.D. Holland (ed.) Mineral deposits and the evolution of the biosphere; report of the Dahlem Workshop on biospheric evolution and Precambrian metallurgy: Physical and chemical sciences research reports, Springer-Verlag, Berlin, Federal Republic of Germany, v. 3, p. 275-286.

Williams, S.J., Williams, I.R., Chin, R.J., Muhling, P.C., and Hocking, R.M., 1983a, Mount Phillips, W.A.: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

Williams, S.J., Williams, I.R., and Hocking, R.M., 1983b, Glenburgh W.A.: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

APPENDIX 1

CARNARVON BASIN: BASE-METAL EXPLORATION

GE91NWR388A(1E)

ITEM NO.	ROLL NO.	TENEMENT NO.	MINES DEPT 'M' NO.	MAP SHEET DETAILS	DURATION	COMPANY NAME(S)	SUMMARY DETAILS OF EXPLORATION	SUMMARY RESULTS AND COMMENTS
556	183	Mineral Claims	1641	Winning Pool 6 Kennedy Range 3	1972-1973	Aquitaine Australia Minerals Pty Ltd	Exploration of several properties in Devonian (Gneudna Formation) and Carboniferous (Moogooree Limestone) for Mississippi Valley-type mineralization following discovery of anomalous chip samples in helicopter survey. Williambury: chip sampling and augering. Ebbra: photogeology, gridding, soil and auger sampling, stratigraphic sections. Lyndon: Chip sampling, gridding, auger and soil sampling, percussion drilling (3 holes, 178 metres). Moogooree: Chip sampling, diamond drilling (2 holes, 175.26 metres) then photogeology, augering and percussion drilling (11 holes, 509 metres).	Williambury: Chip samples to 390 ppm Pb. Ebbra: Chip samples to 540 ppm Pb/390 ppm Zn (further exploration in item 561). Lyndon: Chip samples to 300 ppm Pb/3000 ppm Zn, anomalies associated with 'patch reefs'. Moogooree: Chip samples to 1900 ppm Pb/1% Zn. D.D. samples to 2.2% Zn (1.1% Zn/1400 ppm Pb over 1 metre) in porous, oolitic limestone. Further base metal anomalies located by percussion drilling.
561	184	TR 5716H	1216	Winning Pool 6	1973-1975	Aquitaine Australia Minerals Pty Ltd	Partly same ground covered by item 556. Ebbra and Lyndon with additional ground. Photogeology, gridding, soil and auger sampling, IP surveys, petrology, percussion drilling, diamond drilling (3 holes, 539.49 metres).	Soil/auger anomalies to 3200 ppm Pb/275 ppm Zn on Lyndon grid near Ebbra Bore. No significant IP anomalies. Galena crystals in fractured vuggy dololutite in drill core. Petrology suggests 'back reef facies'. Assays in DD1 4000 ppm Pb/219 ppm Zn/4 metres. DD2 6500 ppm Pb/1850 ppm Zn (grab) DD4 3000 ppm Pb/2000 ppm Zn (grab).
1571	483	TR 6842H TR 6843H	2406	Winning Pool 1	1978-1979	International Nickel Australia Limited	Exploration of Cretaceous Winning Group for base-metal mineralization following location of anomalous silver values. Photogeological mapping, chip and stream sampling; auger sampling (111 holes, 1270 metres) air-core reverse-circulation drilling (7 holes, 1062.5 metres). Trial 'Input' survey.	Anomalous silver values from microgossan chips, goethitic nodules and pyrite marcasite nodules, to maximum 352 ppm Ag, with most samples over 30 ppm Ag. Low order zinc stream anomalies. Zinc to 1250 ppm in surface rock chips, to 3%, with sphalerite textures in microgossan chips from water bore. Bedded, stratiform barite to 40 cm in drill core but no significant base metal assays.
*		Mineral Claims	2800	Kennedy Range 3	1979 - (current)	International Nickel Australia Limited	Partly same ground as item 556 (Moogooree). Exploration of Carboniferous Moogooree Limestone for Mississippi Valley-type mineralization. Chip and stream sampling, photogeology, gridding detailed geology, soil geochemical sampling, IP surveys, combined percussion, reverse circulation and diamond drilling. (4 holes, 195.4 metres)	Several gossans, apparently associated with unconformity over 11 km strike, assays to 5800 ppm Pb/8500 ppm Zn. Coincident lead and zinc soil sediment anomalies and IP anomalies. Drilling problems (cavities) left majority of anomalies untested. Best assay in drill hole 1.3% Pb from near surface gossan.
**		TR 7863H	2702	Kennedy Range 3,6	1982	Amoco Minerals Aust. Co.	Base-metal search in Permian Lyons Group. Photo-geology, aeromagnetics, gravity survey; soil and stream sampling	Barite, galena and sphalerite veins in basement gneiss and Lyons Group. Contoured distribution map indicates relationship to basement 'highs' shown by magnetic survey. Soil anomalies to 9400 ppm Ba, stream anomalies to 4400 ppm Ba.

* Reports currently being processed for 'M'-series open-file system

** Permission to publish information received from company

APPENDIX 2

CARNARVON BASIN: DIAMOND EXPLORATION

ITEM NO.	ROLL NO.	TENEMENT NO.	MINES DEPT 'M' NO.	MAP SHEET DETAILS	DURATION	COMPANY NAME(S)	SUMMARY DETAILS OF EXPLORATION	SUMMARY RESULTS AND COMMENTS
1025	268	TR6822H	2371	Winning Pool 2	1978-1979	Cultus Pacific NL	Mapping, airborne magnetic and radiometric surveys ground magnetic and radiometric surveys	Circular structures examined no kimberlites found
1034	268	TR6960H	2493	Byro 1, 4	1979-1980	Stockdale Prospecting Ltd	Photo mapping, indicator-mineral stream-sediment sampling, loaming. Low-level airborne magnetic surveys, ground magnetic surveys and drilling. Test of area between Darling and Meeberrie Faults	Reported locating microdiamonds and chrome diopside in indicator-mineral samples. Follow-up failed to locate kimberlite and it was concluded that the source was Permian tillites (more recent information suggests the probability that the microdiamonds and indicator minerals may have resulted from laboratory contamination).
1035	269	TR7038H	2513	Winning Pool 2	1978-1979	Swan Resources Ltd	Prospecting, heavy-mineral sampling of drainages, loaming, ground magnetics, petrology	No indicator minerals of kimberlites found. Trace chalcopyrite in stream sample.
1036	269	TR6854H TR6855H	2520	Winning Pool 1,2,3,4	1978-1979	Forsayth Mineral Exploration NL	Aeromagnetic and radiometric surveys	No ground follow up.
1038	269	TR 7355H	2549/1	Winning Pool 4,5	1979	Stockdale Prospecting Ltd	Landsat interpretation, aeromagnetic surveys, ground magnetic surveys, photo-geology, stream-sediment indicator-mineral sampling, loaming, reverse-circulation drilling. Largely infill sampling of ground relinquished by CRA	Kimberlitic garnet found mid 1970s. 1979 infill sampling as indicator-minerals spread appeared too great from known CRA bodies. Magnetics suggest one small dyke-like body. Scattered indicator-mineral anomalies suggest a source from Cretaceous sediments.
1040	269	TR7092H TR7093H TR7094H	2565/1	Glenburgh 1 Mt Phillips 4	1979-1980	CRA Exploration Pty Ltd	Low-level airborne magnetic and radiometric surveys, ground magnetic and radiometric surveys, loaming. 6 non-core drill holes	Thorium sourced radiometric anomalies
1043	269	TR7197H TR7198H TR7199H TR7200H	2590	Ajana 2,3	1979-1980	Dampier Mining Co Ltd	Low level airborne magnetic surveys	No anomalies for follow-up.
1129	287	TR7355H-7357H	2549/3	Winning Pool 2	1979-1980	Stockdale Prosecting Ltd	See comments under item 1038	See comments under item 1038.
1192 1289 1290 1291	403) 417) 417) 417)	TR7049H + Mineral Claims	2529/1 2529/2,3,4	Byro 1,4 Glenburgh 1,2, 4,5 Yaringa 3,6	1979-1980	CRA Exploration Pty Ltd	Low-level airborne magnetic and radiometric surveys, indicator-mineral sampling and loaming, ground magnetic follow up and drilling	Results of loaming negative, non-kimberlitic chromites found in Daurie Creek property. Magnetic anomalies due to magnetic (Permian) basement at 45 metres
1288	417	TR7088H TR7089H TR7090H TR7091H	2565/2	Kennedy Range 6 Mt Phillips 4	1979-1981	CRA Exploration Pty Ltd	Low-level airborne magnetic and radiometric surveys and ground follow-up. Stream and loam indicator-mineral sampling. Drilling (non core) Bulk sampling	Possible kimberlitic chromites found. One microdiamond reported but believed to be from laboratory contamination. Follow-up indicates that chromite is from non-diamond-bearing kimberlite from recycling in sediments. Magnetic anomalies are due to heavy-mineral concentrations in channels in Permian sediments

ITEM NO.	ROLL NO.	TENEMENT NO.	MINES DEPT 'M' NO.	MAP SHEET DETAILS	DURATION	COMPANY NAME(S)	SUMMARY DETAILS OF EXPLORATION	SUMMARY RESULTS AND COMMENTS
1319	421	TR8701H	2952	Glenburgh 1	1981-1982	Broken Hill Pty Co Ltd	Reconnaissance drainage sampling. Follow up indicator mineral sampling	3 kimberlitic-chromite grains reported, but could not be confirmed by follow up.
*		Mineral Claims	2954	Byro	1979-1981	Carr Boyd Minerals Pty Ltd/Seltrust Mining Corp Pty Ltd	Low-level airborne magnetic surveys, loaming, rock geochemistry, microprobe analysis. Rotary-air-blast drilling	Drill test of pre-Cretaceous sequence, no kimberlites found.
*		TR7385H	2635	Ningaloo	1980	Magnum Minerals Pty Ltd Open Pit Mining & Exp. Pty Ltd	Test of 4 Pleistocene gravel shorelines for alluvial diamonds. Colour photography, mapping, augering, trenching, pitting, TBE heavy media separations	No-heavy mineral concentrations found.
1613	496	TRs + Mineral Claims	2405	Kennedy Range Winning Pool	1979-"	CRA Exploration Pty Ltd	Main CRA Wandagee exploration area - details remain confidential	Published information summarized in body of report

* Reports currently being processed for 'M'-series open-file system.

APPENDIX 3

CARNARVON BASIN URANIUM EXPLORATION (EXPLORATION FOR SANDSTONE HOSTED MINERALIZATION IN CRETACEOUS (and TERTIARY/QUARTERNARY) SEDIMENTS)

ITEM NO.	ROLL NO.	TENEMENT NO.	MINES DEPT 'M' NO.	MAP SHEET DETAILS	DURATION	COMPANY NAME(S)	SUMMARY DETAILS OF EXPLORATION	SUMMARY RESULTS AND COMMENTS
145	114	TR5920H TR5921H	1558	Yanrey 3,6	1974-1975	Agip Nucleare Pty Ltd	Test of Nanutarra Formation - outcrop areas: Airborne and ground radiometric surveys, 1:40 000 geological mapping hydrogeochemistry, petrology, surface rock sampling, rotary-percussion drilling (42 holes - 1115 metres) and gamma-ray logging	Surface values to 1300 ppm U from lateritized micaceous sand unit in Nanutarra Formation. 580 ppm U from granite pegmatites. Carnotite noted from granite exfoliation surface. No anomalies located in drilling. Nanutarra Formation mostly less than 50 m thick and wholly oxidised.
299	147	TR6336H	1377	Yanrey 2,5	1972-1973	Pacminex Pty Ltd	Test of Yanrey River channel system (Tertiary and Cretaceous target) by Drilling (17 hole - 1720 m),gamma-ray logging, assaying for uranium and basel metals and testing of shale samples for oil shale	No anomalous assays or oil shale indications. No Cretaceous sands tested. Pyritic dolomite at 92 m interpreted as Proterozoic but is probably Carboniferous.
409	165	TR5929H	1593/2	Yanrey 2,3	1973-1974	Pechiney (Aust) Exp Pty Ltd	Part of larger area and study. Regional magnetic interpretation used to locate Drilling (2 holes 413 m). Gamma-ray logging and assaying	Sequence drilled: Muderong Shale over Birdrong Sandstone; glauconitic at top separated by silt from arkosic basal unit). All sediments reduced, max. assay 10 ppm U 217 m to granitic basement.
422	169	TR5904H TR5905H TR5906H TR5907H	1509	Yanrey 6	1976-1977	Pechiney (Aust) Exp Pty Ltd	Airborne radiometric and magnetic surveys ground radiometrics, mapping, hydrogeochemistry, radiometric bore probes	Unsuccessful exploration of Cainozoic channel sediments of Rous Creek.
428	170	Mineral Claims	1431	Yanrey 6	1972-1973	Pacminex Pty Ltd	Drilling, rock sampling, percussion drilling (21 holes), borehole radiometry	Test of Rous Creek sequence. No anomalous radioactivity.
431	170	TR6336H	1888	Yanrey 2,3	1972-1973	Pacminex Pty Ltd	Rotary drilling programme to test Cretaceous sequence (7 holes 1100 metres) SP, resistivity, natural gamma-ray and density logs. Selective assays	Possible channel recognized in arkosic Birdrong Sandstone. Basement 113-240 metres. Reduced facies throughout, some dolomite interbeds suggest possible deltaic environment. (Now known to be basinwards of the Manyingee mineralization.)
520) 521) 663	179))- 202)	TR6564H TR6566H TR6567H	2114	Onslow 6 Yarraloola 1,2,4	1977-1978	Newmont Pty Ltd	Test of basal Cretaceous Nanutarra Formation and Yarraloola Conglomerate near Robe, Fortescue and Cane Rivers. Hydrogeochemistry, ground radiometrics non-core drilling (20 holes) borehole radiometry, SP, resistivity	Roll front located near Robe and Cane Rivers but maximum assay 8 ppm U. Fine-grained, "non-oxidised" Yarraloola conglomerate near Fortescue River.
670	203	TR6649H	2287	Yarraloola 1,4	1977-1978	CRA Exploration Pty Ltd	Test of Yarraloola Conglomerate by hydrochemistry, ground radiometric surveys, gravity surveys, non-core drilling (4 holes) and borehole logging	Thin palaeochannels found but no uranium anomalies encountered
671	203	TR6694H	2237	Yarraloola 1,2,4	1978	CRA Exploration Pty Ltd	Hydrogeochemistry, radon surveys (alphameter), gravity surveys, non-core drilling (10 holes) bore hole radiometric surveys	Palaeochannel in Yarraloola Conglomerate. Redox front tested but no anomalous radioactivity.

ITEM NO.	ROLL NO.	TENEMENT NO.	MINES DEPT 'M' NO.	MAP SHEET DETAILS	DURATION	COMPANY NAME(S)	SUMMARY DETAILS OF EXPLORATION	SUMMARY RESULTS AND COMMENTS
804	224	TR6965H	2346/3	Yanrey 3	1979	CRA Exploration Pty Ltd	Mapping, hydrogeochemistry, interpretation of BMR gravity	Research suggested possible palaeochannel but mapping shows only a thin cover of Nanutarra Formation not worth drilling. Hydrogeochemical values to 55 ppb U thought to derive from nearby 'hot' granites.
863	232	TR6900H TR6901H TR6902H	2541	Winning Pool 2	1978-1979	CRA Exploration Pty Ltd	Regional study, hydrogeochemistry, gravity survey, drilling (10 holes 1288 metres)	Drilling and gravity showed probable fluvial-deltaic channels in Birdrong Sandstone but with main redox front probably east of ground tested (see Item 1385). Assays to 90 ppm U_3O_8 from Muderong Shale above oxidised Nanutarra Formation sands (away from channel). Hydrochemical assays to 64 ppb U from Quaternary sediments of Lyndon River.
860 861	232	TR7073H TR7074H	2532	Onslow 6	1979	Western Mining Corp Ltd JV Armco Resources Pty Ltd	Radon surveys, hydrogeochemistry and drilling. XRD tests on clays	West of redox front. XRD tests of Saponite, nontronite and attapulgite.
1101 1102	280	TR7035H	2500	Yanrey 5	1979-1980	Utah Development Company	Radon surveys ('track-etch'), drilling, borehole radiometric surveys	West of redox front. Drilled 'open marine' Birdrong Sandstone at 120 metres to 200 metres depth.
1170	295	TR6890H TR6924H TR7174H	2346/5	Onslow 6 Wyloo 1 Yanrey 3,6 Yarraloola 4	1978-1980	CRA Exploration Pty Ltd	Regional study, hydrogeochemistry, gravity survey, drilling	Drilling defined palaeochannels with redox fronts but sequence relatively thin and only very minor uranium concentrations defined. Assays to 17 ppb U and radiometric assays to 320 ppb (E)U/0.5 metres.
*		TR6795H	2385	Winning Pool 2,3	1978-1981	Minatome Australia Pty Ltd	Geological mapping, hydrogeochemistry, gravity, drilling	Test of Cretaceous sand sequence in major north south palaeo-embayment. Defined deltaic facies Birdrong Sandstone, including pyritic and lignitic facies, with Nanutarra Formation fluvial sands at head of embayment. Minor U values in lignite. Hydrogeochemistry to 730 ppb U from well on granitic headland, west of embayment. Channels west of headland defined in Item 2541, apparently not tested.
		Current tenements	1593 2422 2423	Onslow, Yanrey	1978-	Minatome Australia Pty Ltd	Confidential current exploration area	Published information summarized in text, for details see Proceedings of the Australasian Institute of Mining and Metallurgy. No.279 September 1981. "Uranium Mineralisation in the Manyingee Channel, W.A." (Valsardieu et al).
CARNARVON BASIN URANIUM EXPLORATION FOR SANDSTONE HOSTED MINERALIZATION IN PERMIAN MOOGOOLOO SANDSTONE								
805	224	TR6749H TR6750H	2347	Kennedy Range 3,6	1978-1979	Afmeco Pty Ltd	Test of Moogooloo sandstone in the Lyons River area following encouraging results in Pells Range area (Item 1171). Geological mapping, stratigraphic sections and drilling (6 holes). Some palaeontology	No uranium anomalies. Concluded south of Lyons River Fault unfavourable intertidal facies; between Lyons River Fault and Arthur River Fault mixed intertidal and fluvio-deltaic facies; north of Arthur River Fault fluvial-deltaic facies. (The latter potentially prospective zone was not tested by drilling.)

* Reports currently being processed for 'M'-series open-file system

ITEM NO.	ROLL NO.	TENEMENT NO.	MINES DEPT 'M' NO.	MAP SHEET DETAILS	DURATION	COMPANY NAME(S)	SUMMARY DETAILS OF EXPLORATION	SUMMARY RESULTS AND COMMENTS
806	224	TR6785H TR6786H	2368	Wooramel 2,3	1978-1979	Afmeco Pty Ltd	Test of Moogooloo sandstone adjacent to major faults for mineralization associated with oxidizing groundwaters. Photogeology, hydrogeochemistry, drilling and down-hole radiometric logging	No uranium mineralization found. Strong radiometric anomalies associated with springs in the Jacobs Gully/Salt Gully area, but uranium values are low.
859	232	TR6951H	2491	Byro 1	1979	Nord Resources (Pacific) Pty Ltd	Airborne radiometric surveys, ground radiometric surveys, mapping	Limited follow up of radiometric anomalies. 75 ppm U in laterite.
1171	296	TR6623H TR6328H TR6329H TR6330H TR6631H	1889	Glenburgh 1 Kennedy Range 6 Wooramel 3	1976-1980	Afmeco Pty Ltd (with Australian Occidental Minerals)	Helicopter and ground radiometric traversing, photogeology, hydrogeochemistry, seismic refraction survey, radon surveys (alphameter), rotary-drill, air-core and diamond drilling (84 holes - 10 211.2 metres)	Extensive test of Moogooloo Sandstone for roll-front mineralization. Hydrochemical anomalies to 85 ppb, surface samples with Weeksite. Best drill intersection 2619 ppm U over 0.3 metres. Thucolite or autunite associated with framboidal pyrite in "organo-phyllitic sediments". (This mineralization appears to be more akin to peneconcordant mineralization of the Niger type than with simple roll-front mineralization).

CARNARVON BASIN URANIUM EXPLORATION OF DEVONIAN CARBONATES AND SANDSTONE OF THE LYONS GROUP SEDIMENTS

ITEM NO.	ROLL NO.	TENEMENT NO.	MINES DEPT 'M' NO.	MAP SHEET DETAILS	DURATION	COMPANY NAME(S)	SUMMARY DETAILS OF EXPLORATION	SUMMARY RESULTS AND COMMENTS
10	101	TR5696H	1209	Kennedy Range 3	1973-1974	Uranerz (Aust) Pty Ltd	Airborne radiometric surveys (unreported) helicopter and ground radiometrics, ground reconnaissance	51 'uranium' source anomalies examined - all were considered to be due to 'hot'granites.
11	101	TR5698H	1211	Kennedy Range 3	1973-1974	Uranerz (Aust) Pty Ltd	Airborne radiometric surveys (unreported) helicopter and ground radiometrics, trenching	Grab samples to 125 ppm U_3O_8 with yellow minerals in shales of Lyons Group - considered by Uranerz to be a local enrichment of limited significance.
799	223	TR6701H	2399	Kennedy Range 3	1978-1979	Nord Resources (Pacific) Pty Ltd	Helicopter radiometric survey. 1:20 000 geological mapping and ground traversing	Follow up of item 11 - no new anomalies discovered.
864	232	MCs 2374-2377	2541/3	Winning Pool 6	1979	CRA Exploration Pty Ltd	Follow-up of radiometric anomaly from unreported airborne survey. Ground radiometrics, geological mapping, rotary drilling (8 holes - 396 metres) down hole radiometric logging	Anomalous uranium enrichments in top 10 metres of sandy calcarenite unit of Devonian Gneudna Limestone. Fresh limestone is pyritic. Best assay 203 ppm (e) U.
*		Mineral Claims	1527	Kennedy Range 3 Winning Pool 6	1977-"	Uranerz (Aust) Pty Ltd	Follow-up of unreported airborne surveys. Airborne radiometrics, soil sampling, mapping, grid radiometrics trenching and diamond drilling	Several carnotite-tyuyamunite mineralized zones, mostly within 3 metres of surface in 'marl' zones of Devonian Gneudna Formation. Low-order gamma anomalies with siltstones and oxidized hematitic zones in Devonian Nannyarra Greywacke and Munabia Sandstone.

* Reports currently being processed for 'M'-series open-file system

APPENDIX 4

CARNARVON BASIN: MINERAL SANDS EXPLORATION

ITEM NO.	ROLL NO.	TENEMENT NO.	MINES DEPT 'M' NO.	MAP SHEET DETAILS	DURATION	COMPANY NAME(S)	SUMMARY DETAILS OF EXPLORATION	SUMMARY RESULTS AND COMMENTS
1007	267	TR4924H TR4925H	353	Dampier 4,5 Onslow 3,6 Yarraloola 1, 2,4	1968-1971	Vam Ltd (JV with West Coast & Mazza)	Prospecting and sampling including augering at 100 to 400 feet intervals. Samples every 5 feet analyzed by bromoform and magnetic separation. Quantitative analysis of two composite samples	Calculated reserves at Yardie Creek of 29.4 million cubic yards at 4.7% contained heavy minerals. At Fortescue River 2.0 million cubic yards at 9.0% contained heavy minerals. Mineralogy 49 - 57.7% goethite, 15.8-26.2% martite, 4.7-4.9% ilmenite, 5.4-12% leucoxene, tr - 1.5% magnetite, + silicates.
1515	476	TR4499H	344	Onslow 5,6	1967-1972	Ashburton Sands Pty Ltd Exmouth Salt Pty Ltd Mallina Mining & Exp NL	Prospecting, mapping, aeromagnetics, ground magnetics, resistivity and auger drilling at mouth of Ashburton River. Quantitative mineral determinations	Indicated and inferred resources of 5.84 million tonnes of contained heavy minerals at average 10.4% heavy minerals, using a 5% cutoff. Mineralogy mainly magnetite (43.6% Fe 4-6% TiO_2) hematite, maghemite with minor ilmenite leucoxene, zircon monazite and silicate heavies.
*		Dredging Claims	1318	Albany, Broome, Busselton, Collie, Derby, Geraldton, Onslow, Quobba, Shark Bay	1969	Coastal Titanium Pty Ltd	Reconnaissance exploration near Onslow and Carnarvon using low-level helicopter surveys and sampling. Mapping and post-hole drilling on Peron Peninsula (Shark Bay). Quantitative analysis of concentrates	Onslow concentrates predominantly 'iron oxides' with 15-20% ilmenite. Carnarvon recent beach concentrate 43% ilmenite, 13% zircon, 2% rutile, 10% monazite. Peron Peninsula 300 000 tons ore at 8.9% heavy mineral content, 25-60% ilmenite, 4-11% leucoxene, 20% zircon, 0.5-3% rutile
*		TR7609H	2787	Shark Bay 5,6	1979-1980	Allied Eneabba Ltd	Mapping and vacuum drilling of dune sequences on Peron Peninsula	Concluded that prospects are confined to present beaches and foredunes with only a thin veneer of sand in remainder, best drill intersection 2.0% heavy minerals over 1 metre.
		?open ground	M1445/7	Dampier 5,6 Yarraloola 1,2	1972	Bamboo Creek Gold Mines NL	Prospecting of 50 miles of coast from Robe River estuary to Yannery River, 30 miles south of Dampier (Consulting by Robertson Research)	Quantitative analysis showed very poor heavy-mineral suite, dominated by iron oxides, with small patchy concentrations of titaniferous magnetite.
477	176	TR6534H TR6535H	M2031	Ajana 1	1976-1977	International Nickel Australia Ltd	Exploration of possible Pleistocene sand sequence north of Murchison River by aerial photography, photogeological mapping, airborne magnetic and radiometric surveys and auger drilling. Quantitative analysis of heavy-mineral suite	Possible raised shorelines recognized but no economic heavy-mineral concentrations found. Favourable heavy-mineral suite with 34-35% ilmenite, 6-7% altered ilmenite (65% TiO_2) 4-5% leucoxene, 10-11% rutile, 26-27% zircon, 1-1.5% monazite 4-5% kyanite.
*		MC 09/ 3035-3066	M2811	Shark Bay 5,6	1980-1981	Southern Goldfields Ltd	Sampling and mapping of Recent and Quaternary foredunes on Peron Peninsula, underlain by Peron sandstone. Tests of magnetic and radiometric exploration methods. Metallurgical testing, chemical analysis of ilmenite	Potential to produce high-grade ilmenite, "acceptable in the market place". No encouraging response in geophysical traverses. Interesting mineralogy of heavy-mineral suite with up to 6.9% rutile and leucoxene and up to 34.14% zircon. Grab samples to 42.4% total contained heavy minerals.

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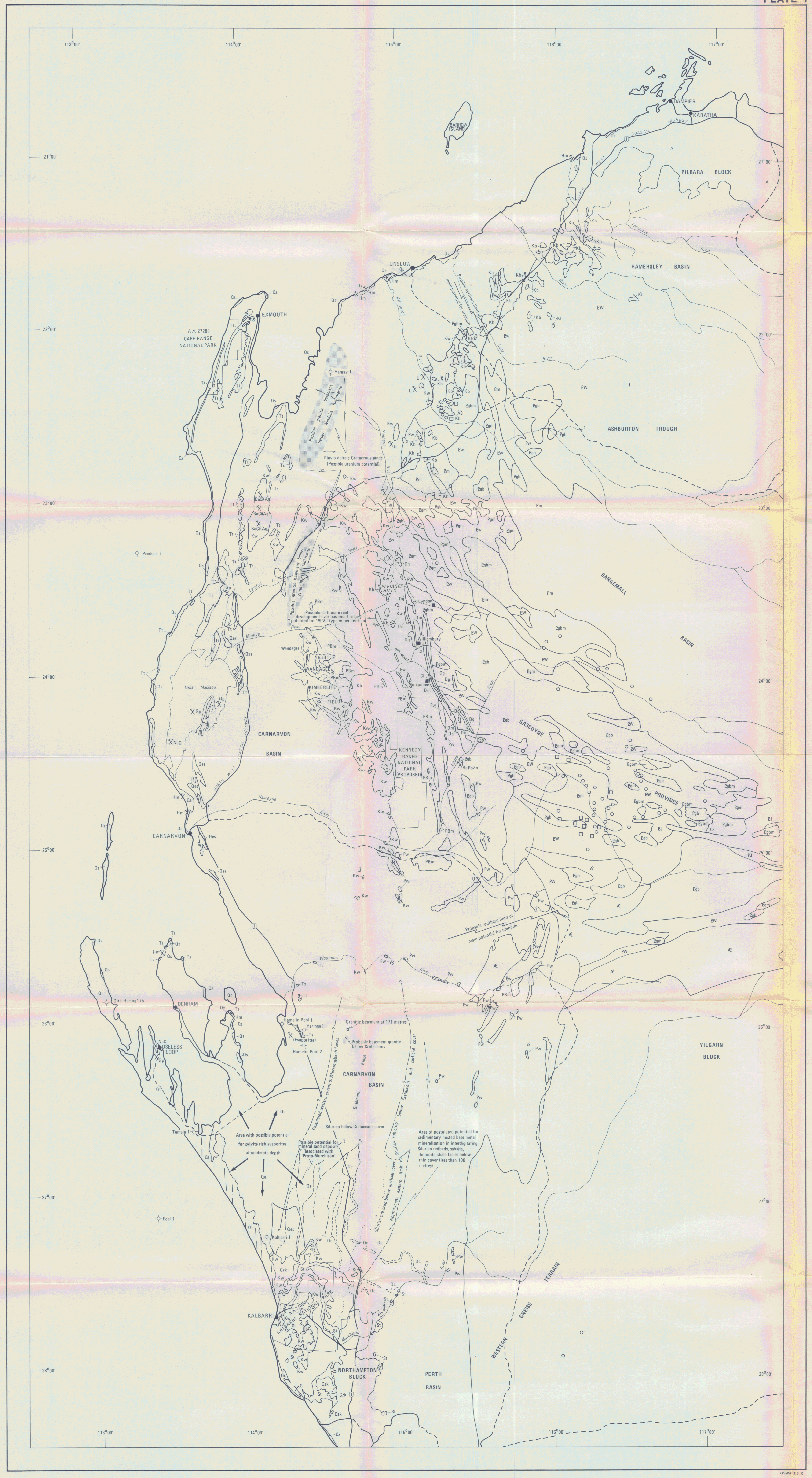

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

CARNARVON BASIN MINERAL OCCURRENCES WITH RECOMMENDATIONS FOR EXPLORATION

REFERENCE

CARNARVON BASIN SEQUENCE

QUATERNARY TO RECENT	Qs	Recent dunes and beach ridges. Potential for H.M. deposits near mouths of rivers with favourable mineralogy, such as Gascoyne and Wooramel Rivers
	Qt	Tamala Limestone lithified eolian calcareous sand sequence
	Qe	Eolian dunes of 'desert' and residual origin
	Qc	Alluvial and colluvial deposits probably representing the trace of former courses of Murchison River
	Qes	Pleistocene coastal sands, including older beach-ridges near Carnarvon. Potential for heavy mineral deposits near Gascoyne and 'Proto-Murchison'.
	Czk	Calcrete duricrust
TERTIARY	Ts	Tertiary coastal sand. Dominently terrigenous component. Potential for heavy mineral deposits near ancient river mouths, but reduced by induration
	Tt	Trealla Limestone. Some potential for fluxing limestone locally, mainly in the Cape Range Area.
CRETACEOUS	Kw	Winning Group, Gearle Siltstone, Windalia Radiolarite, Muderong Shale. Possible potential for stratiform Pb Zn (Ag) deposits, barytes, bentonitic clay
	Kb	Birdrong Sandstone and equivalents including Nanutarra Formation and Yarraloola Conglomerate. Potential for uranium mineralization associated with redox fronts in fluvial-deltaic facies. Possible potential for alluvial diamonds concentrated locally in shoreline facies.
PERMIAN	PBm	Middle Byro Group. Possible potential for stratiform Pb Zn (Ag) mineralization in reduced carbonaceous shales in Bulgadoo Shale and Quinannie Shale
	Pw	Wooramel Group. Potential for 'peneconcordant' and 'roll front' uranium in deltaic and fluvial facies of Moogooloo Sandstone
SILURIAN TO CARBONIFEROUS	Cl	Moogooree Limestone, Yindagindy Formation, Williambury Formation. Potential for Mississippi Valley – type Pb Zn in limestone and uranium in sandstone members
	Dm	Munabia Sandstone and Willaraddie Formation. Potential for uranium mineralization of 'roll front', 'penecondordant' and 'structural stock' types
	Dg	Gneudna Formation and Nannyarra Sandstone. Potential for 'M.V. type' Pb Zn in limestone and uranium in sandstone members.
	St	Tumblagooda Sandstone

BASEMENT ROCKS

Ƥm	Bangemall and Uaroo Groups. Sandstone, shale carbonate, chert
ƤJ	Mount James Formation. Sandstone
ƤW	Wyloo Group, Morrissey Metamorphic Suite, Greywacke, shale, arkose, conglomerate, carbonate (and metamorphic equivalents)
Ƥgb	Proterozoic Granite. Biotite rich, derived from remobilisation of Archaean or Early Proterozoic crust
Ƥgm	Proterozoic Granite Muscovite rich derived by anatexes from metasedimentary sequences. Potential source rock for uranium mineralization in Carnarvon Basin sediments.
Ƥgbm	Proterozoic Granite. Uncertain origin both biotite and muscovite rich, some bodies maybe source rocks for uranium mineralization in Carnarvon Basin sequence
AƤ	Archaean rocks reworked by Proterozoic metamorphic events
A	Archaean rocks of Pilbara Block. (Granite, mafic and ultra mafic intrusive and extrusive rocks, felsic volcanics and sediments)

●	Townsite
■	Homestead
	Sealed road
	Unsealed road
	Former river courses (from Landsat information)
	Photo and landsat traces of possible former coastlines
	Dune trend lines
	Outcrop boundary
	Subcrop boundary below surficial or Cretaceous cover (approximate)
	Approximate boundary of Wandagee Kimberlite occurrences
	Boundary of area with possible potential for sediment hosted stratiform copper mineralization
	Marks northern and southern limit of main area with potential for uranium mineralization within the basin
	National Park boundary
⚒	Mine or proven mineral deposit
⚒	Occurrence or untested prospect
○	Calcrete-hosted uranium mineralization in Gascoyne Province
□	Uranium occurrence in granite or pegmatite in Gascoyne Province
⌖	Petroleum or evaporate exploration well
Na Cl	Salt
Gp	Gypsum
G	Garnet
Hm	Mineral sands
Ba Pb Zn	Barytes, galena, sphalerite
Ba Ci (Ag)	Barytes, bentonitic clay, trace anomalous silver
U	Uranium
Ls	Limestone

0 50 100 km

Approximate scale 1: 1 000 000