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BRACHIOPODS AND BIVALVES OF KUNGURIAN (LATE EARLY PERMIAN) AGE FROM THE TOP OF THE COOLKILYA SANDSTONE, CARNARVON BASIN, WESTERN AUSTRALIA

N.W. Archbold* and S.K. Skwarko

ABSTRACT

A small previously undescribed fauna from the top of the Coolkilya Sandstone at Wandagee Hill, Carnarvon Basin, consists of two brachiopod species, one of which—*Fusispirifer coolkilyaensis*—is new; three bivalve genera and species, including the new *Pseudomonotis (Trematoconcha) carnarvonensis*; and some worm trails. The age indicated is Late Kungurian, mainly by *F. coolkilyaensis*, which is similar to another *Fusispirifer* lower down in the Coolkilya Sandstone, and is regarded as Irenian (Late Kungurian) in age.

INTRODUCTION

The Coolkilya Sandstone is the lowest of the three members of the Kennedy Group, the top-most group of sediments of Permian age in the Carnarvon Basin. It consists of 215 m of sandstone—in places ferruginous—with hard calcareous beds and many fossiliferous beds; and is conformable between the Baker Formation below and the Mungadan Sandstone above. The name Coolkilya Sandstone was coined by Teichert (1950, p. 1791) in place of his earlier (Teichert, 1947, p. 99) informal name “*Linoproductus* stage”. It was changed to “Coolkilya Greywacke” by Condon (1954, p. 91), and changed back to Coolkilya Sandstone by Hocking and others (1980).

The fossils described below were collected in 1983 from the top of the unit on the east side of the Wandagee Hill, Wandagee Station, Carnarvon Basin; they have not been previously described. The layer which shed them is strongly leached and ferruginized, and only the impressions of shells in the matrix remain. The following genera and species have been identified and are described below.

Brachiopoda: *Taeniothaerus* sp.
Fusispirifer coolkilyaensis
sp.nov.

Bivalves: *Pseudomonotis (Trematoconcha)*
carnarvonensis sp.nov.

Etheripecten sp.
Gen. et sp. indet.
Oriocrassatella sp. cf. *O. stokesi*
Etheridge Jnr 1907

The Coolkilya Sandstone has a rich and varied fossil fauna which has been recently revised (Skwarko, in prep.). In addition to the occasional foraminifers, bryozoans, and conulariids, it contains a host of brachiopods, bivalves, some gastropods and crinoids, and three ammonoid genera and species. The unit is regarded as Irenian (Late Kungurian) in age (Archbold and others, in press).

The small fauna described below is also regarded as Irenian—probably latest Irenian—in age. This is implied by the similarity of *F. coolkilyaensis* to the *Fusispirifer* species lower down in the Coolkilya sequence, and by *O. sp. cf. O. stokesi*, which is probably conspecific with *O. stokesi* (which ranges up from the Nalbia Sandstone) also lower down in the section.

Investigations of the ammonoid fauna of the type Kungurian strata (Bogoslovskaya, 1976; Chuvashev and Bogoslovskaya, 1981) indicate that the Kungurian stage can be differentiated from the underlying Baigendzhinian substage of the Artinskian stage. Although largely contrary to the views of Glenister and Furnish (1961) — and therefore Cockbain (1980) — investigations by Kulikov (1974), Waterhouse (1976), and Zolotova and Baryshnikov (1978) also confirm the validity of the Kungurian Stage. The presence of *Paragastrioceras wandageense* either in the Nalbia Sandstone (Cockbain, 1980) or the Baker Formation (Archbold and others, in press), a species similar to *P. kungurensis* (Mirskaya, 1948) from the type Kungurian, supports the view that in the Carnarvon

There are also some tracks and trails which are to be described elsewhere.

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Basin sequence, the Artinskian-Kungurian boundary is at or close to the base of the Nalbia Sandstone (Archbold, 1981). Dickins (1956) had earlier regarded the bivalves from the Baker Formation as of Kungurian affinity. In terms of the substages discussed by Waterhouse (1976), the Nalbia Sandstone and Baker Formation are probably Filippovian in age, and the Coolkilya Sandstone Irenian. Considering that the elements of the present Coolkilya assemblage such as *Fusispirifer coolkilyaensis* sp. nov. are closest to the species lower down in the Coolkilya sequence (to be expected in terms of stratigraphy), it is probably late Irenian in age. No elements of the fauna suggest a Ufimian or Kazanian age. An early Ufimian age, in the sense of Archbold and others (in press), is possible for the assemblage; but, because marine equivalents of the type early Ufimian have not been convincingly established in the Boreal Realm, recognition of the early Ufimian level in Gondwanan sequences can only be achieved by inference.

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S.K. Skwarko wishes to thank Dr J.M. Dickins, Bureau of Mineral Resources, Canberra, for helpful suggestions regarding the identity of the bivalves.

In the current paper, N.W. Archbold is responsible for the description of the brachiopods and the discussion on the age of the collection, while S.K. Skwarko described the bivalves, and wrote the remainder of the manuscript.

SYSTEMATIC DESCRIPTIONS BRACHIOPODA

Family AULOSTEGIDAE Muir-Wood and Cooper 1960

Genus *TAENIOTHAERUS* Whitehouse 1928

Type species: *Productus subquadratus* Morris 1845; OD Whitehouse, 1928.

Diagnosis and discussion: The genus and type species have been diagnosed and discussed in modern terms by Parfrey (1983) whose understanding is accepted herein.

Taeniothaerus sp.
(Pl. 1, fig. 5)

Material: One external mould of a worn ventral valve, GSWA F43790.

Description: Ventral valve moderately large; total dimensions unclear because of poor preservation but valve probably longer than wide; transverse profile arched with broad, shallow sulcus; spines apparently in single series, arranged in irregular quincunx; spine bases elongate, radially arranged; striations of muscle field weakly visible at posterior of mould.

Discussion: Although inadequate for detailed comparison, the present specimen recalls *Taeniothaerus subquadratus* (Morris), as understood by Parfrey (1983) and Waterhouse and others (1983), sufficiently to indicate its generic position. *Taeniothaerus* is widely distributed in the Permian of Australia and elsewhere (Parfrey, 1983).

Few aulostegids have been recorded from the Coolkilya Sandstone. *Aulosteges* sp. indet. A (Coleman, 1957, p. 51, pl. 5 figs 19-21) is probably a juvenile specimen and hence cannot be directly compared with the present specimen. *Taeniothaerus miniliensis* was recorded by Coleman (1957, Table 2) as occurring in the Coolkilya Sandstone; but he neither listed morphological details nor figured any specimens. *T. miniliensis* has much finer spine bases than the present specimen.

Family SPIRIFERIDAE King 1846

Subfamily NEOSPIRIFERINAE Waterhouse 1968

Diagnosis: The diagnosis is provided by Archbold and Thomas (1984).

Discussion: The composition of the subfamily and distinctions from the Trigonotretinae and Spiriferinae are provided by Archbold and Thomas (1984). The evolutionary origin of *Fusispirifer* is poorly known and hence the genus is only provisionally retained in the subfamily (Archbold and Thomas, in press).

Genus *FUSISPIRIFER* Waterhouse 1966

Type species: *Spirifer nitiensis* Diener 1897; OD Waterhouse, 1966.

Diagnosis: Neospiriferinae characterized by an extremely transverse outline throughout ontogeny, and weakly inflated valves; sulcus narrow, straight-edged, and narrower than the ventral muscle field; containing a broad medium rib. Costae fasciculate; delthyrial plate thick and large for subfamily.

Discussion: *Fusispirifer* is a distinctive, large, transverse genus. Only the inadequately known *Transversaria* Waterhouse and Gupta (1983) approaches *Fusispirifer* closely in gross morphology, and *Transversaria* may be a junior subjective synonym of *Fusispirifer* (Archbold and Thomas, in press). *Transversaria*—type species *Fusispirifer marcouiformis* Ching (Chang and Ching, 1976)—has a low broad dorsal fold and fastigium and a shallow broad ventral sulcus (Chang & Ching, 1976, pl. 13, figs 1, 2, 22 and 23 - the lectotype of *T. marcouiformis*) and is described as possessing fine, equidimensional costae, which are not fasciculate. The variability of *T. marcouiformis* is poorly understood.

Fusispirifer is reliably known from eastern and Western Australia, the Himalayas, Southern Tibet, Afghanistan, and the Kolyma Region of Arctic Siberia, as discussed below.

***Fusispirifer coolkilyaensis* sp.nov.**

(Pl. 1 figs 1-4, 6-10)

Holotype: GSWA F43786, an external mould of a conjoined shell, preserving two-thirds of the dorsal valve and ventral interarea.

Material: Eight specimens, GSWA F43787-F43789, F43791-43794, comprising three external moulds of ventral valves, one external mould of a dorsal valve, and three incomplete internal moulds of ventral valves.

Diagnosis: Transverse, medium-sized species with narrow, low sulcus and narrow, low fold; costae fine, equal, form low fascicles of three costae posteriorly; fascicles obsolescent anteriorly.

Description: Medium-sized for genus; shell biconvex with strongly transverse outline, widest at hinge; widest specimen estimated at 166 mm.

Ventral valve weakly convex, small ventral umbo sharply overturns high ventral interarea. Ventral interarea gently concave with broad triangular delthyrium. Delthyrium with thick apical filling posteriorly. By comparison with shelly material from other Western Australian Permian horizons the apical filling is a true delthyrial plate strengthened by massive apical callosity. Ventral interarea striated transversely and vertically (the latter being denticular grooves). Thickened dental flanges support small, thick teeth, and are supported by short adminicula buried in callus. Delthyrial groove distinct, delthyrial ridge low. Ventral muscle field wide and long, subcircular in outline. Adductor scars distinctly striated.

Ventral sulcus extremely narrow, shallow, V-sided with median sulcal costa, each sulcal flank carries two or three costae. Lateral slopes of valve carry many subequal to equal costae, grouped into fascicles of three costae posteriorly and obsolescent on the transverse extremities of the valve. Costae gently rounded, from 5 - 7 per 5 mm at 2 cm from umbo. Ventral valve massively thickened posteriorly.

Dorsal umbo small, low, overhangs delthyrium; dorsal interarea very low. Internal structures unknown from available material. Dorsal fold low with median costa and costae on flanks. Dorsal lateral slopes carry costae of comparable type and size to the ventral valve.

Microornament of concentric growth lines (2-3 per mm) and radial capillae (4 - 5 per mm).

Discussion: *Fusispirifer coolkilyaensis* sp. nov. is the youngest species of the genus known from Western Australia. Other Western Australian species, discussed briefly by Thomas (1969) and described by Archbold and Thomas (in press) tend to be characterized by higher dorsal folds, and/or coarser costae. *Fusispirifer byroensis* (Glauert, 1912) from Early Baigendzhinian strata of the Carnarvon Basin is less transverse and has coarser costae than *Fusispirifer coolkilyaensis* sp.nov. Specimens from other stratigraphical levels within the Coolkilya Sandstone are close to *F. coolkilyaensis* sp.nov. but generally with consistently coarser costae (3 to 5 per 5 mm at 2 cm from the umbones) otherwise all Coolkilya specimens share similar features of the sulcus, fold, and obsolescence of ornament at the transverse extremities. The present specimens are however, larger and more transverse than other Coolkilya specimens and are therefore described as a new species.

At least two species of *Fusispirifer* are known from eastern Australia (Tasmanian and Sydney Basins) as discussed briefly by Clarke (1973). *F. avicula* sensu Morris (1845) is a form with coarse costae unlike *F. coolkilyaensis* sp.nov. *Fusispirifer* sp. recorded from the Drake area, New South Wales (Telford, 1971, Pl. 16, fig. 5) has a wider sulcus and coarser costae than *F. coolkilyaensis* sp.nov.

Fusispirifer nitiensis (Diener, 1897, pl. 4 figs 4, 5) from Chhidruan faunas of the Himalayas is characterized by a relatively high fold, broad sulcus and coarser ribs. A specimen recorded by Diener (1899, pl. 5 fig. 9) from Po, Spiti, has fine ribs arranged in fascicles of three, and costae that are obsolescent at the transverse extremities of the shell. Diener's (1903, pl. 4, figs 6, 7) specimens from the central Himalayas are far less transverse and have much coarser ribs and hence are unlikely to be congeneric.

Fusispirifer semiplicata Ching (Chang and Ching, 1976) from the Chhidruan of Southern Tibet closely approaches *F. coolkilyaensis* in terms of fine costae and sulcal and fold details, but has a relatively low ventral interarea.

An Early Permian (Asselian - Sakmarian) species from Afghanistan recorded as *F. byroensis* by Legrand-Blain (1968) is highly transverse but has coarser costae and a broader sulcus than *F. coolkilyaensis* sp.nov.

Fusispirifer from the Kazanian of the Kolyma Region of Arctic Siberia, see Zavodovsky and Stepanov (1971, pl. 74 figs 1 - 2) under the name of *Neospirifer kedonensis* Einor and the Asselian of the same region (Zavodovsky and Stepanov, 1971, pl. 30 fig. 2), are transverse shells with coarser ornament, higher folds, and wider sulci, than the new species.

MOLLUSCA

BIVALVIA

Family AVICULOPECTINIDAE Meek and
Hayden 1865

Subfamily AVICULOPECTININAE Meek and
Hayden 1865

Genus *ETHERIPECTEN* Waterhouse 1963

Type species: *Etheripecten striatula* Waterhouse
1963; OD

Etheripecten sp.

(Plate 3 fig. 2)

Material: A single external impression of the outside of proximal part of the right valve.

Description: The single fragment in the collection belongs to a large bivalve radially ribbed by single order (at least in the right valve) closely spaced, numerous radiating riblets of uneven width, separated from each other by apparently flat, equally numerous and narrow interspaces also of varying width. The riblets increase in number by intercalation rather than by bifurcation. The subauricular sulcus is deep. The anterior auricle is prominent, elongate, at right angles to the body of the valve, striated with strong rugae in its ventral part, as well as with some weak radial riblets.

Discussion: The Genus *Etheripecten* was erected in 1963 by Waterhouse (type species *E. striatula* Waterhouse 1963) from the Late Permian of New Zealand) to accommodate bivalves with *Aviculopecten*-like left valves and right valves in which costae increase by intercalation rather than by bifurcation. By the last count (Waterhouse, 1982) *Etheripecten* numbers some nine species from the Permian of eastern Australia and 14 forms from the Permian of New Zealand. A recent revision of the Permian Western Australian bivalves (Dickins and Skwarko, in prep.) revealed a record in the literature of perhaps as many as 13 discrete local forms, only three of which, however, have ever been figured. These are: the *Etheripecten* sp. A from the Sterlitamakian Fossil Cliff Member of the Perth Basin; *Etheripecten*? sp. from the Sakmarian basal Poole Sandstone of the Canning Basin, and *E. tenuicollis* (Dana 1847), widespread in Western Australian Sakmarian.

The sole fragment in our collection does not seem to belong to any of the previously described species, whether from Australia or from New Zealand.

Family PSEUDOMONOTIDAE Newell 1938

Genus *PSEUDOMONOTIS* von Beyrich 1862

Type species: *Gryphites speluncarius* von Schlotheim 1816; SD Stoliczka, 1871.

Subgenus *TREMATICONCHA* Newell and Boyd
1970

Type species: *Pseudomonotis (Trematiconcha) wandageensis* Newell and Boyd 1970; OD

Pseudomonotis (Trematiconcha) carnarvonensis
sp.nov.

(Plate 2 figs 1 - 9; Plate 3 figs 1,3,4,6)

Material: Five incomplete external and one incomplete internal impressions of the right valve; five incomplete internal impressions and two fragments of external impressions of the left valve.

Diagnosis: Combination of fine straight and closely spaced riblets on the right valve, with irregularly directed and widely spaced primary ribs separated by very fine secondary riblets on the left valve.

Closest species: *T. wandageensis* Newell and Boyd 1970 from the Wandagee Formation, Minilya River; the type and only hitherto known species referable to *Trematiconcha*, resembles the new species in the overall shape, general type of ribbing, shape and direction (on the right valve) of the anterior auricle, and the nature of the concentric growth lamellae on both valves. The two species can be distinguished by closer spacing and greater relief of radial ribs on the left valve of the type.

Holotype: GSWA F43796.

Paratypes: GSWA F43795, F43797 - F43809.

Description: Right valve flat, flexed by post-umbonal sulcus, up to at least 85 mm high and 90 mm wide, with broadly and more or less evenly convex periphery except for antero-dorsal tight flexure, and somewhat concave periphery above this flexure, and in rear where modified by broad and shallow post-umbonal sulcus. Anterior ear large, bulbous, well-developed, undercut by deep, angular and proximally rather narrow subauricular sulcus. Surface of valve with linear radial riblets radiating from umbo and separated from each other by flat interspaces some two or three times their width. Growth rugae few and irregularly spaced except close to shell periphery where they apparently increase valve thickness.

Left valve well and evenly inflated except for broad and shallow posterior sulcus. Antero-dorsal shell margin plunges steeply into commissure below inconspicuous anterior ear. Above sulcus posterior wing broad and conspicuous. Primary ribs broad and coarse, fairly widely spaced and separated by wider interspaces lined with fine radial riblets. Both ribs and interspaces complicated by growth rugae. Ligament pit broader than high but of variable length, longitudinally striated in one specimen.

Gen. et sp. indet.

(Plate 4 figs 6 - 9)

Material: Three proximately incomplete impressions of the convex left valve, and two incomplete impressions of the flat right valve.

Description: Left valve probably up to 10 cm high and 8 cm long, well and evenly inflated, with tumidity decreasing suddenly along the distal—particularly the ventral—periphery, with valve surface plunging into the commissure. Surface of left valve with linear, broadly spaced concentric constrictions separated by gently and unevenly convex in cross-section broad and irregular interspaces or ribs. Constrictions persist to inside of valve.

Right valve apparently devoid of ornament, flat, with unevenly and irregularly undulating surface, and turned inwards and considerably thickened distal—particularly ventral—valve margins.

Remarks: The identity of the four incomplete valves is yet to be determined.

Family **CRASSATELLIDAE** Ferussac 1822
Subfamily **CRASSATELLINAE** Ferussac 1822
Genus **ORIOCRASSATELLA** Etheridge Jnr
1907

Type species: *Oriocrassatella stokesi* Etheridge Jnr 1907; OD

Oriocrassatella sp.cf. *O.stokesi* Etheridge Jnr
1907

(Plate 4 figs 1 - 5)

Material: About 20 specimens, almost all incomplete, representing mainly the external impressions of both left and right valves; three incomplete internal impressions of the left valve showing very poorly preserved dentition, and one of the right valve also showing poorly preserved dentition.

Description: Shell rounded-trapezoidal in outline, equivalve, asymmetrical, produced to front and more to rear, prosogyrous, of moderate and even tumidity, less than 50 mm long and 35 mm high.

Shell margin slightly concave in front of umbo, fairly tightly convex anterodorsally, broadly and evenly convex in front, antero-ventrally and posterodorsally, fairly tightly turned postero-ventrally.

Umbo broad and low with pointed beak situated slightly forward. Concentric ribbing fine and dense though not very regular, follows distal periphery of shell.

Posterior adductor scar shallowly incised in front, somewhat vertically elongate. Pallial sinus not positively identified.

Hinge plate elongate, not robust, on left valve with deeply incised triangular resilium beneath beak preceded by short robust triangular 2 and followed by elongate and attenuated and low "septum" and narrow long PII with attenuated socket above it.

Discussion: The generic identity of the heterodont bivalve in our collection cannot be determined with certainty. Although a common enough shell, there are only four impressions of the dentition, all very poorly preserved. The best impression of the left valve dentition shows what could be a remaining proximal fragment of 4b, indicating an *Oriocrassatella*. The overall shape is inconclusive, but the concentric ribbing though irregular would favour the *Oriocrassatella*.

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PLATE 1

All figures of natural size and coated with ammonium chloride prior to photography.

Figs 1-4, 6-10. *Fusispirifer coolkilyaensis* sp.nov.

1. **Holotype**, GSWA F43786, latex cast of external mould of conjoined shell.
2. **Paratype**, GSWA F43787, latex cast of external mould of ventral valve.
3. **Paratype**, GSWA F43788, latex cast of external mould of ventral valve.
- 4,10. **Paratype**, GSWA F43789, latex cast and mould of incomplete ventral valve.
6. **Paratype**, GSWA F43791, latex cast of incomplete internal mould of ventral valve.
7. **Paratype**, GSWA F43792, latex cast of external mould of dorsal valve.
8. **Paratype**, GSWA F43793, incomplete internal mould of ventral valve.
9. **Paratype**, GSWA F43794, latex cast of external mould of incomplete ventral valve.

Fig. 5. *Taeniothaerus* sp.

GSWA F43790, latex cast of external mould of ventral valve.

PLATE 1

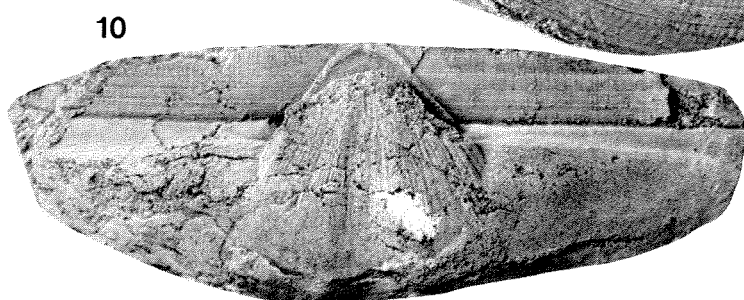
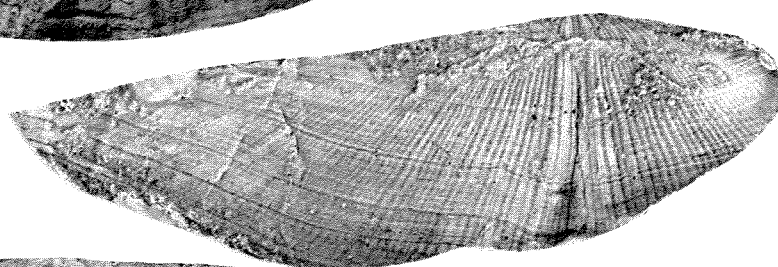
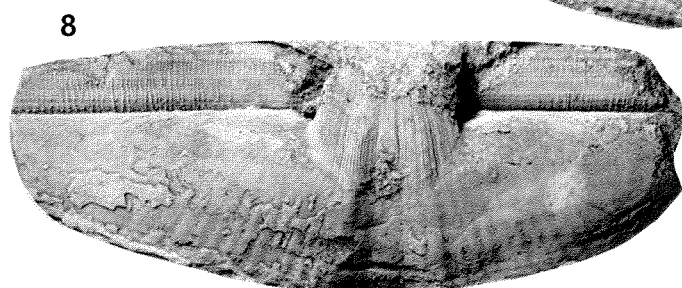
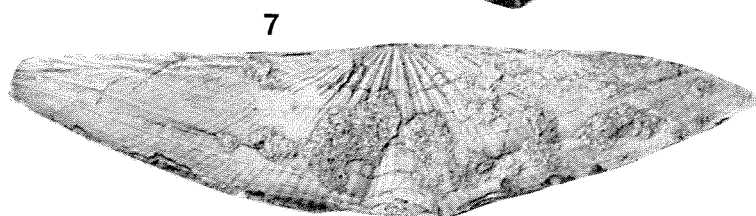
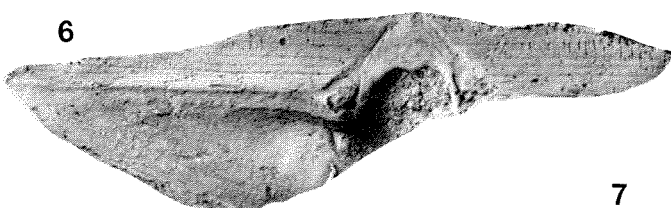
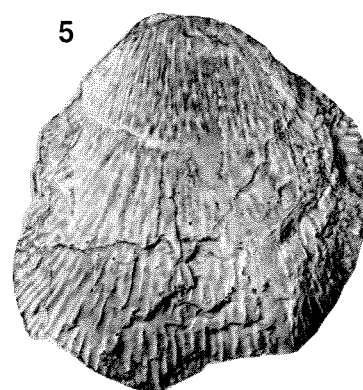
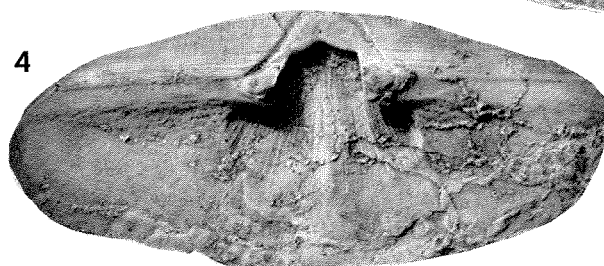
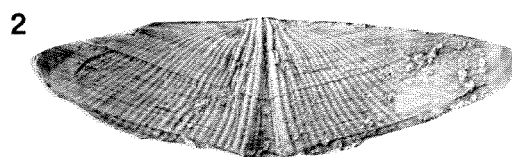
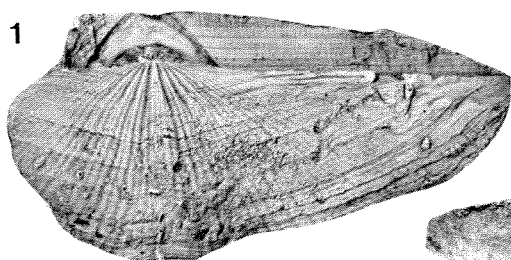


PLATE 2

All figures reproduced at natural size and coated with ammonium chloride prior to photography.

Figs 1 - 9. *Pseudomonotis (Trematiconcha) carnarvonensis* sp. nov.

1. **Paratype**, GSWA F43795, latex cast of external impression of front of right valve.
2. **Holotype**, GSWA F43796, latex cast of external impression of anteroventrally incomplete right valve.
3. **Paratype**, GSWA F43797, latex cast of internal impression of anterior part of right valve.
- 4-7. Latex casts of external impressions of fragments of right and left (fig. 6) valve, paratypes GSWA F43798, F43799, F43800, F43801.
8. **Paratype**, GSWA F43802, latex cast of internal impression of incomplete left valve.
9. **Paratype**, GSWA F43803, internal cast of left valve.

PLATE 2

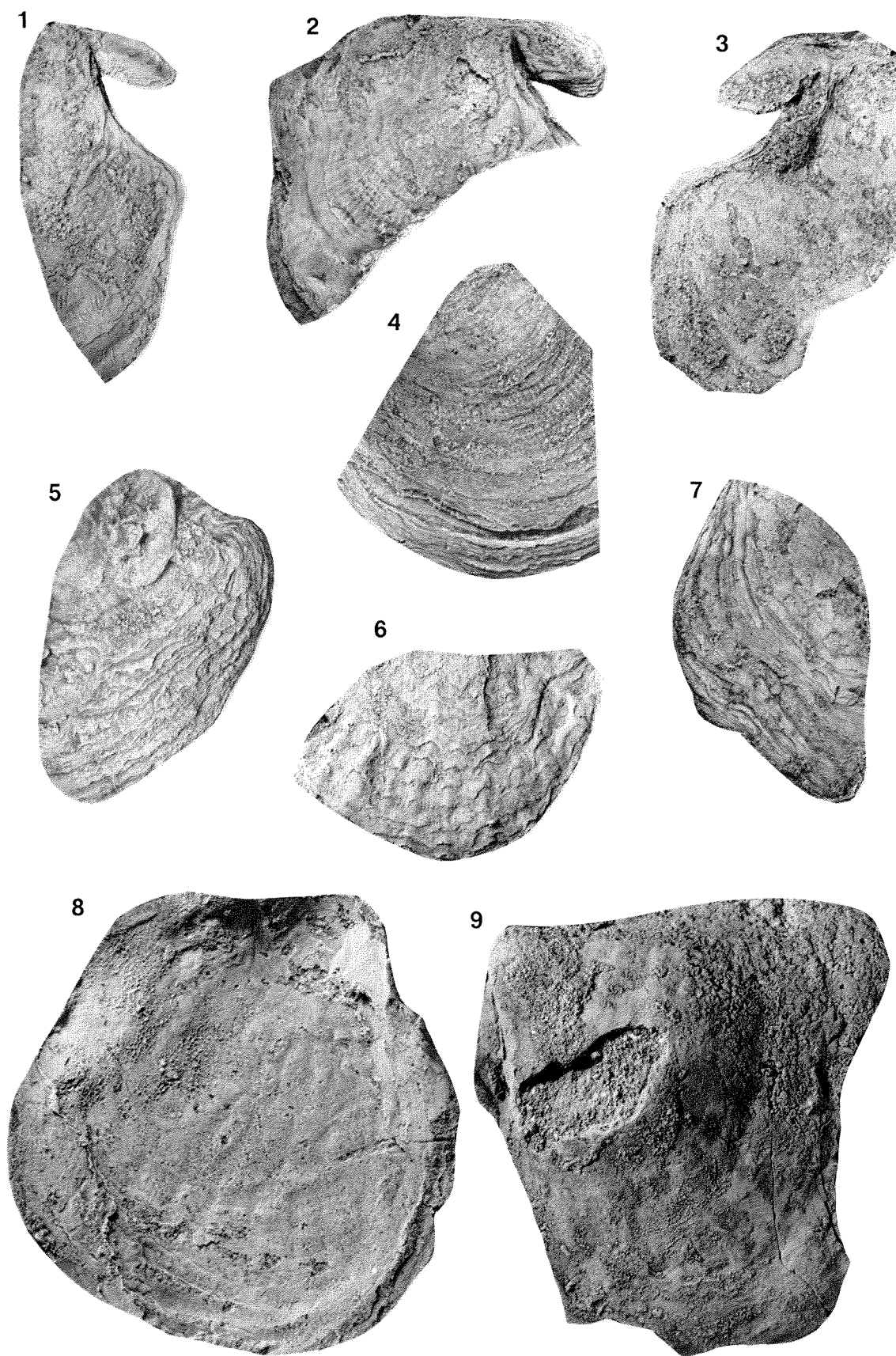


PLATE 3

All specimens of natural size and coated with ammonium chloride prior to photography.

Figs 1, 3, 4, 6. *Pseudomonotis (Trematiconda) carnarvonensis* sp. nov.

1. **Paratype**, GSWA F43813, latex cast of external impression of distal part of left valve.

3. **Paratype**, GSWA F43815, internal impression of left valve.

4,6. **Paratype**, GSWA F43816, latex cast and actual mould showing internal impression of left valve.

Fig. 5. *Etheripecten* sp.

Latex cast of external impression of proximal part of right valve. GSWA F43814.

Fig. 2. Worm trail indet.

Latex cast of trail, GSWA F43817.

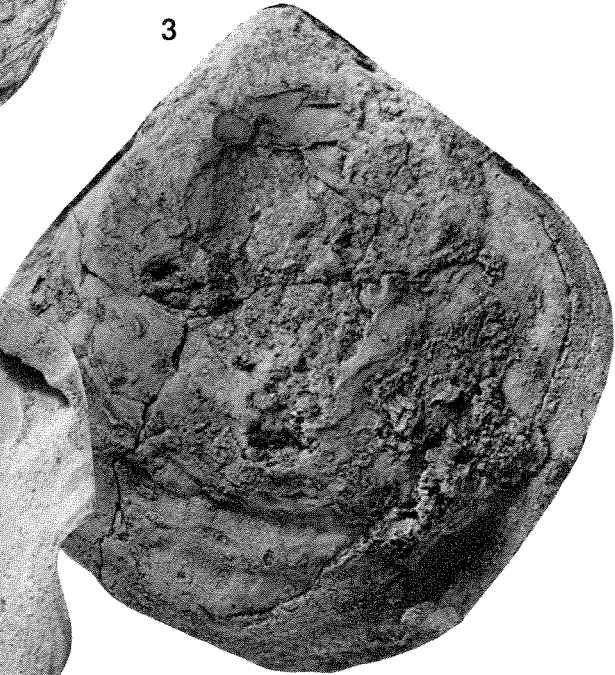
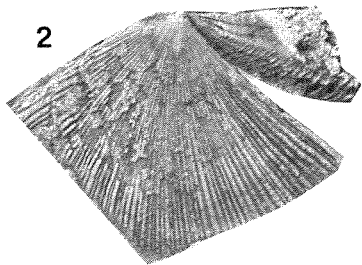


PLATE 4

All figures of natural size and coated with ammonium chloride prior to photography.

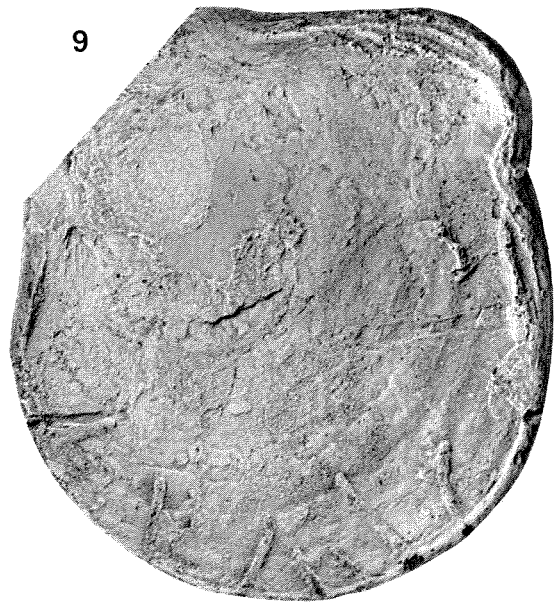
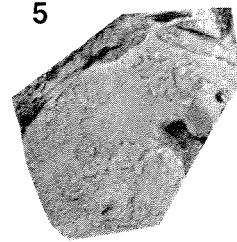
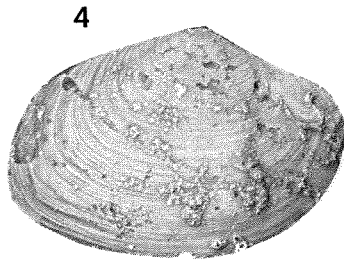
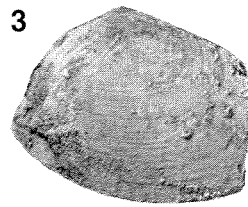
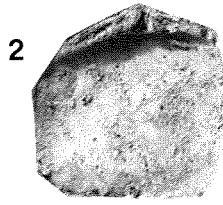
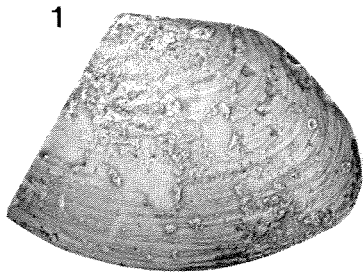
Figs 1 - 5. *Oriocrassatella* sp. cf. *O. stokesi* Etheridge Jnr 1907

1. Latex cast of external impression of anteriorly incomplete left valve, GSWA F43804.
2. Latex cast of internal impression of dorsocentral part of right? valve, GSWA F43805.
3. Latex cast of poorly preserved external impression of left valve.
4. Latex cast of external impression of right valve. GSWA F43807.
5. GSWA F43808.

Figs 6 - 9. **Gen. et sp. indet.**

6. Latex cast of internal impression of incomplete right valve, GSWA F43809.
7. Cast of inside of incomplete left valve, GSWA F43810.
8. Cast of internal impression of left valve, GSWA F43811.
9. Latex cast of internal impression of incomplete right valve, GSWA F43812.

PLATE 4



GEOLOGY AND EXPLORATION HISTORY OF URANIFEROUS AND AURIFEROUS PYRITIC CONGLOMERATES WESTERN AUSTRALIA

by J.D. Carter and R.D. Gee

ABSTRACT

Precambrian pyritic conglomerates carrying uranium or gold occur in four tectonic units, the Pilbara Block, the Hamersley Basin, the Nabberu Basin, and Halls Creek Province. So far, no concentration of uranium or gold of commercial significance has been identified in these conglomerates.

Only the uraniferous pyritic conglomerates of the lower part of the Fortescue Group of the Hamersley Basin are sufficiently well known to allow comparisons to be made with the uranium- and gold-bearing conglomerates of Canada and South Africa. The Fortescue Group conglomerates were formed between about 2.75 and 2.70 Ga ago. In the Hardey Sandstone formation of this group, uranium occurs as fine uraninite grains in thucholite pellets, and detrital grains of anatase contain a uraniferous phase which is almost certainly brannerite.

Overlying the Hardey Sandstone, and separated from it by the Kylene Basalt, is an unnamed uraniferous sequence of sandstones and conglomerates with detrital grains composed of intergrowths of illite, uranite, galena, and intergrowths of illite, coffinite, uraninite, and galena. No thucholite pellets have been identified in these rocks.

The uraniferous, pyritic conglomerates, and associated rocks of the Fortescue Group contain very little gold.

INTRODUCTION

It is now nearly thirty years since the similarity of some sedimentary sequences in Western Australia with the Elliot Lake and Witwatersrand sequences stimulated exploration for uraniferous and auriferous pyritic quartz-pebble conglomerates in this State. During this time, nearly 40 exploration programs have been mounted, but all without commercial success.

Large amounts of valuable geological, geophysical and geochemical exploration data are now available on the microfilm open-file system of the Geological Survey. These are not normally published, but a review of the data provides the best means for outlining the results of exploration of pyritic conglomerates*. By way of acknowledgement, the following companies are noted as having made useful contributions to the testing of the pyritic quartz-pebble conglomerate model: Goldfields Exp. Pty Ltd; BP Minerals Aust. Pty Ltd; and Asarco (Aust) Pty Ltd.

Uraniferous and auriferous pyritic conglomerates occur in four localities in Western Australia, but only the well-known uraniferous pyritic conglomerates of the lower part of the Fortescue Group have been investigated in sufficient detail to allow satisfactory comparisons to be made between these rocks and the uranium- and gold-bearing pyritic

conglomerates in other parts of the world. Lower Fortescue Group conglomerates outcrop principally along the northern margin of the Hamersley Basin (Fig 1). Other Precambrian pyritic conglomerates—traces of uranium or gold—occur in the Pilbara Block, the Nabberu Basin, and the mobile belt of Halls Creek Province, where the basal rocks include a sequence containing a little pyrite and uranium. Age controls on pyritic conglomerates are shown in Table 1.

For completeness, a brief description is included of the Woodline Beds (about 1.6 Ga old), which were explored for palaeoplacers of uranium and gold. Reference is also made to the Kaluweerie Conglomerate as there was a suggestion that the unit may have carried Proterozoic uranium placers.

OTHER THAN PILBARA BLOCK AND HAMERSLEY BASIN

Two occurrences of pyritic conglomerate which could correspond in age to those of the lower part of the Fortescue Group are found: in the Peak Hill Metamorphics of the Nabberu Basin, and the Saunders Creek Formation of the Halls Creek Province. But, unfortunately, descriptions of exploration are too general to allow useful comparisons to be drawn between these rocks and those of the lower Fortescue Group.

Geological Survey microfilm open-file item numbers of exploration operations now described are: Peak Hill Metamorphics - Item No. 1263, Gold-

*"Pyritic conglomerate" is a general term employed for pyrite-bearing rocks including "oligomictic quartz-pebble conglomerates" and "polymictic conglomerates".

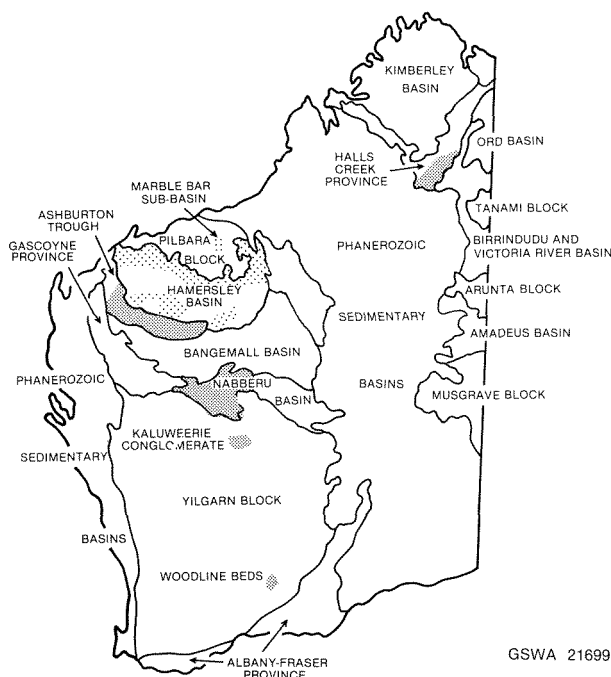


FIGURE 1. Major tectonic units of Western Australia showing prospective areas of Precambrian clastic sequences. Light stippling—areas of clastic sequences containing quartz-pebble conglomerates 2.5 to 3.0 Ga in age. Dark stippling—area of clastic sequences of about 2.0 Ga in age.

fields Exp Pty Ltd; Saunders Creek Formation - Item No. 839, BP Minerals Aust Pty Ltd; and Woodline Beds - Item No. 390, Asarco (Aust) Pty.

NABBERU BASIN PEAK HILL METAMORPHICS

The Nabberu Basin contains two sedimentary sequences, the older being the western sequence of the Glengarry Sub-basin. Here, the oldest rocks, the Peak Hill Metamorphics, have weakly auriferous pyritic conglomerates with traces of uranium at their base. The conglomerates are oligomictic quartzite-pebble varieties. Immediately overlying the pyritic conglomerates are magnetite-bearing rocks of the Peak Hill Metamorphics; and these are overlain by the Glengarry Group, which is believed to be about 2.0 Ga old.

The pyritic conglomerates and associated rocks are probably less than 20 km² in extent. An exploration program including 10 drill holes totalling about 1 000 m tested the sequence for gold and uranium palaeoplacers. One hole proved more than 80 m of variably pyritic quartzite and conglomer-

TABLE 1. AGE CONTROLS OF PYRITIC CONGLOMERATES

Age (Ga)	Pilbara Block	Ashburton Trough Hamersley Basin	Nabberu Basin Glengarry Sub-Basin	Yilgarn Block	Kimberley Basin Halls Creek Province
1.9				Kaluweerie Conglomerate Woodline Beds: about 1.6 Ga; weakly uraniferous pyritic sequence contains conglomerates.	
2.0		Wyloo Group Mount Bruce Supergroup (3) Turee Group (2) Hamersley Group: about 2.5 Ga; magnetite bearing rocks (1) Fortescue Group: about 2 750 to 2 500 Ga; uraniferous and weakly uraniferous pyritic conlomerates	Glengarry Group Peak Hill Metamorphics age uncertain; magnetite-bearing rocks overlie weakly auriferous and uraniferous pyritic conglomerates		Kimberley Basin: pyritic conglomerates unknown Halls Creek Group: age uncertain; near the base the Saunders Creek Formation contains a weakly uraniferous pyritic sequence including conglomerates
2.8	Gorge Creek Group: about 3.0 Ga; weakly auriferous pyritic conglomerates				
3.0	Warrawoona Group: about 3 550 to 3 400 Ga				

ate; the best gold values were 2.2 ppm over 0.3 m and 1.3 ppm over 1 m. The best uranium analysis was 22 ppm U_3O_8 , and the highest value obtained in other holes was 30 ppm U_3O_8 . The mode of occurrence of uranium is not described and detrital pyrite is not mentioned.

Gee (1980) suggested that a broad lithological similarity exists between the Glengarry Group and the Wyloo Group. Should these groups be similar in age, then the pyritic rocks at the base of the Peak Hill metamorphics could correspond to the pyritic conglomerates of the lower Fortescue Group.

HALLS CREEK PROVINCE

SAUNDERS CREEK FORMATION

The Saunders Creek Formation contains the oldest conglomerates of the Halls Creek Group—the age of which is uncertain, though likely to be more than 2.0 Ga. The formation is about 190 m thick and consists of quartz greywacke, shale, and conglomerate beds with radioactive horizons. These rocks outcrop around domes, and exposures are probably less than 15 km².

A diamond-drill hole intersected pyrite at various intervals below 106 m. The best uranium analysis was 1 300 ppm U_3O_8 over 0.1 m, but the majority of results fell below 40 ppm U_3O_8 over 2 m. The best gold analysis was 0.2 ppm over 2 m. A radioactive mineral was determined as thorogummite, but detrital pyrite is not described.

No information in available descriptions (Mercer, 1961; and BP Minerals Australia Pty Ltd) suggests that this formation contains rocks similar to the uraniferous pyritic conglomerates of the lower Fortescue Group.

YILGARN BLOCK

WOODLINE BEDS

Poorly exposed, gently dipping shales and quartzites of the Woodline Beds outcrop in low hills over an area of about 330 km² in the Yilgarn Block. The sequence is about 240 m thick; and the lower part, of some 148 m, is described as pyritic quartzite and shale with (apparently) thin beds of pyritic sandstone and conglomerate.

Some 270 drill samples were analyzed for gold and uranium, but most results lay near or below the limits of detection. The best uranium analysis was 47 ppm U_3O_8 , and 0.32 ppm gold. The source of uranium (contained within shales) was not determined.

An age for the Woodline Beds of 1620 ± 100 Ma is given by Low (1975). Overall, descriptions of these rocks indicate they are not similar in lithological composition to the uraniferous conglomerates of the lower Fortescue Group.

KALUWEERIE CONGLOMERATE

It has been suggested (Allchurch and Bunting, 1976) that a sequence of carnotite-bearing sediments—including polymictic conglomerate overlying granitic rocks at Kaluweerie Hill in the Yilgarn Block, is of Proterozoic age and may have contained uranium “possibly of placer type”. No features of the descriptions of these rocks and their mineralization suggest that this is a likely possibility.

PILBARA BLOCK AND HAMERSLEY BASIN

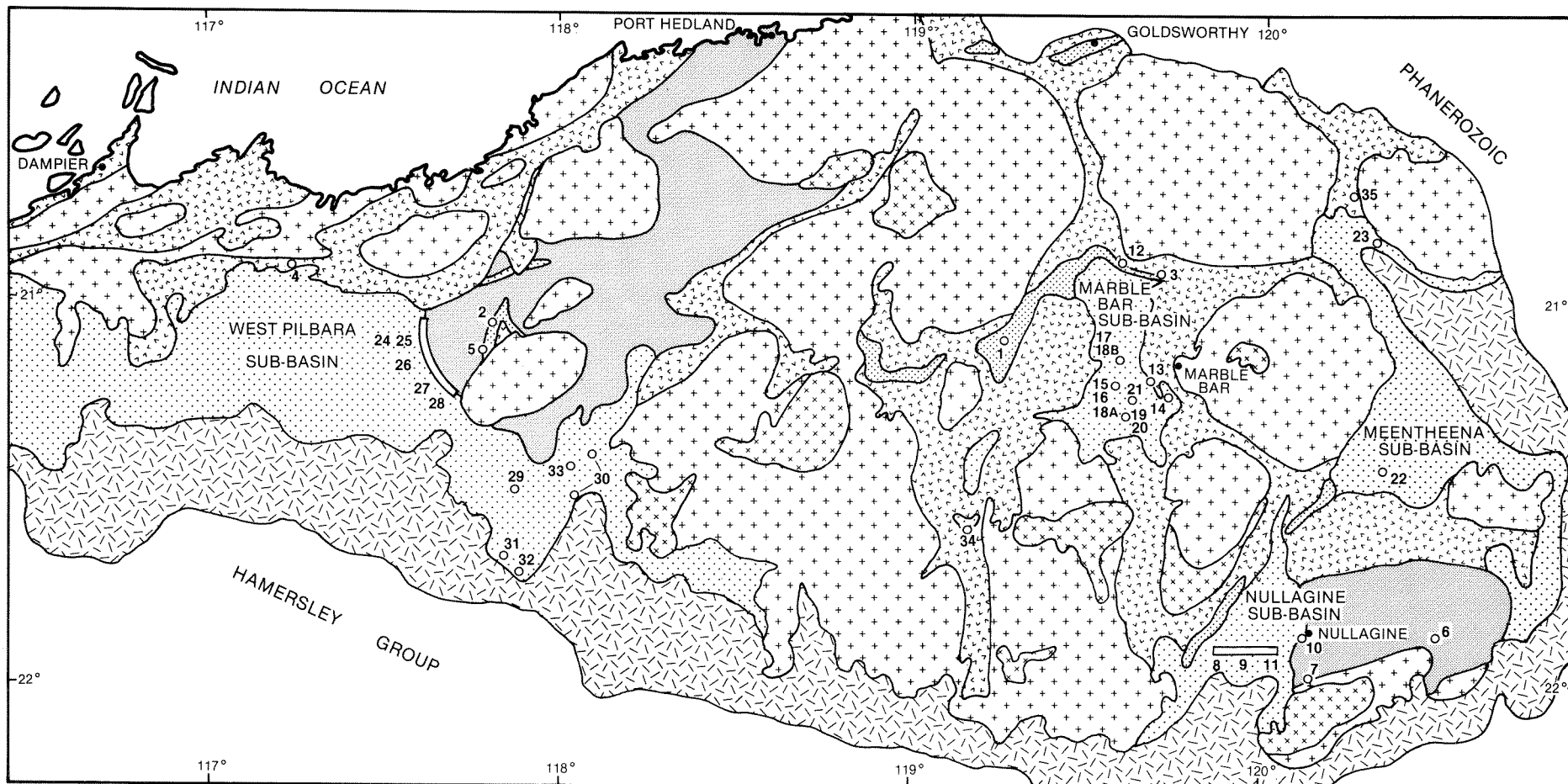
Pyritic conglomerates occur at several stratigraphical levels within the upper part of the Gorge Creek Group of the Pilbara Block, and in the lower formations of the Fortescue Group of the Hamersley Basin. But, as Table 2 shows, uraniferous pyritic conglomerates are found only in the lower Fortescue Group. Conglomerates of the Gorge Creek Group (approximately 3.0 Ga) include pyritic oligomictic quartz-pebble varieties which are sometimes weakly auriferous. As no uranium mineralization is known in these rocks, Gorge Creek Group conglomerates add to evidence for a maximum age constraint for the appearance of uraniferous pyritic conglomerates.

Uraniferous thucholite pellets have been identified in the Hardey Sandstone of the lower Fortescue Group, and in a younger, unnamed unit. Uranium occurs in detrital grains composed largely of illite with uraninite or coffinite, and possibly brannerite. Grades found, so far, are too low to attract mining. Gold is rare and, when present, usually occurs in little more than trace amounts. The base of the Fortescue Group is dated at about 2.75 Ga (Richards and Blockley, 1984). Age dating of the Brockman Iron Formation of the Hamersley Group at 2.49 Ga provides a minimum age for Fortescue Group uraniferous pyritic conglomerates, which probably accumulated between about 2.75 and 2.70 Ga ago.

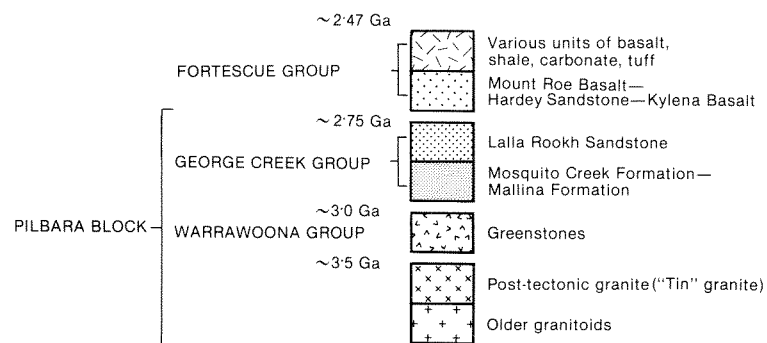
PILBARA BLOCK

Figure 2 illustrates the general geology, and Table 2 shows the principal elements of stratigraphy of the Pilbara Block, which is divisible into three main components:

- (1) synclinal greenstone belts of the Pilbara Supergroup;
- (2) older granitoids (migmatites, gneisses, foliated granodiorite, adamellite, and tonalite), which intrude the greenstone belts and form the bulk of the intervening batholithic domes; and
- (3) younger granitoids including the “tin granites”, which occur as small post-tectonic plutons within major granitoid domes.



GSWA 21700



○₉ Mineral – exploration areas: numbers refer to various projects listed in Table 3

FIGURE 2. Simplified geology of the Pilbara Block and adjacent Hamersley Basin (modified from Hickman, 1983) showing mineral-exploration areas listed in Table 3.

Three stratigraphical units form the Pilbara Super-group:

- (1) the Warrawoona Group, a predominantly volcanic assemblage of ultramafic, mafic, and felsic volcanics, and subordinate chert and sediments; overlain by,
- (2) the Gorge Creek Group, largely a sedimentary sequence with subordinate mafic volcanics and iron-formation. Auriferous pyritic conglomerates occur within the upper part of this group; and
- (3) in the western part of the Pilbara Block, these groups are overlain by a volcanic unit of relatively small extent, the Whim Creek Group (not shown on Fig. 2 or in Table 2).

URANIUM AND GOLD

The Pilbara Block is the obvious source of heavy minerals for younger sedimentary rocks of this region. However, contrary to what may be expected from the evidence of weak or only trace gold mineralization in the Gorge Creek and Fortescue Groups and the sometimes strongly mineralized uraniferous conglomerates of the latter, uranium mineralization now is rare in the Pilbara Block although gold is found in a number of environments.

The sole uranium "mineral" known (formerly termed "pilbarite") is a mixture of kasolite and thorogummite (Hornea, 1957) and is a minor constituent of a few pegmatites associated with the older granitoid suite. Older granitoids carry up to 5 ppm uranium, but some "tin granites" are enriched in the metal and contain values up to a mean of 12 ppm uranium. In general therefore, "tin granites" apart, the Pilbara Block is an apparently unpromising source for uranium.

Gold occurs in a number of environments. Hickman (1983) classifies sources into four principal types. They are gold in quartz veins within:

- volcanic and ultramafic rocks (Warrawoona Group);
- sedimentary rocks (Mosquito Creek Formation);
- granitic rocks; and
- quartz-feldspar porphyry.

Production has been moderately important and three gold mining centres in the Pilbara Block are classed as being production centres of the second rank of importance within the State (Geological Survey Map: "Mineral Deposits of Western Australia 1981).

GORGE CREEK GROUP

Pyritic conglomerates occur in two of the three clastic formations of the group, the Lalla Rookh

Sandstone and Mosquito Creek Formation. Some Gorge Creek Group pyritic conglomerates are auriferous but none are uraniferous.

Lalla Rookh Sandstone

This formation ranges up to 5 km thick and is composed predominantly of fluvial sandstones, quartzites, and conglomerates. The principal lithology is a well-sorted, sometimes pyritic, feldspathic sandstone. In pyritic varieties, the mineral is occasionally concentrated on foreset bedding planes.

Conglomerates are found usually as thin pebble beds but coarse pebble and cobble conglomerates, tens of metres in thickness, also occur. Pebbles are subrounded to rounded and include quartzite, chert, vein quartz, felsic lava, basalt, serpentinite, and, rarely, granite. Mature oligomictic quartz-pebble varieties carry detrital pyrite, including buckshot pyrite, which frequently forms 5% of some conglomerates and may constitute up to 15% of the rocks.

The environment of deposition of Lalla Rookh Sandstone was predominantly fluvial, but included deltaic and possibly shallow-water marine conditions. Many palaeochannels exist within the formation and there is evidence of several phases of reworking of parts of the sequence.

Available mineral exploration evidence, which is not large (Table 3 and personal communications), suggests that the conglomerates are unlikely to contain significant uranium. Radioactivity over the formation has been ascribed to thorium minerals.

Low gold values have been detected in pyritic oligomictic quartz-pebble conglomerates, but so far no gold-mining operation is known to have been based on these rocks, and their economic potential is uncertain.

Mosquito Creek Formation

This formation and its equivalent in the West Pilbara, the Mallina Formation, consist largely of poorly sorted schistose sandstone, shaly sediments, and occasional weakly auriferous pyritic conglomerates. No uranium of significance is known in them. A radioactivity survey failed to detect an anomaly over auriferous conglomerates (Table 3 No. 7).

The sediments are described as wacke-siltstones and wacke-sandstones, and turbidites. Rock composition and (often) poor sorting suggest relatively

TABLE 2. SIMPLIFIED STRATIGRAPHY AND TYPE OF MINERALIZATION—PILBARA BLACK AND NORTHERN PART OF HAMERSLEY BASIN.

Group	General Thickness (km)	Formation	Lithology	Type	Age (Ga)	
HAMERSLEY GROUP	0.5	Various formations	Shale, iron-formation, and dolerite		2.49	
	0.6	Brockman Iron Formation	Banded iron-formation			
	0.6	Various formations	Dolomite, chert, shale, iron-formation			
FORTESCUE GROUP	0.3	Jeerinah Formation	Shale, sandstone, and chert			
	0.2	Maddina Basalt	Basalt			2.6
	0.1	Kuruna Siltstone	Siltstone			
	0.3	Nymerina Basalt	Basalt			
	0.1	Tumbiana Formation	Carbonate rock and tuff			
	0 to 0.5	Various unnamed lithologies	Local sandstone, conglomerate, and siltstone	(a)	about 2.7	
	0.3	Kylena Basalt	Basalt, minor sandstone, and conglomerate			"TIN GRANITES"
	1.0	Hardey Sandstone	Sandstone, conglomerate, shale and minor basalt	(a) and local (c)		
	0.2	Mount Roe Basalt	Basalt and local conglomerate and sandstone	local (b)		
						2.7
----- Unconformity -----					2.8-----	
GORGE CREEK GROUP	5.0	Mosquito Creek Formation (Mallina Formation)	Psammitic and pelitic schists	minor (b)	about 3.0	2.9
	5.0	Lalla Rookh Sandstone	Sandstone and conglomerate	(b)	3.0	
			Local unconformity			"OLDER GRANITOIDS"
	3.0		Mafic volcanics and iron-formation			
	1.5	Corboy Formation	Quartzite, sandstone and and psammo-pelitic rocks			
						3.3
----- Local unconformity -----						
WARRAWOONA GROUP	15.6		Ultramafic, mafic, and felsic volcanics; iron-formation, chert and sediments	(d)	3.4 to 3.55	

(a) Uraniferous pyritic oligomictic quartz-pebble conglomerate.

(c) Auriferous pyritic polymictic conglomerate.

(b) Auriferous pyritic oligomictic quartz-pebble

(d) Auriferous quartz veins.

After Hickman (1983)

rapid accumulation under unstable conditions. Turbidity currents probably accounted for the deposition of a large part of the sequence in an environment generally unsuitable for the generation of uranium and gold placer deposits.

HAMERSLEY BASIN

At about 2.75 Ga, volcanic activity accompanied by clastic sedimentation commenced across the Pilbara Block Basalt flows and sequences of conglomerate, sandstone, and shale, of this episode, are assigned to the Fortescue Group. The early basalt and sedimentary sequences pass upwards into the Tumbiana Formation and younger basalt and clas-

tic formations which in turn pass upwards into iron-formations, and shales of the Hamersley Group (Table 2).

The landscape over which Fortescue Group rocks were laid down consisted of granite and quartzite uplands, with lowlands following the more readily weathered rocks of the greenstone belts. The earlier formations, Mount Roe Basalt and Hardey Sandstone, were deposited within intermontane basins lying along the greenstone lowlands, and as these filled, younger rocks such as lavas of Kylena Basalt encroached progressively on to the uplands. Over granitic terrain, the basal formation is often Kylena Basalt. Basal conglomerates usually underlie basalts where these rest directly upon the Pilbara Block. The more important basins shown on Figure 2, are

the Nullagine Sub-basin, the chief scene of exploration for palaeoplacers of uranium and gold; the Marble Bar Sub-basin, in which the unnamed unit occurs; and the West Pilbara Sub-basin (Blake 1984).

Many accounts of Fortescue Group rocks employ superseded stratigraphical nomenclature, which Hickman (1983) explains and rationalizes. He incorporates within Hardey Sandstone an equivalent formation, Cliff Springs Formation. Beatons Creek Conglomerate, Glen Herring Shale, and Green Hole Conglomerate, are separated as members of the Hardey Sandstone.

Mineral Exploration

A considerable volume of exploration for palaeoplacer deposits of uranium and gold in conglomerates and sandstones has taken place over the lower formations of the Fortescue Group. Figure 3 illustrates generalized lithologies and principal uranium intersections of drill holes. A summary of exploration statistics is contained in the Appendix. For both Figure 3 and the Appendix, the cut-off value employed in the selection of uranium intersections (with one or two exceptions) is 250 ppm U_3O_8 .

The only mineralization in the lower Fortescue Group, known to have attracted mining attention, occurs as small and sporadic auriferous, pyritic conglomerates at its base. These are almost invariably restricted to the immediate vicinity of gold occurrences in the Pilbara Block. Early in the century a little gold was produced from localities such as the Just-in-Time and Tassy Queen mines, a few kilometres southwest of Marble Bar. Gold was won also from the conglomerate at Beatons Creek near Nullagine.

It was not until 1955 that possibilities of uranium occurring in Fortescue Group conglomerates were considered. In that year, Enterprise Exploration Pty Ltd conducted a brief survey based on the similarity of these conglomerates to the uranium-bearing conglomerates of Blind River, Canada. Ground scintillometer traverses were made but no anomalous radioactivity was discovered.

In the same year, the Australian Bureau of Mineral Resources flew an airborne reconnaissance scintillograph survey of part of the east Pilbara region

No further exploration activity is known until 1968 when large exploration operations began. The gen-

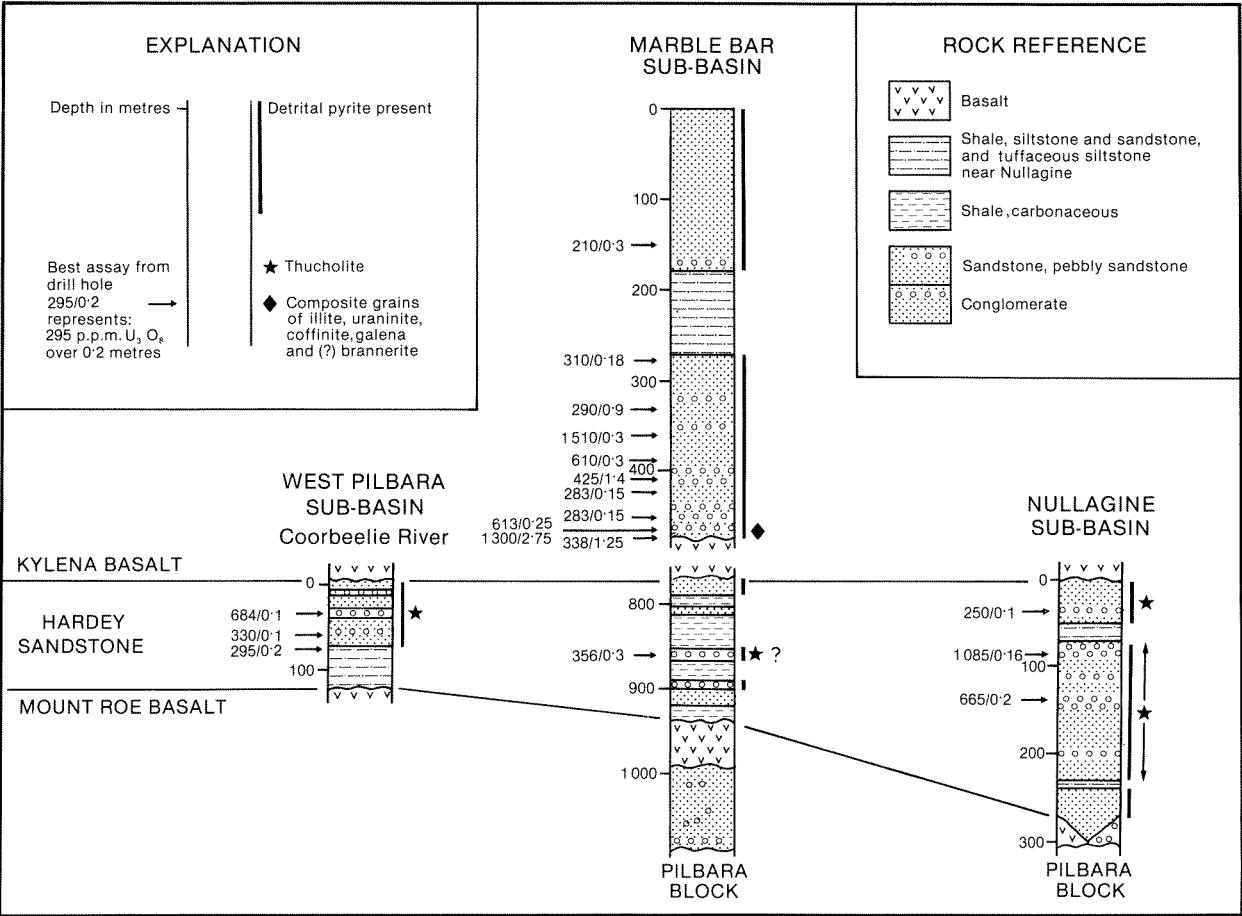


FIGURE 3. Composite lithological sections of the lower Fortescue Group and U_3O_8 data in the three sub-basins that have attracted most exploration attention. Data derived from company reports.

eral approach was to employ airborne radiometric surveys to locate radioactive outcrops and to follow-up with ground radiometric surveys, geological mapping, and drilling. By 1982, when operations had largely ceased, no economic occurrence of uranium had been identified, although a number of good drill-hole intersections were made.

Mineral explorers obtained very high uranium and gold values from analyses of surface rock-chip samples. Values of uranium in excess of 4 000 ppm U_3O_8 and of gold up to 6 ppm are mentioned in reports, but analyses of drill core from corresponding horizons reveal uranium values generally below 500 ppm U_3O_8 and gold, at best, in little more than trace amounts. Surface enrichment of uranium is readily explained. The large pyrite content of Fortescue Group conglomerates and sandstone when oxidized, produces acid weathering conditions in which limonite is ultimately formed. Uranium is mobilized during hydrolytic reactions accompanying the formation of limonite; and the metal is concentrated by coprecipitation with, and absorption by, hydrous iron oxides. Most gold values above 1 ppm probably result from near-surface enrichment.

A weakness in some exploration work is the failure to determine the mode of occurrence of uranium responsible for high uranium values. A number are known to be derived in part from heavy-mineral resistates such as monazite, xenotime, and zircon-minerals commonly found in Fortescue Group sediments. Only two operators report the mode of occurrence of uranium mineralization (Table 3, Nos 8 and 11). The mineralogy of uraniferous drill core from the unnamed unit was determined by the Western Australian Government Chemical Laboratories

NULLAGINE SUB-BASIN

Stratigraphy and lithology

This fan-shaped basin is more than 60 km long. To the north it is bounded by greenstone belts and granitoid batholiths; and, in the south, it opens into the Hamersley Basin (Fig. 2). The lower part of the Fortescue Group is represented by the following sequences:

- | | |
|---|--|
| (3) Kylenea Basalt (up to 300m) | Extensive basalt flows |
| (2) Hardey Sandstone (probably about 300 m in the southwest of the sub-basin) | In places it rests directly upon the Pilbara Block; it is intruded by a dacite porphyry, the Spinaway Porphyry, towards its base |
| (1) Mount Roe Basalt (up to 50 m) | Basalt flows confined to palaeovalleys |

Radioactive conglomerates in the Hardey Sandstone were explored for uranium and gold in the southwest part of the sub-basin along a strike length of more than 20 km of gently southward dipping sediments. Most if not all of the prospective parts of the formation in this area were tested by diamond drilling (Table 3 Nos 8 and 11).

A composite stratigraphical column of Hardey Sandstone is shown in Figure 3. Within the formation there are frequent facies variations, and gross lithological characteristics are controlled by a structural high which divides the sub-basin about its long axis. From west to east across the high, pyritic oligomictic conglomerate beds give way to polymictic conglomerates with diminishing pyrite content, shaly sediments increase, and great thicknesses of the basal conglomerate are developed, probably within fault-bounded troughs. Recent drilling near Nullagine proved more than 700 m of basal conglomerate.

In the southwest of the sub-basin the predominant lithology is coarse feldspathic sandstone which is frequently pebbly; there are five principal beds of conglomerate in addition to a basal conglomerate. The sequence includes siltstones and shales, which may be tuffaceous, and a thick bed provides a useful marker horizon (Fig. 3).

Sandstones consist of angular to subangular, coarse to very coarse, poorly sorted quartz grains, and up to 30% matrix of light-green sericite derived from altered feldspar. Quartz pebbles are scattered throughout, and may form discontinuous layers. Carbonaceous material occurs both as thin stringers and specks in the matrix.

Most sandstone contains pyrite and thucholite in thin discontinuous layers on bedding and cross-bedding surfaces as well as in the matrix. Such sandstones may yield enhanced uranium values and an intersection of 305 ppm U_3O_8 over 0.6 m has been reported.

Up to 12% of Hardey Sandstone consists of conglomerates which occur in bands up to 20 m thick. These are stained red by limonite derived from pyrite. Conglomerates are both clast and matrix supported. Clasts are composed chiefly of light-grey or milky vein quartz, black and white chert, and, less frequently, quartzite, andesite, granitoid, siltstone, sideritic carbonate, and light-yellow clay galls. They are subangular to subrounded and range in size from 0.5 cm to 10 cm.

The matrix is formed of poorly sorted quartz and feldspar grains; a high proportion of sericite lends green colours to the rocks. In some cases, up to 60% carbonaceous material occurs in the matrix. Pyrite and thucholite commonly occur as disseminations and as concentrations around quartz grains. Buckshot pyrite of detrital origin ranges from 0.2 to

TABLE 3. URANIUM AND GOLD OPERATIONS ON PYRITIC CONGLOMERATES AND SANDSTONE, GORGE CREEK GROUP AND LOWER FORTESCUE GROUP

<i>Formations and sub-basins</i>	<i>Map No. (a)</i>	<i>Item No. (b)</i>	<i>Company</i>	<i>Duration</i>	<i>Drilling cd: core d:non core</i>	<i>Significant intersections and analyses U₃₀₈ ppm (Au) ppm</i>	<i>Comments</i>
Lalla Rookh Sandstone	1	1148	Western Mining Corp. Ltd	1970-72	—	28 (—)	Radioactivity principally due to thorium
	2	1408	Freeport Australia Inc	1980-82	—	— (0.04)	Weakly auriferous conglomerates believed to have been deposited in an offshore-marine environment
	3	1420	Pancontinental Mining Ltd	1981-82	—	—	Quartz- and chert-pebble conglomerates, placers mostly magnetite; no clearly pyritic placers observed
Mosquito Creek Formation and Mallina Formation	4	1363	Union Corp Australia Pty Ltd	1980-82	—	— (3.5)	Weakly auriferous pyritic chert and quartz-pebble conglomerates; no anomalous radioactivity detected
	5	1389	CRA Exploration Pty Ltd	1981-82	—	18 (0.12)	Low uranium and gold values in sulphidic sandstones and shales of turbidite sequence
	6	1464	Asarco Australia Pty Ltd	1981	—	— (0.16)	Weakly auriferous pyritic sandstones and conglomerates. Conglomerate returned 0.158 ppm Au, only value above 0.1 ppm Au
	7	1462	Union Corp Australia Pty Ltd	1980-83	—	— (3.14 over 1.2 m)	Auriferous chert and quartz-pebble conglomerates; no anomalous radioactivity
	7A	1467	Western Mining Corp Ltd	1981-83	—	—	"Largely concealed pyritic feldspathic wackes and impure sandstones of the Mallina Formation" examined for gold in quartz veins and within sediments over two areas totalling some 600 km ²
Nullagine Sub-Basin Hardey Sandstone	8	414	Cominco Exploration Pty Ltd	1968-74	cd 14 for 1851 m	425 over 0.6 m	"Uranium occurs as fine uraninite inclusions in carbonaceous pellets within the conglomerate matrix"
	9	147	Esso Australia Ltd	1974	d 11 for 1291 m	124 over 1.0 m (0.1)	Percussion-hole samples may not be representative of horizons intersected
	10	1460	Essex Minerals Company	1978-79	—	130 (<0.1)	Petrography suggests detrital zircon and monazite? In conglomerate unlikely to contributed to uranium assays
	11	1468	Otter Exploration NL Marathon Petroleum Aust	1978-81	d;cd 23 for 1887 m	1085 over 0.16 m (0.5 over 0.1 m)	Uranium mineralization, low grade, thin, and discontinuous
Marble Bar Sub-Basin Mount Roe Basalt	12	1461	Anaconda Australia Inc	1980-83	cd 1 for 86.4 m	— (0.15 over 0.7 cm)	A thin immature quartz cobble and pebble conglomerate with up to 50% iron oxides after detrital pyrite was tested
	13	1463	International Nickel Aust Ltd	1981-82	—	(1.87 ppm over 1.0 m)	Gold analysis of channel sample; auriferous polymictic conglomerates are radioactive

(a) Map number Figure 2

(b) GSWA microfilm open file Item No.

TABLE 3—(Continued).

Formations and sub-basins	Map No. (a)	Item No. (b)	Company	Duration	Drilling cd: core d: non core	Significant intersections and analyses U_3O_8 ppm (Au) ppm	Comments
Hardey Sandstone	14	1466	CRA Exploration Pty Ltd	1981-82	—	2 (0.008)	Immature channel-fill deposit within basalt sequence contains conglomerate and pyritic sandstone
	15	352	Cominco Exploration Pty Ltd	1968	d 3 for 137 m	(seven analyses) <10 (<0.1)	Drill holes failed to intersect anticipated conglomerate extension; yellow gummite in trench ran up to 105 ppm U_3O_8
	16	195	Western Mining Corp Ltd	1971-72	cd 1 for 271 m	356 over 0.3 m (0.6 over 0.3 m)	Hole intersected entire "apparent dip" sequence of Hardey Sandstone of 163 m (Fig. 3); one weakly uraniferous conglomerate analyzed
	17	612	Alcoa of Australia (WA) Ltd	1976-78	(Shaft 6.1 m)	210 (0.07)	"North-east area"; conglomerate in shaft ran up to 33 ppm U_3O_8
	18(a)	1459	Otter Exploration NL Marathon Petroleum Aust	1978-81	—	590 (5.4)	"Main area"; immediately south of ground of Cominco (No. 15) and Western Mining (No. 16). 5.4 ppm Au from outcrop of "middle unit" conglomerate but 62 samples at 25 m intervals did not yield encouraging gold values
unnamed unit	18(b)				—	424 (0.05)	"North-east area"; similar to Alcoa's north-east area (No. 17). Only one of 57 rock chip samples returned detectable gold (0.05 ppm)
	19	612	Alcoa of Australia (WA) Ltd	1976-78	d;cd 9 for 1061 m	1510 over 0.3 m (0.06)	"Main" area. Repeat analyses of high-grade (up to 1510 ppm) intersections gave values ranging only between 7 and 220 ppm U_3O_8 ; see section, "Exploration above the Kylenea Basalt"
	20	1416	Marathon Petroleum Aust Ltd	1981-82	—	436 (nd-below 0.1)	Systematic description of unnamed unit is given; examination of core from Alcoa holes 7 and 9 failed to detect thucholite
	21	1463	International Nickel Aust Ltd	1980-82	cd 1 for 68 m	613 over 0.25 m (0.02)	Mineralogical work by W.A. Government Chemical Laboratories shows uranium occurring in detrital composite grains of illite-uraninite-galena, and of illite-coffinite-uraninite-galena (brannerite possibly in both types)
	22	489	Western Mining Corp Ltd	1970-72	—	— (—)	Ferruginous quartz-pebble conglomerates considered to be too small in extent
East Hamersley Basin Hardey Sandstone	23	1307	CRA Exploration Pty Ltd	1981	—	4 (—)	Quartz-pebble conglomerates briefly examined for gold
West Pilbara Sub-Basin Hardey Sandstone Coorbeelie River	24	427	Utah Development Company	1969	—	—	Reconnaissance radioactivity surveys of conglomerates

TABLE 3—(Continued).

Formations and sub-basins	Map No. (a)	Item No. (b)	Company	Duration	Drilling cd: core d:non core	Significant intersections and analyses U_3O_8 ppm (Au) ppm	Comments
	25	106	International Nickel Aust Ltd	1971-72	cd 3 for 256 m	648 over 0.5 m (0.12)	Intersection of 648 ppm U_3O_8 made in middle of three principal uraniferous conglomerate horizons
	26	385	Pacminex Pty Ltd	1975-76	—	212— (nd)	Reviews Internation Nickel's drill results (No. 25)
	27	662	CRA Exploration Pty Ltd	1976-77	d 3 for 587 m	— (—)	Drilling showed down-dip extensions failed to intersect conglomerates
	28	1304	Marathon Petroleum Aust Ltd	1980-82	cd 4 for 247 m	684 over 0.1 m (0.15 over 0.1 m)	Drilling showed down-dip extensions of uraniferous conglomerates severely disrupted by dolerite intrusion
Other Locations	29	467	CRA Exploration Pty Ltd	1976-77	d 3 for 450 m	39 over 2 m (0.2 over 2 m)	Down-dip extension of an anomalous horizon tested by drilling
	30	450	CRA Exploration Pty Ltd	1977	—	— (—)	Follow-up of airborne radiometric surveys failed to detect mineralized conglomerates
	31	438	Occidental Minerals Corporation	1977	—	20 (0.05)	Follow-up of airborne radiometric surveys failed to detect mineralized conglomerates
	32	1418	Pancontinental Mining Li1982		—	— (—)	"Low degree of sedimentological maturity and marine origin of the Hardey Sandstone rocks preclude them as targets for mineralized pyritic quartz pebble conglomerates"
	33	1465	Carpentaria Ex Co Pty Ltd	1981-82	—	—	A fault-angle depression in Hardey Sandstone where auriferous placers could exist was considered
Locations Elsewhere Hardey Sandstone	34	1458	Texasgulf Australia Ltd	1975-76	—	— (8.15)	Apart from Hardey Sandstone a few values probably due to surface enrichment, gold in Hardy Sandstone conglomerates averaged less than 2 ppm; "in general results are disappointing"
	35	1326	Broken Hill Pty Co Ltd	1979-80	d	— (—)	Hematitic conglomerates believed to be Hardy Sandstone briefly investigated for base metals
90 km southeast of Nullagine (not shown on Fig. 2)		293	Asarco (Aust) Pty Ltd	1969-70	cd 2 for 156 m	47 (<0.05)	Pyritic quartz-pebble conglomerates tested for uranium
		1365	Electrolytic Zinc Co.	1979-81	—	— (1.07)	Gold potential of pyritic quartz-pebble conglomerates in Asarco area was investigated

2 mm in diameter and typically has abraded and pitted surfaces. Thucholite pellets are less abundant and usually smaller than pyrite grains.

Siltstones and shales occur as thin partings and as thick beds of grey-green rock that incorporate minor fine volcanoclastic sediments. A 20 m thick tuffaceous silty shale occurs in the upper part of the formation, and is a useful marker horizon. Uranium values of up to 80 ppm U_3O_8 have been recorded from the shales.

The composition of sandstones and conglomerates indicates both granitoid and quartzite provenance. Sedimentary features point to fluvial deposition from a largely southerly source of sediment. Some explorers also believe that parts of the sequence contain intertidal and estuarine sediments.

Mode of occurrence of uranium

In most analyses from drill core, thorium values are low, indicating that resistate minerals such as monazite do not contribute significantly to the uranium content (Table 4). Although high uranium values such as 1 085 ppm U_3O_8 were obtained by drilling, no detrital uraninite grains have been identified. Cominco Exploration Pty Ltd describe results of investigations as follows:

"Uranium occurs as fine uraninite inclusions in carbonaceous pellets within the conglomerate matrix. The bulk of the pyritic conglomerate sections examined contained the following heavy mineral assemblage:

Pyrite, rounded, up to 2 mm diameter, with chalcopyrite, pyrrhotite, and possibly ilmenite inclusions

Carbonaceous pellets, up to 1 mm diameter, containing fine inclusions of uraninite, pyrite and occasionally veinlets of chalcopyrite

Anatase-quartz intergrowth

Monazite-zircon-xenotime."

Petrographical and mineralogical work reported by Marathon Petroleum Australia Ltd is summarized below:

"Thucholite pellets contain fine inclusions mainly of galena and thorite ($ThSiO_4$). The thorite contains minor uranium, almost certainly as partial substitution of Th, not as a specific phase. Persistent detrital accessory grains of cellular anatase carry minute (1 to 3 micron) grains of a uraniferous phase, almost certainly brannerite. These are the only two modes of occurrences of uranium identified by this investigation. Detailed examination failed to reveal any gold."

Pyrite ranges in size from 0.3 to 1.5 mm and forms up to 10% of individual samples. Some grains enclose chalcopyrite and pyrrhotite. Pyrite is essentially rounded and detrital though authigenic growth probably accounts for some large euhedral crystals.

Thucholite consists of subrounded pellets of compact carbonaceous material, consistently with a diameter of about 1 mm. Pellets contain minute inclusions of galena, thorite and chalcopyrite. Like pyrite, these pellets are detrital but less abundant.

Zircon (to 2%) is a common accessory. An electron microprobe of a grain showed it to be devoid of uranium and thorium.

Anatase, also a common detrital accessory, has an average size of 0.2 mm and an average abundance of 1-2%. Anatase grains contain minute (1 to 3 μ m) inclusions of a uraniferous phase, probably brannerite but possibly though less likely, uraninite. Marathon also report as follows:

"There is a direct correlation between the U_3O_8 and Pb abundance in carbon (thucholite) pellets. Also these pellets appear to be more abundant in samples which also contain more abundant pyrite and quartzose pebbles.

"The grains of detrital zircon and cellular anatase also appear to be more abundant in samples containing most pyrite and thucholite pellets.

"In samples which contain relatively abundant lithic clasts, the quartzose pebbles (and the accessory phases) appear to be relatively less abundant."

TABLE 4. SELECTED CHEMICAL ANALYSES NULLAGINE SUB-BASIN—HARDEY SANDSTONE

(All results in parts per million)

Sample	U_3O_8	U	Th	Cu	Pb	Ni	Co	Cr	Mo	As	Se	Sn	Au	Ag	Zr	Ce	Y	La	Zn	V	Nb	Yb	Sc	Ti
SURFACE ROCK CHIP-SAMPLES																								
54918	-	3000	2	220	130	80	40	20	28	17	1	2	0.025	0.5	100	150	60	25	730	100	10	10	5	800
54703	-	2000	40	65	180	35	15	20	8	5	4	-	0.005	0.5	-	-	-	-	165	30	-	-	-	-
54706	-	1750	85	315	60	55	45	35	0.5	70	1	-	0.005	1	-	-	-	-	300	25	-	-	-	-
53011	-	1550	2	390	110	150	150	20	2	8	2	2	0.025	0.5	200	150	40	25	210	40	10	8	3	800
53938	-	400	1000	75	1200	30	2.5	300	5	60	1	8	0.025	0.5	700	600	300	500	85	40	60	150	5	3000
53969	-	240	340	110	1700	80	2.5	100	8	60	11	10	0.025	0.5	200	10	250	100	50	60	10	60	3	2000
54925	-	430	170	460	250	250	100	50	8	32	1	2	0.025	0.5	200	150	40	25	460	360	10	5	10	10000
DRILL CORE SAMPLES																								
79917	1200	-	135	36	620	34	2	310	10	12	2	8	0.025	0.5	85	10	70	10	-	-	-	-	-	-
84032	1000	-	170	100	690	125	85	55	2	32	2	2	0.025	2	330	40	105	10	-	-	-	-	-	-
79916	970	-	170	70	540	28	3	135	4	12	2	6	0.025	0.5	260	50	70	10	-	-	-	-	-	-
84592	660	-	180	135	570	60	70	28	2	38	2	6	0.025	1	470	40	105	10	-	-	-	-	-	-
84589	580	-	150	105	430	55	65	36	2	24	2	2	0.025	1	440	60	80	10	-	-	-	-	-	-
84029	510	-	80	40	300	75	50	38	4	28	2	20	0.025	0.5	140	30	46	10	-	-	-	-	-	-
84509	470	-	75	105	300	40	65	8	2	38	2	2	0.025	1	135	30	55	10	-	-	-	-	-	-

Marathon Petroleum Australia Ltd Annual Report T.R. 6846 H 3.11.80 - 2.11.81.
Drill-core samples were analyzed by Comilabs Pty Ltd, Adelaide South Australia.

MARBLE BAR SUB-BASIN

Stratigraphy and lithology

This hour-glass shaped basin extends approximately 50 km from north to south, and is enclosed by granitoid batholiths and greenstone belts (Fig. 2). The lower Fortescue Group stratigraphy is represented by:

- | | |
|---------------------------------------|---|
| (4) unnamed unit
(475 m) | Coarse sandstone and conglomerate; minor siltstone |
| (3) Kylene Basalt
(up to 300 m) | Basaltic and andesitic flows |
| (2) Hardey Sandstone
(163 m) | Shale, siltstone, and fine sandstone; minor coarse sandstone and conglomerate |
| (1) Mount Roe Basalt
(up to 150 m) | Mainly basalt and intraflow conglomerate, sandstone and shale |

Exploration in the Mount Roe Basalt

Discontinuous beds of pyritic polymictic and oligomictic quartz-pebble conglomerate, and pyritic sandstone occur below the basalt flows, in fluvial channels cut into the basement. These may attain thicknesses of 100 m. These and smaller sequences of similar sediments within the basalts have been explored for gold and uranium but analyses were low. (Table 3).

Exploration in the Hardey Sandstone

Stratigraphy of the Hardey Sandstone, derived from a drill section is shown in Figure 3. The gross lithology of shale, siltstone, fine sandstone, and minor amounts of conglomerate, contrasts with the largely coarse sandstone and conglomerate of the Nullagine Sub-basin. By way of comparison, however, the uraniferous conglomerate and overlying shaly sequence may correspond to the principal uraniferous conglomerate and tuffaceous siltstone "marker horizon" of the Nullagine Sub-basin.

Three coarsening-upward sequences of shale, siltstone, feldspathic sandstone, and minor amounts of conglomerate, were established by diamond drilling. The conglomerate beds are usually only one metre thick, but are of good oligomictic quartz-pebble conglomerate; they contain pebbles averaging 1.5 cm in diameter and abundant buckshot pyrite

At a locality in the centre of the Marble Bar Sub-basin known as Shady Camp Well, particular attention was given to a bed of oligomictic quartz-pebble conglomerate containing buckshot pyrite which yielded—at the surface—values of 5.4 and 3.85 ppm gold (Table 3, 18

(a)). However, follow-up close-spaced rock-chip sampling at 25 m intervals recorded few gold values greater than 1 ppm; and, in a majority of samples, gold was either very low or not detected.

A diamond-drill hole in this bed made an intersection of 356 ppm U_3O_8 over 0.3 m and a maximum gold value of only 0.6 ppm (Table 3, 16). The mode of occurrence of uranium in this drill core is not known but surface samples of conglomerate returning high uranium analyses are accompanied by high thorium and rare-earth element values, indicating that some uranium is bound up in resistate minerals such as monazite and xenotime.

Ten kilometres to the northeast of the Shady Camp Well area, two coarsening-upward sequences of shale, sandstone, and conglomerate, have been explored. An exploratory shaft (6.1 m deep) exposed a metre of flat-lying conglomerate immediately below Kylene Basalt, and bottomed in sandstone. Best values of 33 ppm U_3O_8 and 0.07 ppm Au were returned from analyses of shaft samples (Table 3 - 17).

No detailed investigation was made of the occurrence of uranium in the Hardey Sandstone, but an electron probe of a green arkosic sandstone from the Shady Camp Well locality showed finely disseminated grains (2-3 μ m) of an unidentified uranium mineral associated with phosphorus, occurring both in lead-bearing graphite grains and along narrow fractures containing pyrite. These graphite grains are probably metamorphosed thucholite particles and thus, as in the Nullagine Sub-basin, uranium is likely to occur at least in part as fine uraninite inclusions in carbonaceous pellets.

Exploration above the Kylene Basalt

In the southern part of the Marble Bar Sub-basin near Limestone Well, a thick sequence of sandstone, conglomerate and subordinate shale is preserved in a fault-bounded basin some 70 km² in area. Formerly these rocks were thought to be a sedimentary sequence intercalated within Kylene Basalt and are shown on maps as "Kylene Basalt: sandstone and grit" (Hickman and Lipple, 1978).

Detailed mapping and drilling have demonstrated that the sequence occupies channels cut into Kylene Basalt, is 475 m thick, and is not overlain by basalt. This sequence, as yet, has no convenient lithostratigraphic name.

The unit was tested for palaeoplacers during three exploration programs, two of which included diamond drilling (Table 3 - 19, 21). High uranium intersections were made, but gold values were insignificant. Curiously, the high uranium values obtained by Alcoa of Australia (Figure 3) were not reproduced during subsequent analyses when values

as low as 10-50% of the originals were obtained. The reason for these discrepancies is not known. International Nickel Australia Ltd, however, obtained 613 ppm U_3O_8 over 0.25 m in a drill hole sited close to an Alcoa hole with an initial value of 1 300 ppm U_3O_8 over 2.75 m (Fig. 3). It is felt, therefore, that Alcoa's high values could have substance, but these clearly need to be treated with caution.

Hunting Geology and Geophysics (Australia) Pty Ltd in a report for Marathon Petroleum Australia Ltd provided the following comprehensive account of this unnamed unit.

Lower sequence (205 m): Pyritic, coarse pebbly feldspathic sandstone and pyritic conglomerate fill at least three palaeochannels in Kylene Basalt. Trough cross-bedding points to deposition in a fluvial environment.

Middle sequence (90 m): Poorly bedded and poorly sorted feldspathic sandstone and carbonaceous siltstone, shale, and rare tuff, apparently represent rapid sedimentation in shallow water following basin subsidence, possibly caused by graben-type fault movement. There is an unconformable relationship with the lower sequence at one locality. Pyrite is rare.

Upper sequence (180 m): Very coarse feldspathic sandstone, and conglomerate, and trough cross-bedding demonstrate a return to fluvial deposition. The sequence is a monotonous succession of very coarse feldspathic sandstone containing some nine intervals of laterally persistent pyritic polymictic and oligomictic quartz-pebble conglomerate. Detrital grains of pyrite are locally abundant in thin bands.

Sandstone which makes up the greater part of the sequences is feldspathic and contains detrital pyrite. Thucholite has not been identified in the sandstone or in any other rock types. The best (but qualified) uranium intersection of 1 510 ppm U_3O_8 over 0.3 m was made in pyritic, coarse, pebbly, feldspathic sandstone.

Conglomerate, which makes up to 5% of the sequences, mostly consists of pebbles and cobbles of vein quartz and chert. A uraniferous zone near the base of the lower sequence was in a matrix-supported greenish grey conglomerate with subrounded 2 cm clasts of quartz and chert, and a matrix largely of green illitic clay, altered feldspar, mica, quartz grains, and detrital pyrite grains up to 2 mm in diameter. Pyrite forms up to 5% of the conglomerate matrix.

Mode of occurrence of uranium

Interesting uranium intersections were made in three drill holes in the lower sequence (Fig. 3), but no significant gold values were found either at the surface or in drill holes (Table 3). Core from the

drill hole of International Nickel Australia Ltd obtained 613 ppm U_3O_8 , 831 ppm Th, and 0.018 ppm Au, over 0.25 m, and contained conspicuous bands of heavy minerals. These bands consist of detrital pyrite and small amounts of molybdenite, galena, chalcophyrite, zircon, monazite, xenotime, tourmaline, and composite radioactive grains. Monazite contains significant amounts of thorium, and xenotime carries thorium and a small amount of uranium.

The major sources of radioactivity are in small (up to 100 μ m) composite grains of two types. One consists of intergrowths of illite, uraninite, and galena; and the second, an intergrowth of illite, coffinite, uraninite, and galena. Titanium is abundant in both types and may be present as brannerite. Uraninite is "earthy" but shows remnant cleavage traces indicating an original crystalline nature. Other radioactive sources, not positively identified, include uranium- and thorium-rich biotite as inclusions in quartz grains, and uranium-rich coatings on zircon.

This mineralogical composition points to a primary source of either a uranium-enriched granite, or pegmatite that contained intergrowths of uraninite and feldspar. Coffinite may have formed by alteration of uraninite or could be a primary mineral.

WEST PILBARA SUB-BASIN

Stratigraphy and lithology

Exploration for uranium and gold has been undertaken at several localities in the Pyramid region some 200 km west of the Marble Bar Sub-basin. Here, the lower Fortescue Group forms a broad embayment on the Pilbara Block, a feature that probably represents an early sub-basin of the Hamersley Basin. The stratigraphic sequence consists of Mount Roe Basalt, restricted to palaeodepressions, followed by Hardey Sandstone, Kylene Basalt, and Cooya Pooya Dolerite.

Exposures of Hardey Sandstone near Coorbeelie River were the principal scene of exploration which included three separate drilling programs (Table 3 - 25, 27, 28). The formation crops out over an area of about 10 km², but only 120 m of conglomeratic sandstone is present: the upper part of the formation has been removed by erosion following the intrusion of Cooya Pooya Dolerite.

Coarse feldspathic sandstone and conglomerate are generally similar in composition and pyrite content to those in the Nullagine Sub-basin; they also display fluvial sedimentary structures.

Three conglomeratic intervals, within which individual beds range up to 3 m thick, occur. Abundant detrital pyrite, sometimes 10% of the total matrix, is found in thin layers. Pale-green sericite

after feldspar constitutes 5% of some rocks. Carbonaceous grains presumed to be thucholite have been noted in the middle of the three conglomerate intervals (Fig. 3).

Uranium exploration results

The principal uranium intersections were made in conglomerates, the best was 684 ppm U_3O_8 over 0.1 m (Fig. 3). Drilling has demonstrated that down-dip extensions of the uraniferous conglomerates are extensively disrupted by intrusions of dolerite. No significant gold values were obtained (Appendix).

No mineralogical investigation of the mode of occurrence of uranium at Coorbeelie River is known to have been made. Marathon Petroleum Australia Ltd reported what was considered to be thucholite in the middle conglomerate interval with disseminated pyrite and clay galls—an association seen often in Nullagine conglomerates. It is most likely, therefore, that part of the uranium occurs as fine inclusions of uraninite in thucholite or as partial substitutions of thorium in thorite. Such are the modes of occurrence of uranium in thucholite pellets in the Nullagine Sub-basin.

EXPLORATION IN OTHER AREAS OF THE HAMERSLEY BASIN

Exploration operations in the Hardey Sandstone have been carried out elsewhere in the West Pilbara Sub-basin and in the large complex embayments of the eastern Pilbara that are not obviously interpreted as early fluvial basins (Table 3 - 29 to 33). Asarco Australia Pty Ltd and Electrolytic Zinc Co operations of Table 3 (not shown on Figure 2) took place some 90 km southeast of Nullagine. None of these operations yield information adding usefully to the foregoing descriptions.

Blight (1985) describes the lithology and sedimentology of the lower Fortescue Group in the southern part of the Hamersley Basin where the formation is exposed around four basement granitoid domes. The common rock types are coarse-grained arkosic sandstone, fine-grained quartz sandstone and shale, and some are pyritic. The best assay is 29 ppm U_3O_8 , 370 ppm Th, and less than 0.2 ppm Au. He concludes that sediments were derived from a near source to the southeast, and as no identified gold source areas are known to lie in that direction, he considered the southern Hamersley Basin to have low economic potential.

DISCUSSION

THE NATURE OF PYRITE

A notable feature of the conglomerates in the Gorge Creek and lower Fortescue Groups is the large quantity of detrital pyrite (invariably accompanied by authigenic pyrite) and the absence of magnetite. The rounded nature of much of the py-

rite, and distribution of rounded grains on bedding and cross-bedding planes demonstrate a detrital origin. Clearly, there was an era of pyritic-sand movement over an eroding basement, in the period between about 3.0 Ga and 2.7 Ga as there has been in other parts of the world. Pyrite must have been derived, in part, from underlying greenstones; and the development of pyrite palaeoplacers demonstrates that drainage regimes of Lalla Rookh Sandstone and lower Fortescue Group times were efficient in concentrating heavy minerals. Magnetite from source rocks below the Fortescue Group apparently failed to survive in this erosion and transportation event, presumably as a result of its sulphidation and transformation into pyrite with the formation of brannerite (Houston and Karlstrom, 1979, p. 52). However, detrital brannerite (a mineral unlikely to survive transport) has not been identified in the lower Fortescue Group.

GOLD OCCURRENCES

Although gold placers are present in the lower Fortescue Group, no economically significant deposits have been identified in pyritic conglomerates. No gold production is recorded from the Lalla Rookh Sandstone and as this part of northwestern Australia has been searched for nearly a century, it is unlikely that obvious economic concentrations at the surface have been overlooked.

Over 17 t of gold have been produced from the greenstones of the Warrawoona Group. In view of this substantial mineralization, and the fact that, during the deposition of Lalla Rookh Sandstone and Lower Fortescue Group rocks, erosional regimes produced palaeoplacers of detrital pyrite presumably from these rocks, the paucity of gold in the younger rocks is puzzling. Obviously, non-auriferous, rocks such as granitoids, were source rocks for most of the Lalla Rookh Sandstone and Fortescue Group sediments (which in part were derived from the older, gold-poor clastics). Perhaps when the pyrite-rich sandstones and conglomerates were being deposited, gold sources in the Warrawoona Group were not exposed. An additional factor may be the continual lingering of the unstable tectonic regime—as indicated by volcanism and graben-style faulting—which prevented the fluvial reworking of sediment on the scale required to concentrate gold.

URANIUM OCCURRENCES

Concentrations of uranium within Hardey Sandstone and the similar rocks at the top of the Kylena Basalt are high when considered against the generally unpromising source rocks now exposed in the Pilbara Block, which, apart from the "tin granites", are rather uranium poor. Evidently, some granitic

sources were exposed since uraninite travelled within granitic fragments to deposit in palaeoplacers in the unnamed unit along with pyrite and other heavy minerals. No uraninite has been identified in the "tin granites", and illite-uraninite grains in the lower Fortescue Group may have eroded from uranium-enriched upper levels of intrusions such as those of Moolyella and Spear Hill.

Most uranium in the Hardey Sandstone is found in detrital thucholite pellets as fine uraninite inclusions, within thorite grains carrying minor uranium, and as detrital anatase containing brannerite. This suite suggests mineralization of the "modified placer" (Houston and Karlstrom, 1979, p. 43) with uranium moving as very fine particles, and possibly also in solution. Algal colonies probably existed in some areas during the deposition of the lower Fortescue Group, for stromatolites are abundant in the Tumbiana Formation which overlies Kylenea Basalt. Algal colonies could have concentrated uranium by both mechanical filtration of particles and biochemical precipitation of solutes. Subsequent erosional destruction of the colonies would have produced thucholite pellets. Brannerite in anatase could form as a result of replacement of titanium by uranium from solution.

A striking feature of uranium mineralization in the Hardey Sandstone (Fig. 3) is the general similarity of levels of uranium concentration attained in the Nullagine and West Pilbara Sub-basins. The richest uraniferous interval at Nullagine, represented by the uraniferous conglomerate immediately below the main tuffaceous siltstone unit, is the middle of three uraniferous conglomerates. This episode may be reflected by the prominent middle conglomerate at Coorbeelie River which also returned the best uranium values.

In the Marble Bar Sub-basin, where the gross lithology differs, the best uranium value is lower than those of Nullagine and West Pilbara regions. However, this best value occurs in a conglomerate underlying a thick shaly sequence. Stratigraphic equivalence of the main mineralized layers between the three sub-basins is a possibility that cannot be evaluated on available data. In any event, the similarity of Nullagine Sub-basin and Coorbeelie river "best uranium values", and the fact that no uraniferous conglomerates of any consequence are known elsewhere, suggests that the maximum uranium potential of Hardey Sandstone has been demonstrated by recent exploration. Uraninite in the arenaceous sequence above the Kylenea Formation travelled in granitoid detritus to form palaeoplacers with pyrite and other heavy minerals. No large palaeoplacers of illite-uraninite detritals have been identified so far. This may be due to tec-

tonic instability related to graben-style faulting in the Marble Bar Sub-basin, which may not have allowed fluvial environments to develop for any length of time (this suggestion also explains the general paucity of gold). However, the uranium potential of this sequence, particularly the lower part, has not been adequately determined, and this warrants exploration attention.

APPLICATION OF THE QUARTZ-PEBBLE CONGLOMERATE MODEL

Although there are obvious comparisons, the sub-economic levels of uranium and gold distinguish the pyritic conglomerates of northwestern Australia from similar rocks in South Africa and Canada. Houston and Karlstrom (1979, p. 69) set out a preferred exploration model for metalliferous quartz-pebble conglomerates based upon features of known economic placer deposits. These features define constraints which are discussed below in respect to the Lalla Rookh Sandstone and lower Fortescue Group.

- (1) Age constraints for gold bearing placers from about 3.0 Ga onwards, and for uraniferous conglomerates from 2.8 to about 2.0 Ga, incorporate age ranges of pyritic conglomerates of the Pilbara-Hamersley region.
- (2) Source area constraints: for uranium, a period of K-rich granite emplacement within the age range 3.0 to 2.5 Ga; for gold and detrital pyrite, early greenstone belts with some gold mineralization. Both these constraints are met.
- (3) Stratigraphic constraints: favourable early cratonic sequences of sandstone, conglomerate and shale with minor proportions of volcanic rocks. These requirements are in part met. However, in the lower Fortescue Group, basalts comprise about 0.5 km of the 2 km thick sequence up to the base of Tumbiana Formation. As noted previously, tectonic instability and widespread basalt eruptions may have interfered with the development of extensive fluvial environment on the scales needed to produce economic concentrations of uranium and gold.
- (4) Sedimentological constraints call for a fluvial deltaic environment with braided river characteristics producing fining-upward sequences. The latter are not obviously developed in the Pilbara region where coarsening upward sequences are found (e.g. Hardey Sandstone in the Marble Bar Sub-basin) though most other sedimentological features are found in pyritic conglomerates of the Pilbara region.
- (5) Lithologic characteristics of colour, composition (generally), textural maturity and sericite

content are largely met, although the degree of sorting is not advanced in the Fortescue Group sandstones.

- (6) Mineralogical characteristics: Pyrite, thorium-bearing minerals (e.g. monazite, thorite and xenotime) and thucholite are present in the Pilbara-Hamersley region. Gold, even though in small quantities, is present in fossil placers in the basal part of Hardey Sandstone conglomerate reefs. However, most importantly, detrital uraninite, the most common uranium mineral of the model, has not been identified in matrices of lower Fortescue Group conglomerates. It occurs only as minute crystals in thucholite pellets. Uraniferous thorite and coffinite, and probably brannerite, are, however, present. Despite this encouragement, the uranium content of lower Fortescue Group conglomerates rarely achieves the content of ore-grade conglomerates—between 1 000 and 1 500 ppm.

CONCLUSION

Pyritic conglomerates of the Pilbara and Hamersley regions are comparable to the gold- and uranium-bearing conglomerates of South Africa and Canada in age, broad tectonic setting, and most sedimentological, lithological and mineralogical characteristics. They differ in that the Western Australian conglomerates do not host gold of any significance, and known uranium accumulations are not mining propositions.

ACKNOWLEDGEMENTS

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APPENDIX

LOWER FORTESCUE GROUP—PRINCIPAL EXPLORATION STATISTICS

WEST PILBARA SUB-BASIN

HARDY SANDSTONE COORBEELIE RIVER

Table 3: Nos 24 to 28

Surface

Four rock-chip sample programs (about 250 samples)—U, Th, Au, and multi-elements; minor stream-sediment survey; petrography; radiometric and resistivity surveys.

Drilling

Two diamond-drill programs—7 holes for 503 m

Best intersections:

U ₃ O ₈ (ppm)	Length (m)
684	0.1 m
684	0.1 m
648	0.5 m
566	1.6 m
480	0.3 m
401	0.6 m

Analyses (U, Th, Au):

U ₃ O ₈ (ppm)	Samples (no.)	Au (ppm)	Samples (no.)
250-500	9	>1.0 (max.0.15)	none
>500 (max. 684)	4		
Total:	320	Total	319

Percussion-drill program—3 holes for 587 m (no analysis) no analyses)

MARBLE BAR SUB-BASIN

UNNAMED UNIT

Table 3: Nos 19, 20 and 21

Surface

Two stream-sediment surveys (up to 120 samples)—U, Th, Au; three rock-chip sample programs (up to 140 samples)—U, Th, Au, and multi-element; radiometric surveys.

Drilling

Two diamond- and percussion-drill programs—one of nine holes for 597 m diamond and 464 m percussion, and a one hole diamond-drill program for 68 m.

*Best intersections:

U ₃ O ₈ (ppm)	Length (m)
1 510	0.3 m
1 300	2.75 m
613 (INCO)	0.25 m
610	0.3 m
425	1.4 m
338	1.25 m

Analyses:(U, Th, Au):

SU ₃ O ₈ (ppm)	Samples (no.)	Au (ppm)	Samples (no.)
250-500	6	> 1.0 (max. 0.06)	none
500-1 000	2		
>1 000	2		
Total	76	Total	52

*NOTE: Repeat analyses of intersections (other than INCO) obtained values ranging between 7 and 220 ppmU₃O₈.

NULLAGINE SUB-BASIN

HARDEY SANDSTONE

Table 3: Nos 8, 9, 10 and 11

Surface

Four rock-chip sample programs (about 660 samples): U, Th, Au, and multi-element; petrography; mineralogy; electron-probe analyses; radiometric surveys

Drilling

Two diamond-drill programs—37 holes for 3 738 m

Best intersections:

U ₃ O ₈ (ppm)	Length (m)
1 085	0.16
665	0.2
580	0.1
470	0.1
460	0.2
460	0.1

Analyses (U, Th, Au, and multi-element):

U ₃ O ₈ (ppm)	Samples (no.)	Au (ppm)	Samples (no.)
250 - 500	23	>1.0 (max. 0.5)	none
500 - 1 000	2		
> 1 000 (1 085)	1		
Total about	1 500	Total about	1 190

Percussion-drill program—11 holes for 1 291 m.

Analyses (U, Th, Au):

U ₃ O ₈ (ppm)	Samples (no.)	Au (ppm)	Samples (no.)
<125	all	<0.1	all
Total about	315	Total about	318

NUNYERRY

Table 3: No. 29

Surface

Petrography; radiometric survey

Drilling

Percussion-drill Program—3 holes for 450 m

Analyses: (U, Au):

U ₃ O ₈ (ppm)	Samples (no.)	Au (ppm)	Samples (no.)
>250 (max.39)	none	>1.0 (max. 0.2)	none
Total	71	Total	73

HARDEY SANDSTONE

Table 3 : Nos 15, 16, 17 and 18

Surface

One stream-sediment survey (up to 70 samples)—U, Th; five rock-chip sample programs (about 280 samples—U, Th, Au and multi-element; petrography; radiometric surveys

NOTE: One close-spaced rock-chip sample program tested the gold potential of the conglomerate at about 860 m in the section on Figure 3.

Drilling

Diamond-drill program—1 hole for 271 m

Best intersections:

U ₃ O ₈ (ppm)	Length (m)
356	0.3
71	0.2

Analyses (U, Th, Au, Ag):

U ₃ O ₈ (ppm)	Samples (no.)	Au (ppm)	Samples (no.)
>250 (max. 356)	1	(max. 0.6)	
Total	6	Total	6

Percussion-drill program—3 holes for 137 m; seven analyses for U, Th, Au; all values less than 10 ppm U and 0.01 ppm Au

MOUNT ROE BASALT

Table 3: Nos 12, 13 and 14

Surface

Nos 12 and 13—(basal sequences); two rock-chip sample programs (about 40 samples) U, Th, Au

Drilling

One diamond-drill program—for 86.4 m

Analyses (U, and multi-element):

U (ppm)	Samples (no.)	Au (ppm)	Samples (no.)
(<15)	all	>1.00 (max.0.15)	none
Total	30	Total	30

No. 14—(intrabasalt sequence); rock and loam sampling programs (about 20 samples)—U, Th, Au, and multi element; U insignificant; Au max. 0.008 ppm.

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GEOLOGY AND HYDROGEOLOGY OF THE SUPERFICIAL FORMATIONS AND COASTAL LAKES BETWEEN HARVEY AND LESCHENAULT INLETS (LAKE CLIFTON PROJECT)

by D.P. Commander

ABSTRACT

Sixty-one bores, between 10 m and 61 m deep, on seven cross-section lines, were drilled for the Geological Survey of Western Australia to investigate the geology and hydrogeology of the superficial formations in a 10 km wide coastal strip between Mandurah and Australind. Additional bores were drilled at eight sites for test pumping to determine aquifer characteristics.

The Quaternary superficial formations are up to 90 m thick and unconformably overlie Cretaceous sediments. They include the Jandakot beds, the Bassendean Sand, and the Tamala Limestone. The Tamala Limestone is sandy in the east, calcareous in the west, and contains interbedded marl associated with the coastal lakes.

Groundwater discharges into the coastal lakes and the tidal inlets. The coastal lakes, which range in salinity from 8 000 to 190 000 mg L⁻¹ TDS, are groundwater sinks, where groundwater input is balanced by evaporation. A body of saline or hypersaline groundwater underlies both the lakes and the relatively thin layer of fresh or brackish groundwater near the coast.

INTRODUCTION

LOCATION AND LAND USE

The South West Coastal Groundwater Area extends from Mandurah in the north to Leschenault Inlet in the south and for up to 10 km inland (Fig. 1).

The largest settlements are at Falcon and Davesville in the north; smaller settlements are situated at Preston Beach, Myalup, and Binningup.

About one-fifth of the area is occupied by state forest in which the native vegetation is being cleared and replanted with pines. Yalgorup National Park, which includes a series of coastal lakes, also lies within the area. The remainder of the land is in private ownership, and consists of areas of native vegetation, pasture, and small areas of irrigated arable land on which lucerne and vegetables are grown.

Although the area of irrigated land is comparatively small, substantial quantities of groundwater are used. Following reports of lowered water tables and increases in salinity, the South West Coastal Groundwater Area was proclaimed in 1977 by the Public Works Department under the Rights in Water and Irrigation Act to enable control of groundwater abstraction.

PURPOSE AND SCOPE

The Lake Clifton bores were drilled to enable the Geological Survey of Western Australia to assess the shallow groundwater resources of the South West Coastal Groundwater Area, to establish approximate water balances for the coastal lakes in

order to assess the possible effects of groundwater abstraction on lake levels, and to provide a network of bores to monitor changes of water level in relation to variations in rainfall and groundwater abstraction.

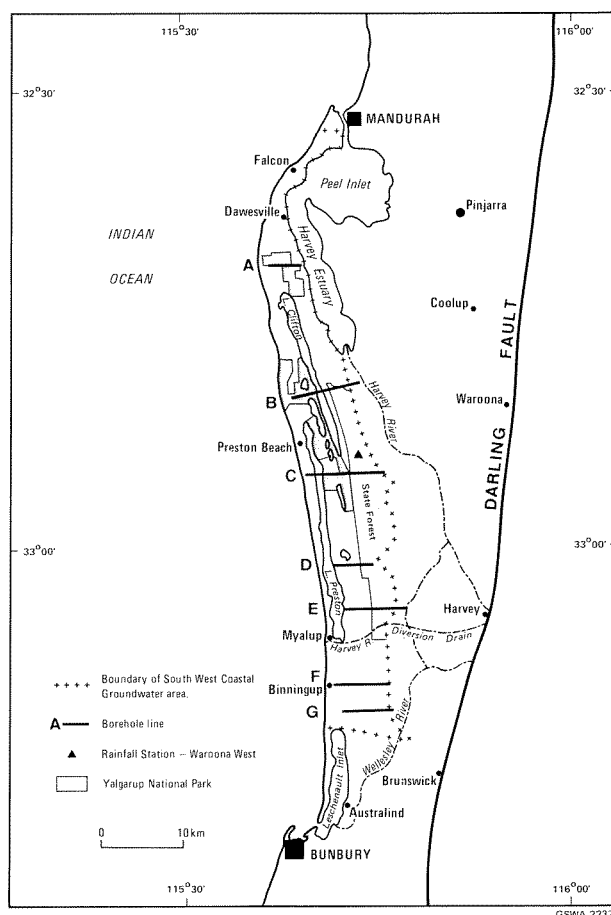


Figure 1. Locality map

This report describes the stratigraphy of the sediments intersected by drilling and delineates the groundwater systems that maintain the coastal lakes or discharge to tidal inlets.

Some data from recently drilled bores of the Harvey shallow-drilling project are also included where the bores are within the groundwater catchment areas of the coastal lakes.

PREVIOUS WORK

The hydrogeology of the area was outlined by Allen (1977), who recommended the monitoring of water levels and salinities in private bores used for irrigation. Later, Bestow (1978) reviewed the monitoring results and set out an exploratory drilling program to define the groundwater resources and enable water balances to be made for the coastal lakes (Lake Clifton shallow-drilling project) the results of which are described in this report.

PHYSIOGRAPHY AND DRAINAGE

The area lies at the western edge of the Swan Coastal Plain, where the physiography is dominated by sets of stabilized dunes, which are parallel to the present coastline, and separated by lakes and swamps in the low-lying interdunal areas (McArthur and Bettenay, 1960; McArthur and Bartle, 1980).

The Bassendean Dune System (Bassendean Sand in Figure 2) forms low hills with intervening swamps in the east of the area close to the Harvey and Wellesley Rivers.

The Spearwood Dune System (Tamala Limestone in Figure 2) occupies most of the area of investigation. The dunes form prominent parallel ridges up to 70 m above sea level, and there is a distinct scarp at the boundary with the Bassendean dunes.

There are three parallel lake systems within the Spearwood dunes: Lake Clifton to the east, Martins Tank and associated lakes in the centre, and Lake Preston in the west. The Yoongarillup Plain (McArthur and Bartle, 1980) is a flat-lying area, only a few metres above lake level, on the eastern shores of Lakes Clifton and Preston.

The Quindalup Dune System (Safety Bay Sand in Figure 2) is a belt of dunes extending along the coast and as much as 1 km inland.

There are virtually no natural drainages within the area. A network of drains has been constructed in the Bassendean dunes to link with the Harvey and Wellesley Rivers, and excess runoff from the Harvey River flows down the Harvey River Diversion Drain to the ocean near Myalup. Drains have also been constructed to lower the water table on

low-lying parts of the Yoongarillup Plain east of Lake Preston.

CLIMATE

The climate of the area is Mediterranean: summers are hot and dry; winters, wet and cool. Annual rainfall is about 900 mm and there is a slight increase inland from the coast. Rainfall was significantly below average during the period of investigation, between 1976 and 1981.

DRILLING AND PUMPING TESTS

DRILLING

The drilling program consisted of seven lines of bores, A - G, between three and sixteen kilometres apart (Fig. 1). Five to eight boreholes spaced at approximately one-kilometre intervals (Fig. 2) were drilled on each line. Drilling was carried out by the Mines Department using an Edson rotary rig, which employed a combination of auger and mud-rotary drilling methods.

The bores range in depth from 6 to 61 m (Table 1). The first bore drilled at each site completely penetrated the superficial formations and finished in the Cretaceous bedrock. Several bores failed to reach bedrock because of drilling problems and

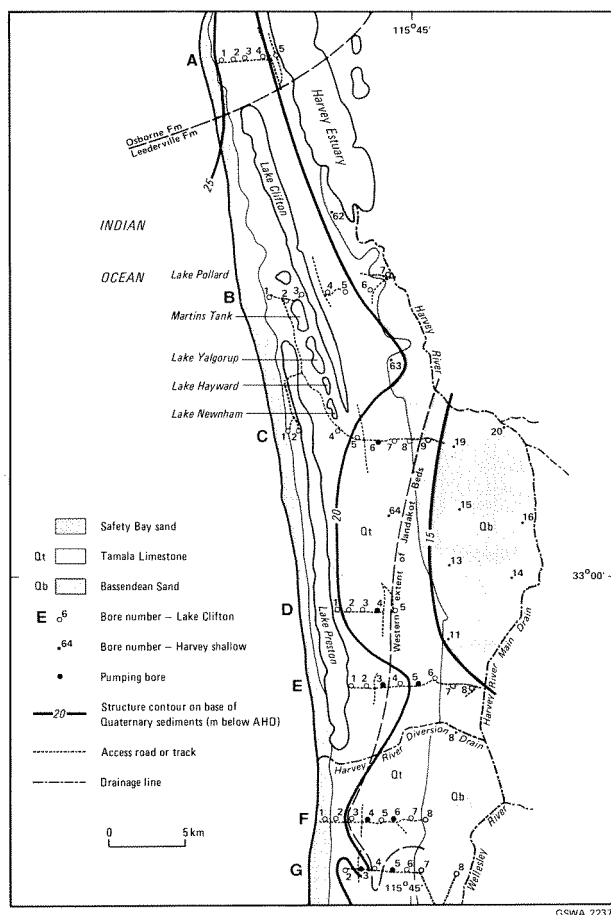


Figure 2. Geology and bore locations

GSWA 22379

were terminated in clay or hard limestone near the base of the superficial formations. Strata samples were obtained at 3 m intervals, but sampling was poor because of lost circulation in the limestones (no recovery of cuttings) and mixing of samples during auger drilling.

Bores were 114 mm or 152 mm diameter, and were cased with slotted 40 mm PVC, with a coarse-sand pack in the annulus. At some sites, several bores were drilled to differing depths in order to measure vertical head differences within the aquifer. Bores A3A and G2B were completed with 76 mm slotted PVC casing for the operation of float water-level recorders. After casing, the bores were airlifted until the water was sediment free.

The bore heads were levelled to Australian Height Datum (AHD). Water levels have been monitored at approximately monthly intervals since completion.

Salinity profiles have been measured in each bore with a conductivity logger, calibrated against standard solutions of sodium chloride. Several logs were run on each bore until a consistent log was obtained; in some cases, several months elapsed before the salinity profile stabilized.

Water samples from test pumping bores were chemically analyzed by the Government Chemical Laboratories.

PUMPING TESTS

Test procedure

Eight sites (Fig. 2) were selected for pumping tests to determine values of hydraulic conductivity in the Tamala Limestone (together with the Jandakot beds in E5). The pumping bore at each site was constructed of 152 mm casing with screens up to 15 m long in order to test the greatest possible thickness of the aquifer. The screens were set from about 6 m below the water table to allow for drawdown in the bore. In two bores (E3, E5) four 3 m screen lengths were alternated with three 3 m lengths of blank casing in order to increase the overall screen length. A 100 mm-diameter submersible electric pump was used, and a maximum pumping rate of 1 531 m³ d⁻¹ was achieved using the available drawdown (Table 2).

One or two additional observation bores were drilled at each site, at distances of 10 to 30 m from the pumping bore in an east or west direction, and constructed with 40 mm PVC casing slotted over short intervals.

Electric pressure transducers and chart recorders were used to measure drawdowns in both the pumping and observation bores. Water levels were also checked manually. The pumping rate was measured using a piezometer tube and appropriate orifice plates.

TABLE 1. BORE DATA
(Elevations referred to AHD)

Bore	Completion date	Elevation of casing top (m)	Total depth (m)	Slotted interval (m)	Elevation of water table (a) (m)
A1	8.79	11.705	36	6-36	0.22
A2	8.79	7.005	30	6-30	0.09
A3A	10.78	8.630	33	14.8-32.8	0.08
A3B	10.78	8.646	14	8-14	0.08
A4	8.79	4.636	27	6-27	0.05
A5	8.79	1.723	21	0-20.7	0.04
B1	7.79	3.896	28	2-28	-0.04
B2	8.79	4.627	28.5	2-28.5	-0.11
B3	8.79	4.109	26.5	2-26	-0.20
B4	10.79	4.163	30	0-30	-0.09
B5	10.79	26.234	49	27-49	0.13
B6	10.79	5.458	27	0-27	1.65
B7	10.79	4.974	30	0-30	1.80
C1	7.79	5.411	30	2-30	0.22
C2	7.79	2.811	27	2-27	-0.26
C4	7.79	1.455	26	1.5-25.5	-0.28
C5	7.79	2.500	24	0.5-24	0.26
C6	7.79	19.058	39	5.5-38.5	1.94
C7	10.79	39.331	61	30.5-60.5	9.28
C8	7.79	15.446	40	2-40	9.91
C9	7.79	14.391	41	1.5-39.5	10.57
D1	6.79	1.91	32	0.5-29.5	-0.39
D2	6.79	10.896	42	16-40	0.52
D3A	7.79	20.036	45	25-45	1.85
D3B	7.79	20.001	26	10-25	1.85
D4	7.79	5.082	35.5	1-35.5	3.13
D5	7.79	14.36	37	6-36	6.55
E1A	3.79	1.087	21	9.6-20.6	-0.64
E1B	3.79	1.140	11	0-10.5	-0.52
E2A	6.79	6.14	21	10-21	0.94
E2B	6.79	6.08	10	0-10	0.94
E3A	2.79	6.587	28.3	20-28.3	2.47
E3B	2.79	6.611	20	9.3-19.3	2.47
E3C	2.79	6.622	10	0-10	2.47
E4A	4.79	17.339	39	29-39	7.92
E4B	5.79	17.380	29	15-29	7.92
E4C	5.79	17.400	15	5-15	7.92
E5A	5.79	14.030	33	6-33	9.18
E5B	5.79	13.903	12	6-12	9.17
E6	5.79	23.794	45.5	7.5-43.5	10.90
E7	5.79	17.914	41	4-40	14.51
E8	5.79	18.097	36	1.5-34.5	15.02
F1	2.79	4.423	25.2	0-25	1.83
F2A	2.79	2.520	30	10-30	0.48
F2B	2.79	2.633	10	0-10	0.48
F3	10.79	8.258	36	0-36	1.54
F4	2.79	11.846	31	5.5-30.5	3.06
F5	2.79	7.239	20	0-20	3.38
F6	1.79	15.691	31.2	6.2-31.2	5.84
F7	10.79	14.332	33	0-33	7.13
F8	1.79	16.186	26.5	1-26.5	13.50
G2A	11.78	4.661	30	8-25	-0.01
G2B	11.78	-	13	4-10	-0.23
G3A	11.78	4.829	37	10-15	1.52
G3B	11.78	5.079	37	17-35	1.43
G3C	11.78	5.033	25	15-25	1.52
G4	11.78	12.988	30	17-29	3.16
G5	11.78	8.536	38	7-35	5.64
G6	11.78	39.098	50	10.5-50	11.66
G7	1.79	15.28	33	2-32	12.17
G8	1.79	14.093	6	1-6	10.82

(a) As of 17/4/80 except Bore D1 which is as 17/3/80

Five-stage step-drawdown tests were carried out on each pumping bore after development. The results showed that well losses were generally small, but a repeat of the tests on E3, in which the yield was low, showed that the bore was less efficient after the constant rate test, presumably as a result of clogging. Significant development also took place in F6 during the step and constant rate tests.

The constant-rate tests were run at 90% of the maximum bore yield (utilizing available drawdown) for periods up to 8 hours. Drawdowns in observation bores were relatively small, ranging from 0.05 to 1.01 m (Table 2).

TABLE 2. MAXIMUM DRAWDOWNS IN OBSERVATION BORES

Bore	Pump rate (m ³ d ⁻¹)	Maximum drawdown Distance from pumping bore				
		10 m (m)	15 m (m)	20 m (m)	30 m (m)	50 m (m)
C6	1224	-	-	0.17	0.11	-
D4	1531	0.065	-	0.05	-	-
E3	567	0.25	-	-	0.05	-
E5	1314	-	0.85	-	-	0.22
F4	1305	1.01	-	0.48	0.09	-
F6	504	0.35	-	0.28	0.11	-
G3	865	-	-	0.60	0.46	-
G5	1278	-	-	0.60	0.46	-

Pumping test analysis

Drawdown in the pumping bores was rapid, occurring within the first minute or so of the test, and analysis of the drawdown/time relationship was not possible. Estimates of transmissivity (Table 3) have therefore been derived from the specific capacity from graphs given by Walton (1970).

Logarithmic plots of drawdown/time from the observation bores produced three-stage curves which could be matched with delayed-yield type curves (Boulton, 1963).

TABLE 3. TEST DATA FROM PUMPING BORES

Bore rate	Pumping (m ³ d ⁻¹)	Screen length (m)	Specific capacity (m ³ d ⁻¹)	Transmissivity (m ³ d ⁻¹)	Hydraulic conductivity (m d ⁻¹)
C6	1224	12	231	230	19
D4	1531	15	475	520	35
E3	567	12	98	90	7
E5	1460	12	311	320	27
F4	1305	15	315	320	21
F6	504	10	146	140	14
G3	865	15	174	170	11
G5	1278	12	175	170	14

The drawdown/time data that fitted best to the type curves were from observation bores slotted within the aquifer interval pumped, where the flow is essentially horizontal. Data from bores which intersected the water table (some of those drilled in

the initial stage of the investigation) could not be analyzed because of vertical flow and aquifer anisotropy.

The most consistent results between observation bores at different distances (Table 4) were obtained from sites E3, F4, F6, G3 and G5, where the derived hydraulic conductivities ranged from 14 to 21 m⁻¹. Except in one case (F4) these results are 20 to 100% higher than estimates of hydraulic conductivity based on the specific capacity (Table 3).

TABLE 4. TEST DATA FROM OBSERVATION BORES

Bore	Overall screen interval	Transmissivity Distance from pumping bore			Average hydraulic conductivity (m d ⁻¹)
		10 m (m ² d ⁻¹)	20 m (m ² d ⁻¹)	30-60 m (m ² d ⁻¹)	
C6	12	-	(a)1050	750	60
D4	15	No match	1200	-	80
E3	21	260	-	333	14
E5	21	840	-	(a)1900	40
F4	15	216	203	(a) 469	14
F6	10	180	180	No match	18
G3	15	-	260	150	14
G5	12	-	221	290	21

(a) Value not used to calculate hydraulic conductivity because of poor match or fully penetrating observation bore

GEOLOGY

SETTING

The South West Coastal Groundwater Area lies within the Perth Basin, which in this region contains about 6 km of Phanerozoic sediments (Playford and others, 1976).

The superficial formations of Quaternary age (Table 5) have a maximum thickness of 90 m and lie on a gently west-sloping unconformity, below which are sediments of Cretaceous age.

The Cretaceous sediments (Table 5) at the unconformity are represented by the Osborne Formation in the north and the Leederville Formation elsewhere (Fig. 2).

STRATIGRAPHY

Jandakot beds

The Jandakot beds (G.W. Kendrick, written comm.) range from medium to coarse sand through to fine sand, silt, and clay; and characteristically contain large numbers of small gastropod and bivalve shells. Carbonaceous material is often present at the top of the unit. The mollusc fossils are indicative of brackish and salt-water environments.

The Jandakot beds unconformably overlie the Leederville Formation (Cretaceous) and are overlain, presumably unconformably, by the Bassendean Sand and the Tamala Limestone (Fig.

3). They are present in the eastern and southeastern sections of the area, and have a maximum thickness of 13 m in bore E7.

The beds are believed to be of Early Pleistocene age (G.W. Kendrick, written comm.).

Bassendean Sand

The Bassendean Sand (Playford and others, 1976) is a uniform well-sorted coarse-grained quartz sand, commonly brown stained. It unconformably overlies the Cretaceous Leederville Formation or the Jandakot beds, and is probably overlain unconformably in the west by the Tamala Limestone.

The formation occurs in the east of the area forming the physiographic subdivision of the Bassendean Dune System, and appears also to extend westwards beneath the Spearwood Dune System, although these sands are often indistinguishable from beds of leached quartz sand within the Tamala Limestone. The maximum thickness of the formation is about 30 m.

Tamala Limestone

The Tamala Limestone consists of interbedded limestone, calcarenite, sand, and subordinate marl and shell beds. Marine and lacustrine sediments probably make up the bulk of the formation below +3 m AHD; whereas above this, the formation is predominantly of eolian origin. The proportion of limestone in the formation is greatest in the west. Sands in the east may have been limestone subsequently leached of calcium carbonate. The effects of leaching, and the formation of limestone pinnacles and solution pipes, can be observed in outcrop.

The eolian sediments may have differed originally as to their carbonate content: this is thought to reflect differing provenance because of varied palaeogeographic conditions, such as the positions of the lakes; and probably also to represent several stages of dune formation, the earliest of which have presumably been subject to the greatest leaching.

An extensive and previously undescribed white marl underlies the coastal lakes in line C and the western end of line B. It appears to be contiguous with the former bed of Lake Clifton in bore C5 and may represent the changing position of the lake. It is both underlain and overlain by limestone and therefore is presumed to be a facies of the Tamala Limestone. Beds of bivalve shells and carbonate sand encountered in C2 also overlie the marl, and may represent a shoreline deposit. Both marl and shelly sand are associated with the present lake beds.

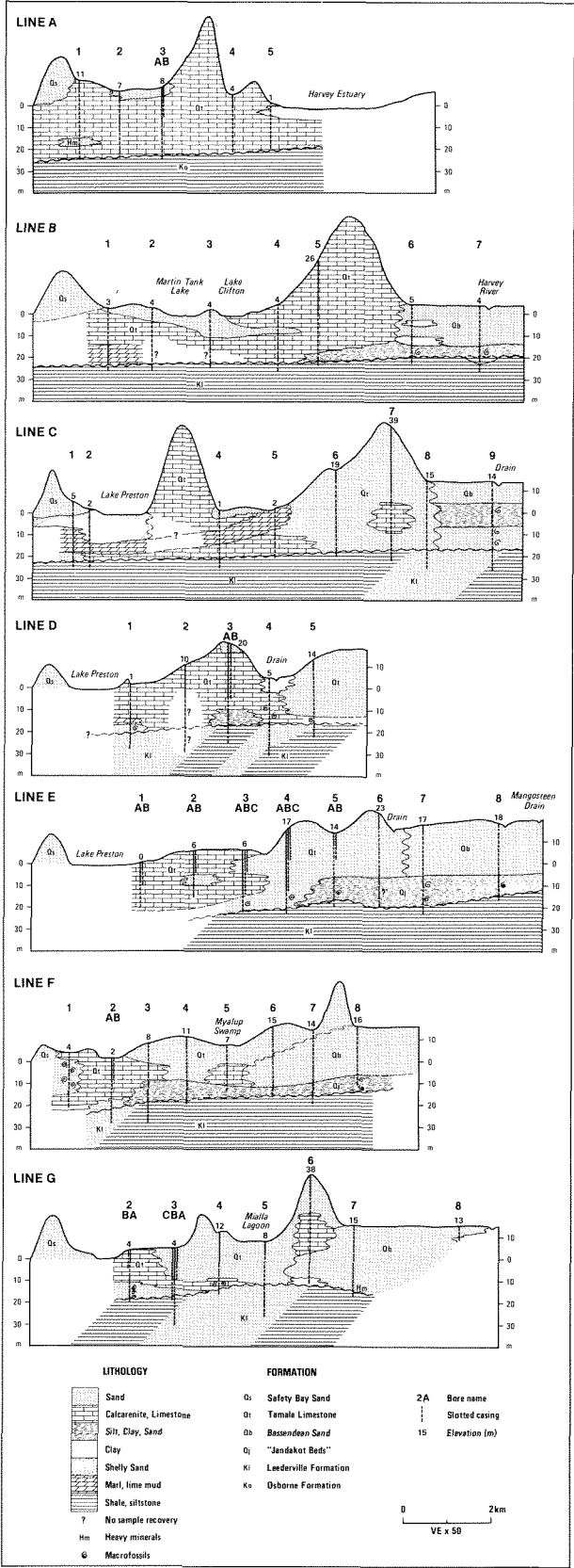


Figure 3. Geological cross sections

TABLE 5. STRATIGRAPHY

<i>Age</i>	<i>Formation</i>	<i>Lithology</i>	<i>Maximum thickness (m)</i>
Quaternary:			
Holocene:	Safety Bay Sand	Sand	50
Pleistocene:			
Middle-Late	Tamala Limestone	Limestone, calcarenite	90
Early-Middle	Bassendean Sand	Sand	30
Early	Jandakot beds	Sand, silt and clay	13
UNCONFORMITY			
Cretaceous:			
Late	Osborne Formation	Siltstone, clay	-
Early	Leederville Formation	Sand, siltstone and shale, glauconitic	-

The Tamala Limestone unconformably overlies the Leederville and Osborne Formations in the west, and the Jandakot beds and Bassendean Sand in the south and east. It is overlain close to the coast by the Safety Bay Sand (Fig. 2).

The formation extends along the coast and for as much as 10 km inland (Fig. 2), and has a maximum thickness of about 90 m.

The age of the Tamala Limestone has been given as Late Pleistocene (Playford and others, 1976); however, molluscs of Middle Pleistocene age (G.W. Kendrick, written comm.) have been recorded from within the formation.

Safety Bay Sand

The Safety Bay Sand consists of quartzose calcarenites deposited in the Quindalup Dune System. It overlies the Tamala Limestone in a strip as much as 1 km wide along the coast. The maximum thickness is about 50 m.

COASTAL LAKES

There are three parallel lines of lakes within 5 km of the coast. Lake Preston is just inland of the Quindalup Dune System and is separated from the Martins Tank chain of lakes by a limestone ridge. Lake Clifton and Martins Tank lakes are divided only by a low sand ridge.

The lakes receive virtually no runoff, and are maintained by direct rainfall accession and groundwater inflow. The lakes are groundwater sinks, which have no outflow other than by evaporation, and are underlain by hypersaline groundwater, which because it is more dense than seawater allows the lake levels to fall periodically below sea level.

LAKE PRESTON

Lake Preston is the largest of the coastal lakes, 27.5 km long, and 2 km wide at its widest point. The

maximum area of open water of 29.6 km² is substantially reduced in summer when much of the northern part of the lake is dry.

The lake bed is composed of a marly mud, and there is an indurated white marly limestone, presumably deposited from groundwater, along the southeast shore. In places along the western edge, dunes of the Safety Bay Sand extend into the lake.

The fringing vegetation in the northern part of the lake is made up of reeds and paperbarks; in the south, where the salinity is higher, there is samphire and the paperbarks are stunted.

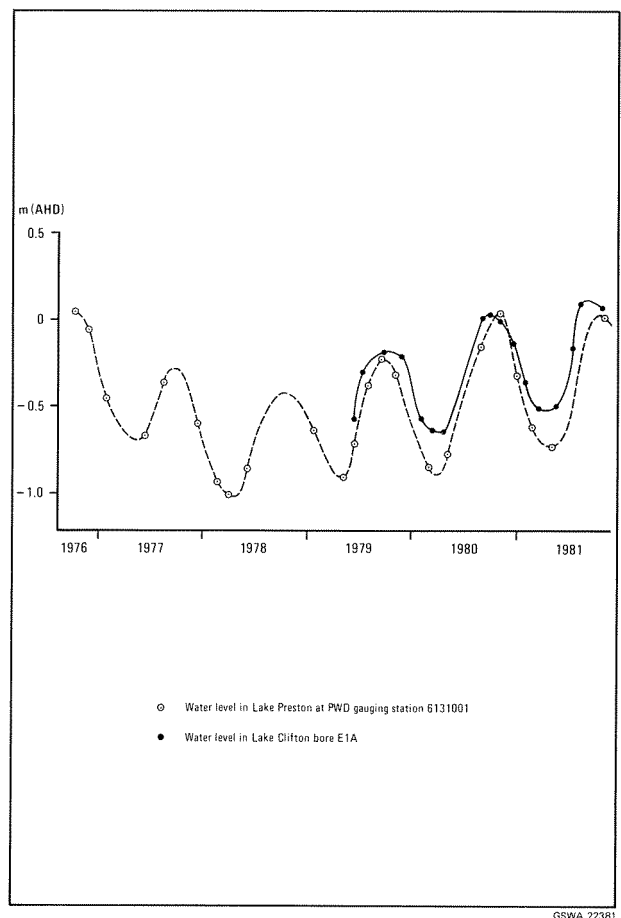


Figure 4. Lake Preston, water levels 1976-81

TABLE 6. SALINITY RANGE OF COASTAL LAKES

Lake	Salinity Range (mg L ⁻¹ TDS)
Eastern Group:	
Clifton	15 000 - 26 000
Middle Group:	
Pollard	20 000 - 42 000
Martins Tank	57 000 - 94 000
Yalgorup	113 000 - 190 000
Hayward	81 000 - 184 000
North Newnham	74 000 - 154 000
South Newnham	36 000 - 125 000
Western group:	
North Preston	8 000 - 20 000
South Preston	42 000 - 90 000

Measured between 1979 and 1984. Includes unpublished results of L. Moore.

The salinity in the northern part of the lake, which dries out each summer, ranged from 8 000 to 20 000 mg L⁻¹ TDS (Table 6) at the Preston Beach causeway. The salinity is much higher in the perennial southern part of the lake, and ranges from 42 000 to 90 000 mg.L⁻¹ TDS. Chemical analysis of the lake water (Williams and Buckney, 1976) shows that it is of the sodium chloride type.

The water level ranged from 0.1 m above to 1.0 m below AHD between 1976 and 1981 (Fig. 4). It fell between 1976 and 1978 because of lower than average rainfall, and rose between 1978 and 1981. The seasonal range of levels is about 0.8 m.

LAKE CLIFTON

Lake Clifton is 21.5 km long and has a maximum width of 1.5 km. The maximum area of open water is 17.8 km², but this is much reduced in summer; and, in March 1981, most of the southern half of the lake was dry; only small areas of permanent water remained.

The lake bed is a muddy marl with microbial mats and stromatolites along the eastern shore (Moore, 1979; Moore and others, 1983). There are limited areas of sand with small gastropod shells, mostly on promontories.

The lake is fringed with reeds and paperbarks which are inundated in years of high or average rainfall.

The salinity ranges from 15 000 to 26 000 mg L⁻¹ TDS (Table 6), and is substantially lower than the groundwater salinity beneath the lake, which is about 40 000 mg L⁻¹ TDS.

MARTINS TANK LAKE

Martins Tank and Yalgorup Lakes, joined by a narrow channel, together are the largest in area (3.2 km²) of the chain of lakes just west of Lake Clifton.

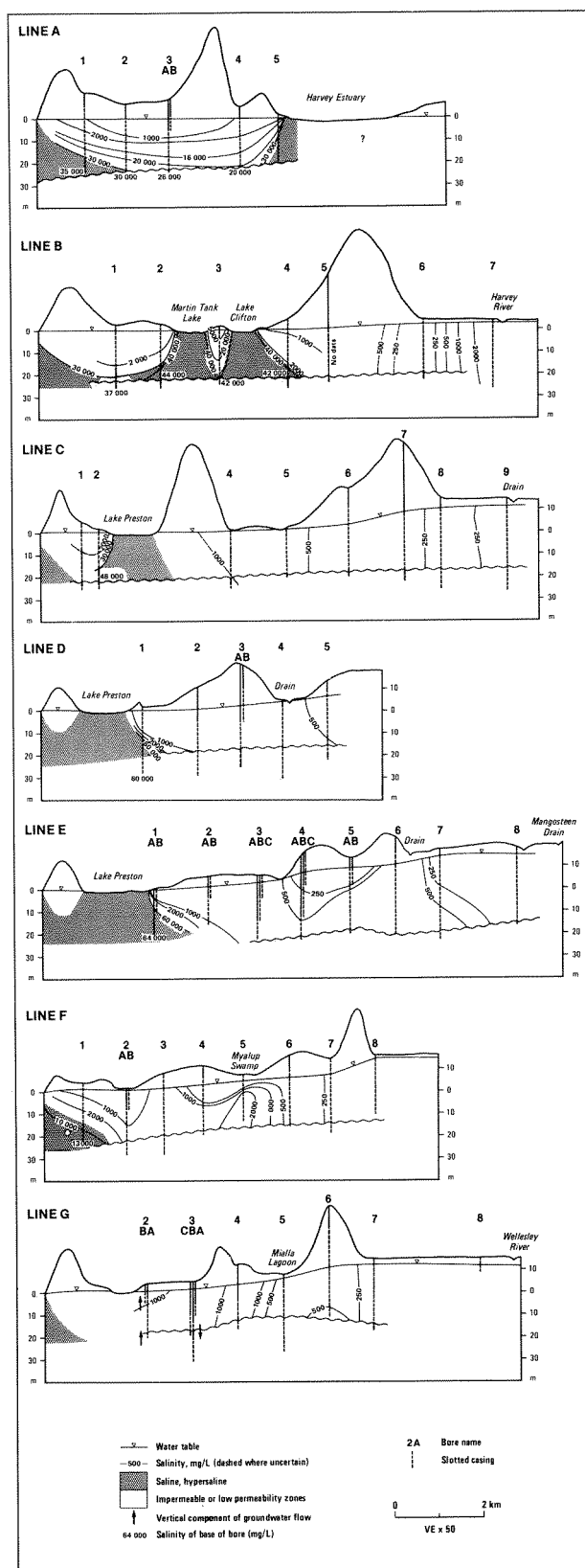


Figure 5. Hydrogeological cross sections

Martins Tank-Yalgorup Lake is perennial; it has a marly bed and marly limestone is deposited around the northern edge. The other lakes are shallower, and some are subject to complete drying out.

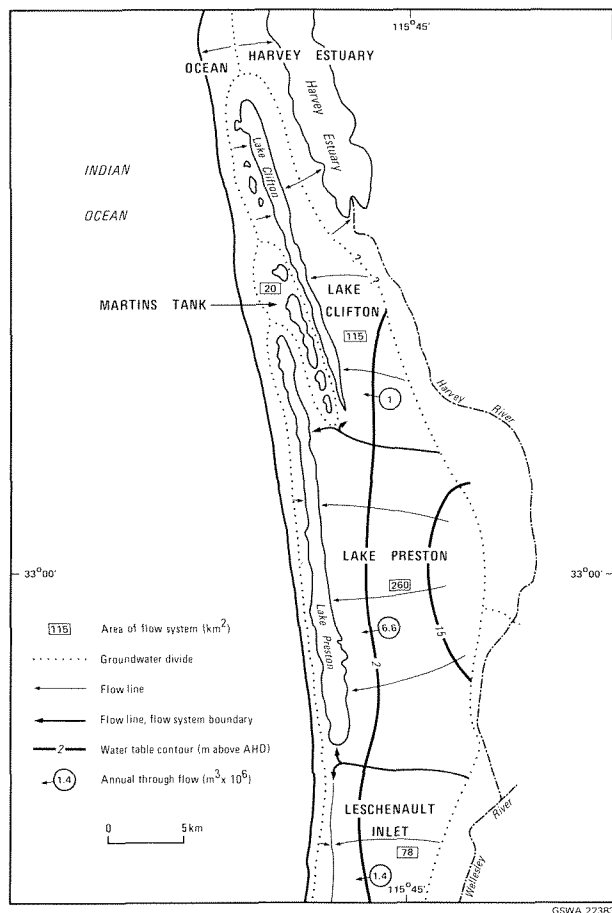


Figure 6. Groundwater flow systems

The salinity of the lakes ranges up to 190 000 mg L⁻¹ TDS (Table 6) compared with the hypersaline groundwater in bores B2 and B3 of 40 000 to 45 000 mg L⁻¹ TDS.

HYDROGEOLOGY

The superficial formations are hydraulically connected to form an unconfined aquifer (Fig. 5) which can be subdivided into six flow systems (Fig. 6). Three of these flow systems are internal, and discharge to the coastal lakes (Lake Preston, Lake Clifton, and Martins Tank) which are groundwater sinks and from which there is no outflow. The other flow systems discharge to Leschenault Inlet, to Harvey Estuary, and directly to the ocean. Groundwater flow systems discharging to the Harvey and Wellesley Rivers lie outside the South West Coastal Groundwater Area, and are beyond the scope of this investigation.

In the north of the area, the Osborne Formation is an impermeable base to the unconfined aquifer; but elsewhere there is potential for groundwater flow between the superficial formations and the Leederville Formation, especially in the south where the Leederville Formation at the unconformity is sandy.

Boundaries between the flow systems are groundwater divides or bounding flow lines whose positions are inferred from the water-table configuration (Fig. 7). Hydraulic boundaries also occur between groundwater bodies of greatly differing salinities. The salinities of these bodies fall into four groups: fresh to brackish (less than 7 000 mg L⁻¹ TDS) which is groundwater derived directly from meteoric water; estuarine from (10 000 to 30 000 mg L⁻¹ TDS), associated with Harvey Estuary; saline (35 000 mg L⁻¹ TDS), from oceanic water; and hypersaline (42 000 to 64 000 mg L⁻¹ TDS), associated with the coastal lakes and derived by evaporation of relic seawater, groundwater, and rainfall.

The relationships between these groundwater bodies and the positions of interfaces between them are shown diagrammatically on Figure 8. Detailed variations of salinity with depth along the borehole lines are also shown on Figure 5.

LAKE PRESTON FLOW SYSTEM

Extent: The Lake Preston Flow System is the largest flow system wholly within the investigation area (Table 7). It is bounded on the east by a groundwater divide and to the north and south by bounding flow lines with the adjacent Lake Clifton and Leschenault Inlet Flow Systems. A groundwater divide on the west separates the lake from the ocean (Fig. 6).

Groundwater Flow: Recharge is direct from rainfall within the area of the flow system, and groundwater flow is westwards from the groundwater divide to discharge along the eastern shore of Lake Preston. A small amount of groundwater flow is from the west of the lake.

The Harvey River Diversion Drain (Fig. 1) passes through the southern part of the flow system taking winter runoff directly to the ocean. The drain collects water from the Bassendean Sand in the east, and there is loss of water from the drain into the Tamala Limestone, but the net effect on groundwater flow is not considered to be significant.

The water table in the Bassendean Sand is fairly flat and close to the surface, thus forming numerous swamps. To the west, there is a zone of steep groundwater gradient (Fig. 7) within the Tamala Limestone or at the contact between the Tamala Limestone and Bassendean Sand in the subsurface. The greatest drop in the water table is about 7 m in one kilometre, which occurs between C6 and C7. There is also a steepening of the hydraulic gradient between E3 and E4 where it is associated with groundwater discharge at a line of swamps. The saturated thickness of the aquifer is greatest in the east (about 30 m) but it decreases westwards to 20–25 m near Lake Preston.

TABLE 7. RAINFALL, AREA, AND EVAPORATION FOR FLOW SYSTEMS

Name	Flow system excluding lakes		Lakes		Evaporation from Lakes		Net evaporation loss from lakes	
	Area	Rainfall	Area	Rainfall	Effective Area	Evaporation	Absolute	Relative to rainfall on flow system
	(km ²)	Rx (10 ⁶ m ³)	(km ²)	RI (10 ⁶ m ³)	(km ²)	EI (10 ⁶ m ³)	EI - RI (10 ⁶ m ³)	100(EI - RI)/Rx (%)
Preston	230	207	29.6	26.6	26.7	37.4	10.8	5.2
Clifton	97	87	17.8	16.0	14.2	19.9	3.9	4.5
Martins Tank	14.5	13	5.5	4.9	4.4	6.2	1.2	9.2

Note: Annual rainfall assumed to be 900 mm; annual evaporation, 1400 mm. Rx =rainfall excluding area of lakes.
RI = rainfall on lakes. EI = evaporation from lakes.

In the east, near the groundwater divide, there is a downward head differential between the water table and the base of the aquifer of as much as 0.4 m (A.C. Deeney, written comm.). This downward hydraulic gradient is greatest at the end of winter but in some bores it is reversed for a short period at the end of summer implying upward groundwater movement. The downward head differential suggests there may be significant leakage into the Leederville Formation. To the west there is no vertical head differential at sites E2, E3, E4, and D3. This reflects the higher transmissivity of the

Tamala Limestone and reduced leakage to the Leederville Formation because of a reduced head differential.

At D4, where there is 6 m of clay at the surface, confined conditions occur in the superficial formations. The potentiometric head is above ground level at the end of winter.

The greatest seasonal range in water-table elevation, 1 to 1.5 m, occurs where the water table is shallow; that of the least seasonal range of 0.3 to 0.5 m is below the dunes of Tamala Limestone.

Lake Preston is a groundwater sink which receives all the groundwater discharge from the flow system, excepting leakage to the Leederville Formation and water (if any) removed by the Harvey River Diversion Drain.

Water is lost from the lake by evaporation, and salt is concentrated in the residual lake water. Presumably when the density of the lake water exceeds that of the hypersaline groundwater beneath, there is transference of water. Some salt loss from the system may occur by diffusion with seawater at the base of the Tamala Limestone. However, it is likely that the salinity of the hypersaline groundwater is gradually increasing because the input of salt probably exceeds the diffusive loss.

The lake level (Fig. 4) is below sea level for most of the year because the density of the hypersaline groundwater is greater than that of sea water. The approximate hydrostatic balance of the hypersaline water and sea water can be calculated from the relation $h_1d_1 = h_2d_2$ where h and d are the respective heights and densities of the two water columns. Sea water has a density of 1.025 g cm⁻³ and the hypersaline water (70 000 mg L⁻¹) 1.05 g cm⁻³. If the base of the aquifer is 25 m below sea level, the height of the hypersaline water balanced by sea water is

$$\begin{aligned} h_2 &= h_1d_1/d_2 \\ &= 25 \times 1.025/1.05 \\ &= 24.4 \text{ m} \end{aligned}$$

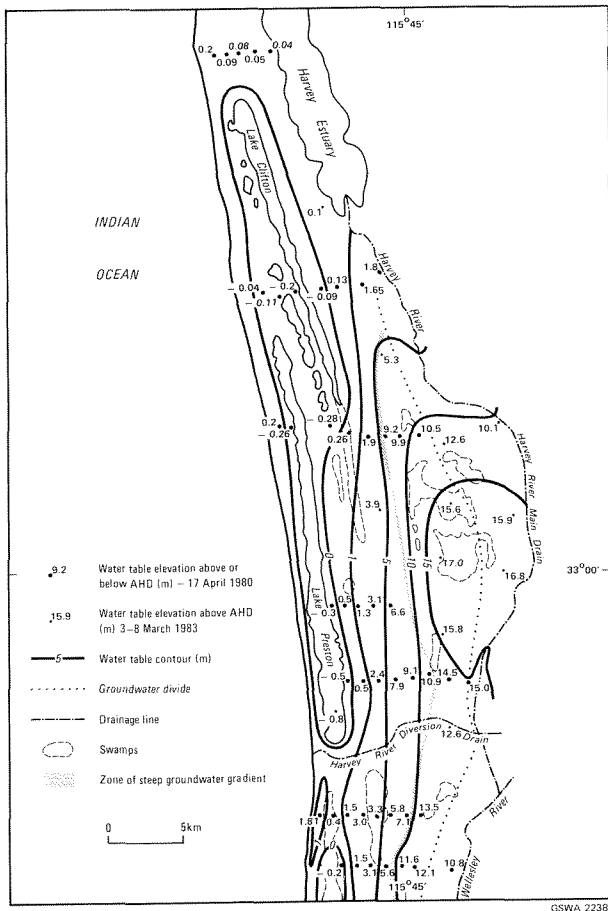


Figure 7. Water-table elevation

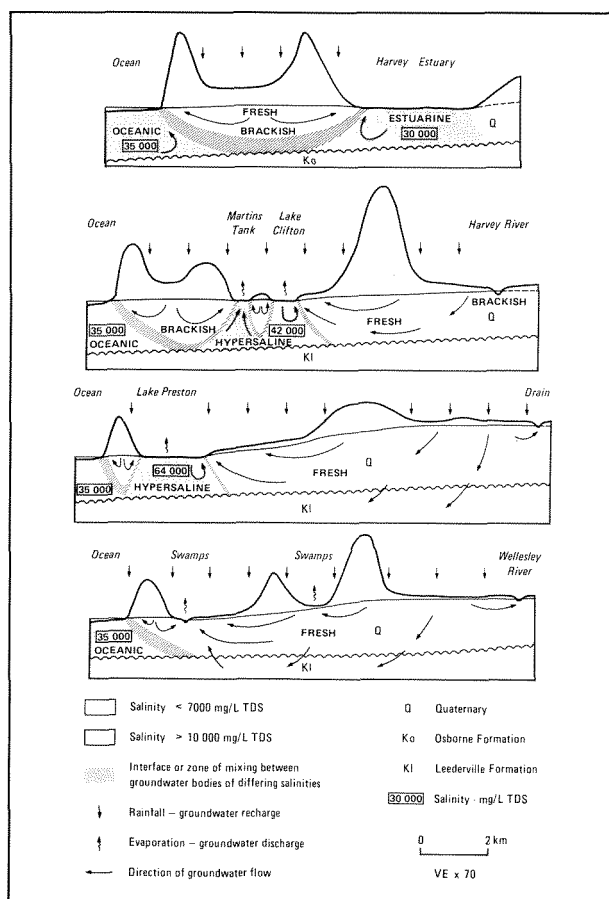


Figure 8. Diagrammatic sections showing groundwater flow

This represents an equilibrium level of the lake at about 0.6 m below sea level. Figure 4 shows that the mean lake level was close to this in 1978.

Salinity: The groundwater salinity is lowest in the Bassendean Sand at 100 to 150 mg L⁻¹ TDS and increases westwards in the Tamala Limestone to about 1 000 mg L⁻¹ near Lake Preston (Figs 5 and 9).

Underlying the lake, and extending about half a kilometre inland from the shore, at the base of the aquifer, is a body of hypersaline groundwater, with a salinity ranging from 48 000 mg L⁻¹ TDS at line C to 64 000 mg L⁻¹ TDS at line E. The hypersaline groundwater is separated from the fresh-water flow system by a zone of mixing, in which the salinity rises from 10 000 to 50 000 mg L⁻¹ TDS within a metre (Fig. 10).

LAKE CLIFTON FLOW SYSTEM

Extent: The groundwater flow system discharging to Lake Clifton covers an area of about 115 km² (Fig. 6). It is bounded on the south by the Lake Preston Flow System and to the east and west by groundwater divides. The divides separating the lake from Harvey Estuary and the ocean are only 1 to 1.5 km from the lake, and the divide with Martins Tank is only a few hundred metres from the shores of both lakes. Near the lower part of the

Harvey River, it is not clear if there is a divide or if the river forms a recharge boundary for a portion of its length.

Groundwater Flow: Recharge to the flow system is from direct rainfall over the area of the flow system. Groundwater flow is towards Lake Clifton under a very low hydraulic gradient. The water table is close to or below sea level except in the southeast, (Fig. 7). Between C5 and C6 the water table rises by 7 m in one kilometre; and east of this zone of high gradient, the water table is as much as 10 m above sea level. A downward hydraulic gradient here indicates potential leakage to the underlying Leederville Formation.

In the east and southeast, the saturated thickness is 20 to 30 m, but elsewhere the fresh water flow system is underlain by hypersaline water (Fig. 5) and consequently its thickness is much reduced.

Water levels in B6 and B7 indicate that there may be some recharge from the Harvey River along its lower reaches.

Like Lake Preston, Lake Clifton is a groundwater sink, which evaporates the groundwater discharge of the flow system, and is associated with an underlying body of hypersaline water whose density maintains the lake level close to or just below sea level.

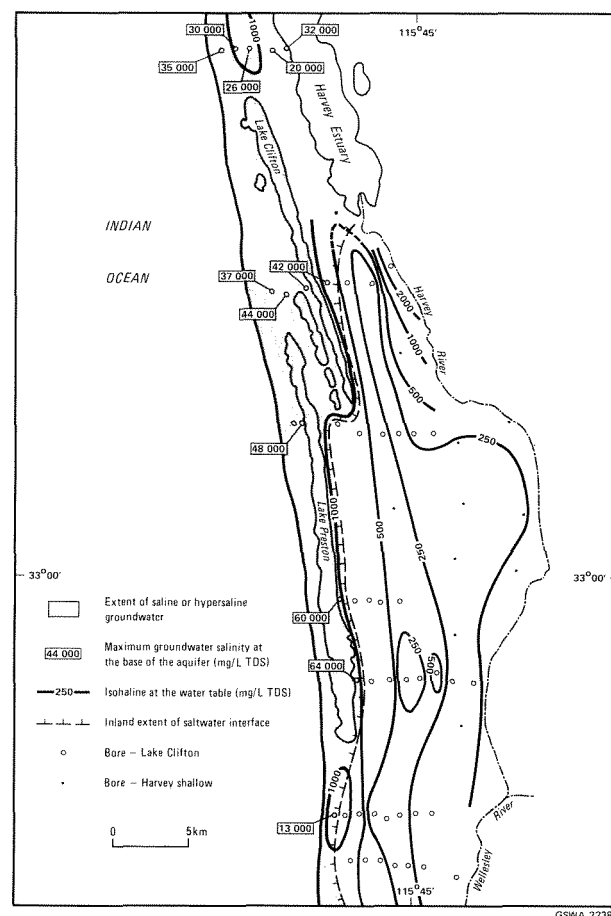


Figure 9. Groundwater salinity

Salinity: The groundwater salinity is least in the eastern part of the flow system in the Tamala Limestone, and increases both to the west and the east from about 250 mg L⁻¹ TDS, (Fig. 9).

Close to the Harvey River, the groundwater salinity in B7 is just over 2 000 mg L⁻¹ TDS, and this may reflect interchange of river water and groundwater.

Near Lake Clifton in B4, the flow system is about 15 m thick and has a salinity of 1 200 mg L⁻¹ TDS, although it is slightly lower within 2 m of the water table (Fig. 11).

Between Lake Clifton and Martins Tank in borehole B3, there is a 14 metre thickness of groundwater with a salinity range of 5 000 to 7 000 mg L⁻¹ TDS, with a distinct interface (Fig. 11) with underlying hypersaline groundwater.

Hypersaline groundwater underlying the lake has a salinity of 42 000 mg L⁻¹ TDS in B3 and B4. This is much higher than the lake salinity, and suggests a poor connection between the lake water and the underlying groundwater, unlike the situation at Lake Preston.

MARTINS TANK FLOW SYSTEM

Extent: The flow system contributing to maintenance of Martins Tank and the other lakes is limited to an area of 20 km², bounded by groundwater divides with Lake Clifton, the ocean, and Lake Preston.

Groundwater flow: Rainfall maintains lenses of fresh or brackish groundwater surrounding the lakes. These extend to a depth of about 14 m in B2 and B3 (Fig. 11), and overlie hypersaline groundwater with a well-defined interface and thin

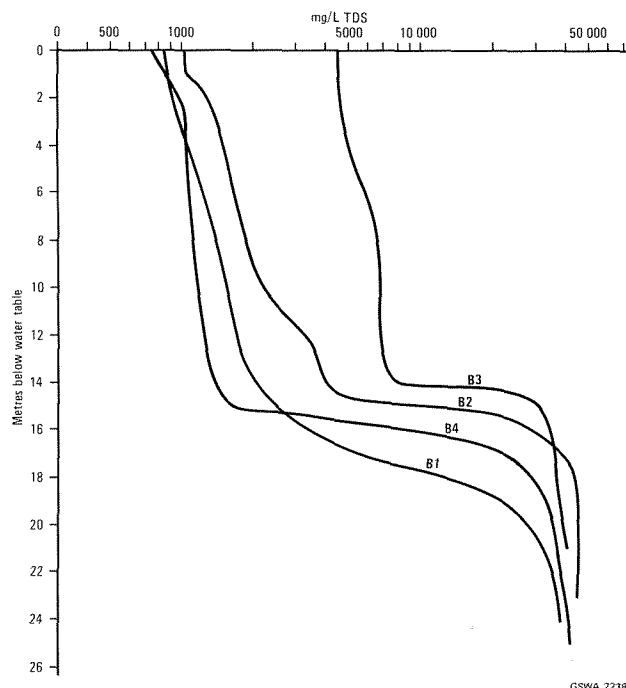


Figure 11. Salinity-depth profiles, line B

mixed zone. The water table has a low hydraulic gradient and is close to sea level, falling below AHD in late summer (Fig. 7). Groundwater discharge is to the lakes.

Salinity: The salinity of the brackish water layers in B1 and B2 ranges from 1 000 to 4 000 mg L⁻¹ TDS, and in B3 from 5 000 to 7 000 mg L⁻¹ TDS (Fig. 11).

The salinity of the underlying hypersaline water from 42 000 to 44 000 mg L⁻¹ TDS along line B (Fig. 9).

HARVEY ESTUARY FLOW SYSTEM

Extent: Harvey Estuary receives groundwater flow derived from rainfall on an area of 41 km² on the peninsula west of the estuary. The groundwater divide along the assumed to be equidistant from the estuary to Lake Clifton or to the ocean (Fig. 6).

Groundwater flow: The slope of the water table and direction of groundwater flow beneath the peninsula change substantially throughout the year because of the effects of variable seasonal recharge, fluctuations in the level of the estuary, and tides in the ocean. For most of the year there is a groundwater divide from which groundwater flow can be assumed to be east and west. Other times of the year the groundwater divide is absent and the water table slopes from the estuary through to the ocean, or *vice versa*. The elevation of the water table along line A ranges from a maximum of 0.5 m above AHD at the end of winter to less than 0.1 m in summer. Consequently the hydraulic gradients are very low.

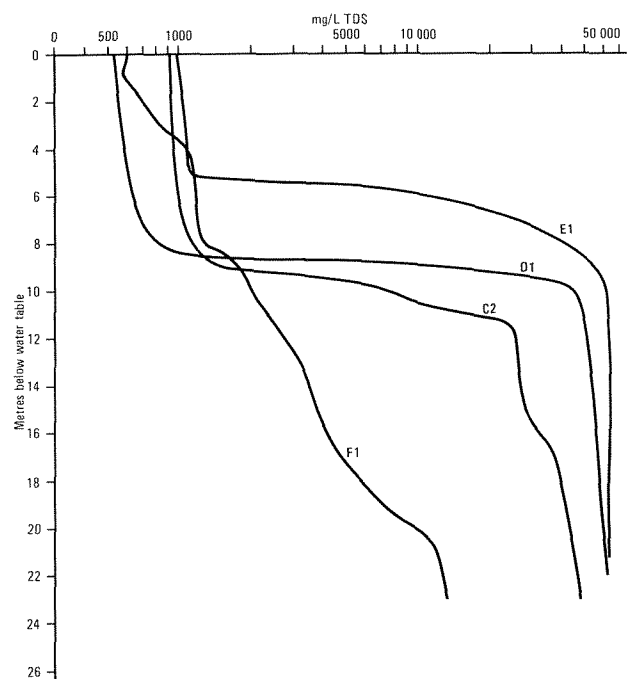


Figure 10. Salinity-depth profiles, bores C2, D1, E1, and F1

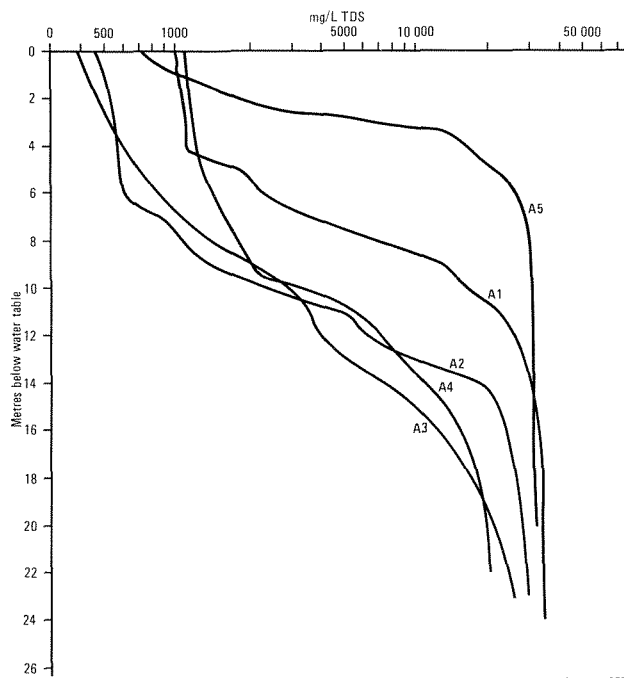


Figure 12. Salinity-depth profiles, line A

Throughout the flow system there is a layer of fresh-brackish water overlying brackish-saline water. Along line A, which is across the widest part of the peninsula, the thickness of this layer ranges from about 10 m in the centre to 2 m in A5 close to the estuary (Fig. 12). The zone of mixing with the underlying saline water is much thicker than the interfaces associated with the coastal lakes, probably because of mixing induced by tidal oscillations.

Salinity: The salinity-depth profile along line A is shown on Figure 5. The minimum salinity at the water table is about 500 mg L⁻¹, in A3. Beneath the narrower parts of the peninsula it is likely that the groundwater salinity will be higher.

At the base of the aquifer the salinity is least in A4, (20 000 mg L⁻¹ TDS) and rises towards Harvey Estuary (32 000 mg L⁻¹ TDS in A5) and the ocean, where the salinity in A1 is similar to that of sea water (35 000 mg L⁻¹ TDS).

LESCHENAULT INLET FLOW SYSTEM

Extent: The flow system discharging to Leschenault Inlet is bounded on the east by a groundwater divide parallel to the Wellesley River, to the north by the Lake Preston Flow System, and to the west by a groundwater divide about half a kilometre from the coast. The flow system also extends south of the area of investigation.

Groundwater flow: Recharge is from rainfall within the area of the flow system, and groundwater flow is mainly in a westerly direction with minor easterly flow from coastal dunes. The hydraulic gradient is very low in the Bassendean Sand; to the

west in the Tamala Limestone there is a zone of steep hydraulic gradient between F7 and F8, and between G5 and G6 (Fig. 7).

Plumes of higher salinity groundwater west of the swamps at Myalup Lagoon and Mialla swamp (Fig. 5) indicate substantial groundwater discharge by evaporation from the swamps. Most discharge however is to the swamps to the north of Leschenault Inlet, and into the inlet itself.

There is also leakage into and out of the Leederville Formation. Downward leakage can occur in the east where the water table is elevated and where the Leederville Formation at the unconformity is permeable. At G3 there is a downward head difference of 0.1 to 0.2 m between the water table and the base of the unconfined aquifer. At G2 the vertical component of groundwater flow is reversed with an upward head difference of 0.12 to 0.25 m.

Salinity: There is a westward increase in salinity at the water table from less than 250 mg L⁻¹ TDS in the Bassendean Sand to about 1 000 mg L⁻¹ at the discharge (Fig. 9). Variation of salinity at depth probably results from plumes of saline water associated with swamps (Fig. 5.).

LAKE WATER BALANCES AND GROUNDWATER DISCHARGE

Since the lakes are groundwater sinks with no outflow other than by evaporation, approximate volumetric lake water balances can be expressed as

$$G + R = E + S$$

where G = groundwater input

R = direct rainfall on the lake

E = evaporation from the lake surface

S = change in storage in the lake.

Rearrangement of this equation for years of average rainfall, in which there should be no change in lake storage from year to year yields

$$E - R = G$$

The evaporative loss from the lake ($E - R$) is the evaporation rate less the rainfall summed over the lake area, and can be determined from meteorological data.

The groundwater input G can be assessed independently by calculation of groundwater flow in the aquifer using Darcy's Law (hydraulic method) and also using a chloride-ion balance. However, these methods cannot be used satisfactorily in areas underlain by saline or hypersaline water where the hydraulic gradients are very low and vertical salinity variations occur. This restricts calculation of groundwater flow to the Lake Preston and Leschenault Inlet Flow Systems but extensions can be made by analogy to the other flow systems.

EVAPORATIVE LOSS

An annual free-water evaporation rate of about 1.4 m has been determined at Robert Bay in Peel Inlet by Hodgkin and others (1980). To calculate the evaporative loss of the coastal lakes this rate should be applied to a reduced lake area, since the lakes recede in summer when the evaporative loss is greatest. Reductions in area of 10% for Lake Preston and the Martins Tank Lakes, and 20% for Lake Clifton are considered appropriate. Areal statistics for the flow systems and evaporative losses from the lakes are set out in Table 7.

The total net evaporative loss from the coastal lakes, i.e. the contribution from groundwater flow, is $15.9 \times 10^6 \text{ m}^3$. Expressed as a proportion of the rainfall on the aquifer area contributing to the lakes, the evaporative loss ranges from 4.5 to 9.2%.

GROUNDWATER DISCHARGE—
HYDRAULIC METHOD

The groundwater throughflow (Q) across a certain width of aquifer (L) normal to the direction of groundwater flow, can be calculated from the form of the Darcy equation:

$$Q = KbiL$$

where K is the hydraulic conductivity, b the aquifer thickness, and i the hydraulic gradient.

Use of this method is restricted to areas of the aquifer in which fresh water extends to the base of the aquifer and where the hydraulic gradient is uniform and known. For these reasons it is appropriate to consider throughflow across the 2 m water-table contour.

Hydraulic data for the Lake Preston and Leschenault Inlet Flow Systems are shown in Table 8. Values of hydraulic conductivity are average values derived from the pumping tests.

TABLE 8. HYDRAULIC DATA FOR FLOW SYSTEMS

Name	K (md^{-1})	b (m)	i (10^{-3})	L (km)	Q (10^3 d^{-1})
Preston	25	22	1.5	22	6.6
Leschenault	14	18	1.5	10	1.4

The area above the 2 m water-table contour is however only 63 to 64% of the total catchment of the flow systems. If the remainder of the area contributes to groundwater throughflow in the same proportion, the total throughflow is increased to the values shown in Table 9.

TABLE 9: GROUNDWATER THROUGHFLOW

Name	Catchment area above 2 m water table contour (%)	Throughflow	
		Absolute (10^6 m^3)	Relative to total rainfall (%)
Preston	63	10.5	5.1
Leschenault	64	1.9	2.7

(a) Catchment area 78 km^2

The derived groundwater throughflow to Lake Preston is very close to the estimated discharge from the lake calculated from the lake evaporation.

The proportion of rainfall contributing to groundwater flow in the Leschenault Inlet Flow System is much lower than in the Lake Preston Flow System. This can be expected because of the presence of large swamps (Myalup Swamp and Mialla Lagoon) above the 2 m water-table contour, which also contribute to groundwater discharge.

GROUNDWATER THROUGHFLOW—
CHLORIDE-ION BALANCE METHOD

By comparing the concentration of chloride ion in rainfall with that in groundwater, the proportion of rainfall contributing to groundwater recharge or throughflow can be estimated. But because there is loss of chloride ion by downward leakage into the Leederville Formation and also some minor loss to surface drainage, the method will over-estimate groundwater flow in the superficial formations.

Hingston and Gailitis (1977) have found the chloride concentration in rainfall at a distance of 3 to 11 km from the coast between Yanchep (100 km north of the study area) and Bunbury to be about 12 mg L^{-1} , and measurements at site G2 in 1981 gave a weighted average of 17.7 mg L^{-1} (Commander, 1984). These values indicate that 14 mg L^{-1} would be a reasonable concentration to apply to rainfall in the catchment area contributing to groundwater throughflow across the 2 m water-table contour.

The average concentration of chloride ion in groundwater from sixteen bores close to the 2 m water-table contour between E3 and C6 is about 240 mg L^{-1} (Commander, 1984).

The net proportion of rainfall contributing to groundwater flow is therefore:

$$(Cr/Cg) \times 100 = (14/240) \times 100 = 5.8\%$$

where

Cr = concentration of Cl in rainfall

Cg = concentration of Cl in groundwater

This is slightly greater than the 5.2% and 5.1% calculated previously by the evaporative loss and hydraulic methods, but this can be expected because of downward leakage yielding an overestimate.

CONCLUSIONS

The drilling has delineated the extent of the superficial formations in the coastal area between about Dawesville and Leschenault Inlet, and identified the presence in them of the Jandakot beds and a previously undescribed marl.

The unconfined aquifer in the superficial formations to the east of the coastal lakes and between Harvey Estuary and Leschenault Inlet is as much as 30 m thick and contains a significant resource of fresh water.

The coastal lakes are maintained by groundwater inflow and rainfall. Water is lost by evaporation so that the lakes are groundwater sinks and are consequently associated with underlying bodies of hypersaline groundwater. The density of this water allows the lake levels to fall below sea level.

West of the lakes, and along the peninsula between Harvey Estuary and the ocean, hypersaline or saline groundwater at the bottom of the aquifer is overlain by lenticular bodies of fresh or brackish water. The mixed zones at the interface between these layers of markedly different salinity are narrow close to the lakes, but more diffuse near the coast and Harvey Estuary where they are affected by tidal oscillations.

Estimates of groundwater flow into Lake Preston by three independent methods indicate that the proportion of rainfall contributing to groundwater discharge is about 5%. As well as contributing to maintenance of the coastal lakes, groundwater in the superficial formations is an important source of recharge to the underlying Leederville Formation.

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GEOCHEMICAL PATTERNS IN GRANITOIDS OF THE CORUNNA DOWNS BATHOLITH, WESTERN AUSTRALIA

by Richard Davy

ABSTRACT

A regional geochemical rock-sampling program, supplemented by petrographic study, has enabled recognition of some 22 different granitoids within the Corunna Downs Batholith. A new intrusive complex with rocks ranging from (hornblende) granodiorite to adamellite has been recognized in the southwestern part of the batholith. Rock types recognized elsewhere include a diorite, a granodiorite orthogneiss, and a syenite, in addition to varieties of tonalite, granodiorite, and adamellite. The overall Na₂O content of the granitoids (~3.7%), and the proportion of tonalites, are lower than in many other Archaean granitoid complexes. An average value for the rocks analyzed suggests a mean composition for the batholith of granodiorite near the adamellite border. The granitoids appear to be of igneous origin (I type) and to belong to the ilmenite series of Ishihara.

The metamorphic history has been complex: there is evidence of chlorite-epidote and prehnite-pumpellyite transformation, and a clastic-dynamic event.

The batholith is unlike other granitoid batholiths of the Pilbara in that it is more potassic and less sodic, and in that no pegmatites, felsic dykes, or rocks of clear sedimentary origin, have been recognized.

There is no obvious economic potential.

INTRODUCTION

The Mount Edgar and Corunna Downs batholiths of the Pilbara region of Western Australia are largely composed of granitoids. Each is almost wholly enclosed by greenstones of Archaean age.

In 1978, a reconnaissance regional rock-sampling program was undertaken in these two batholiths to assess the potential for undiscovered tin deposits. At the same time, opportunity was taken to collect compositional data for each batholith to assist in the understanding of their origins.

The criterion used to distinguish tin granites from others was that they commonly contain in excess of 10 ppm Sn (Beus, 1969; Varlamoff, 1969; Hesp, 1971; Davy, 1972).

Papers on the Mount Edgar Batholith have been published by Davy and Lewis, (1981, 1985) and Lewis and Davy (1981). This paper presents the findings of the studies on the Corunna Downs Batholith.

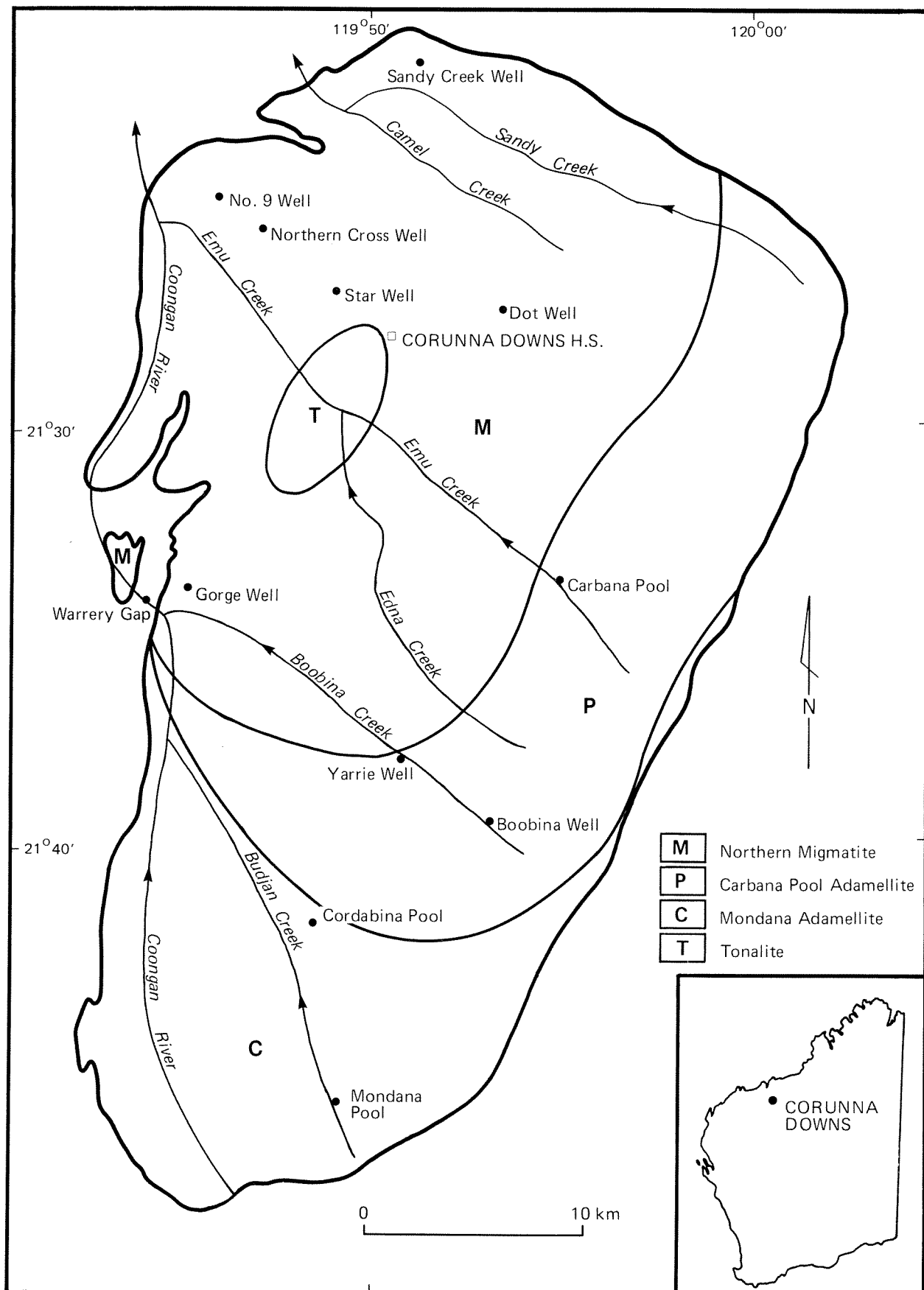
Corunna Downs homestead, in the north-central part of the batholith, is located some 40 km south of Marble Bar (longitude 116° 45'E, latitude 21° 10'S; Fig. 1). The batholith is pear to ovoid shaped, tapering to the south; its maximum dimensions are 52 km in a north-northeasterly direction and 32 km in an east-southeasterly direction. The batholith outcrops on parts of two 1:250 000 geological sheet

areas; Marble Bar was mapped at that scale by Hickman and Lipple (1978) and Nullagine by Hickman (1979). The maps prepared by these authors formed the geological framework for this study. The regional setting was described by Hickman (1975, 1983).

The surface expression of the batholith is a gently undulating plain, which slopes gradually to the northwest. There is little outcrop except in restricted areas north of the homestead and adjacent to the perimeter of the batholith. Elsewhere, granitic tors protrude through an extensive cover of alluvium or wind-blown sand.

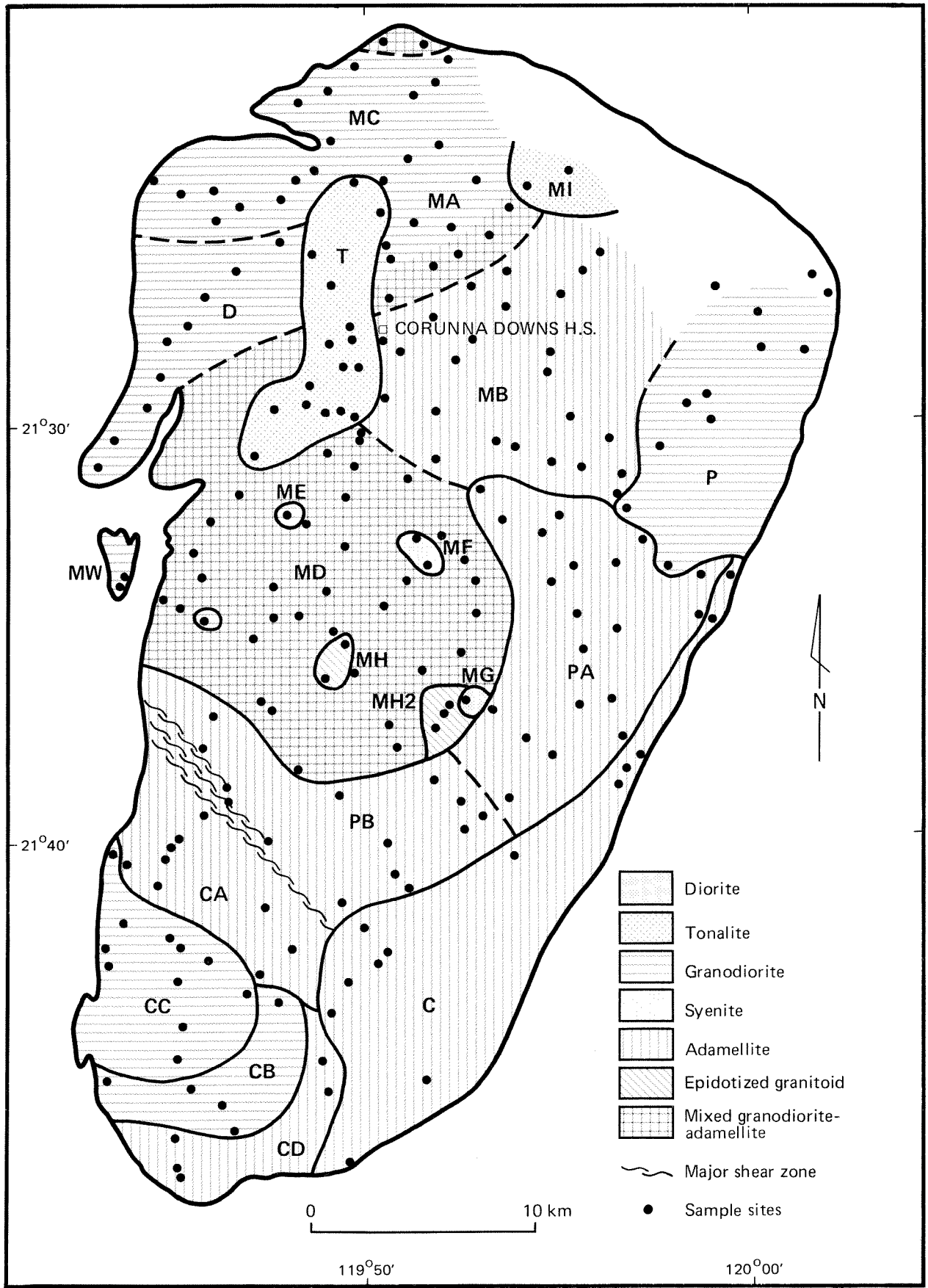
Samples were taken along station tracks, at 3-5 km intervals where possible, or at closer intervals when the rock type changed. Where two or more rock types were identified at an outcrop, each was sampled separately. Some 225 samples were obtained in a two-and-a-half-week collecting period: 164 of these were fresh granitoids. Determinations of major oxides and 24 trace elements were made. Details of analytical methods are given by Davy and Lewis (1985). Analysis was "whole-rock" except that all iron was reported as Fe₂O₃; and loss on ignition was used instead of separate determinations of H₂O⁺, H₂O⁻, and CO₂. A summary of laboratory methods used is given in Appendix 1.

* Appendices 1, 2, and 3 are on microfiche and will be found in pocket inside back cover



GSWA 22309

Figure 1A. Locality map showing rock units suggested by Hickman and Lipple (1978) and Hickman (1983).



GSWA 22310

Figure 1B. Geological map of granitoids of the batholith showing sample sites.

Mines Department statistics record the production of 850 kg of tin concentrates from the Corunna Downs area, but no specific source locality is given (Blockley, 1980). Campana (1963), cited by Blockley (1980), reported tin values from dumps of alluvial material in the vicinity of the wells. The highest figures he reported are:

Locality	Sn (ppm)
North Cross Well	150
Dot Well	67
Star Well	60
No 9 Well	52

These wells are identified in Figure 1A. There has been little other economic interest in the batholith.

Six other chemical analyses of rocks from the batholith have been published: one by Blockley (1980) and five by Hickman (1983). These analyses have been incorporated in the present study. Cooper and others (1982) reported Rb-Sr isotope dates for part of the western side of the batholith.

TERMINOLOGY

Hickman and Lipple (1978) identified three granitic complexes within the batholith: a migmatite complex in the north; a later porphyritic granitoid—the Carvana Pool Adamellite; and, in the south, a post tectonic granitoid—the Mondana Adamellite. Hickman (1983) also identified a tonalite, which he thought intruded the migmatite. On Figure 1A, these units are marked M, P, C, and T, respectively.

In this study, field observations, petrography, and chemical analyses, have allowed the recognition of twenty-two distinctive rock types. However, the contacts are generally soil covered; and, as a result, it is impossible to say whether they are discrete intrusions, or simply phases of one—or more—intrusion. It follows that the mapping of the boundaries (Fig. 1B) is approximate and differs slightly from that of Hickman (1983). In order to relate the rock types of this study (Table 1, Fig. 2B) to the mapped units of Hickman, the map symbols, M, P, T, and C, (Fig. 2A)—with additional letters where necessary—have been used as abbreviations.

PETROGRAPHY

The rock classification used has been primarily that of Streckeisen (1973), with the additional subdivision of the granite field into granite and adamellite. This has been supplemented for those

samples for which no modal determinations have been made by a modification of Harpum's (1963) classification based on the ratio of K_2O to Na_2O . For this report, granodiorites are separated from tonalites at a K_2O/Na_2O ratio of 0.5. This "chemical" classification correlates closely with the "modal" classification of Streckeisen. The petrographic rock names given to the granitoids of the batholith are shown in Table 1.

A summary of the petrography is given in Appendix 2. The main minerals are plagioclase, quartz, and biotite, which are ubiquitous. K-feldspar occurs in all but the most tonalitic samples. Many granodiorite and tonalite samples contain green actinolitic amphibole.

Oligoclase, in the range of An_{10-20} , with a maximum of An_{25} , is the common plagioclase. However, interstitial grains and the rims of larger grains are albite (An_{0-10}). Many of the larger grains are zoned, and the "calcic" cores are now saussuritized or sericitized. Cracking of the larger grains is common and some grains are corroded by reaction with what is now groundmass.

Quartz commonly forms anhedral grains of varying size. Where it has been later recrystallized, it tends to be equant.

K-feldspar is usually fresh, anhedral microcline, which formed with quartz after the larger oligoclase grains. In a few samples there are indications of zoning and, in adamellite PB, the feldspar is coarsely perthitic.

Biotite occurs in relatively small flakes. Alteration to chlorite is common; alteration to prehnite is rare. Muscovite is a common accessory mineral, most frequently as a product of sericitization of plagioclase. Some amphibole has also been altered to chlorite.

Other accessory minerals, in decreasing order of abundance, are sphene, opaques (probably ilmenite), allanite, zircon, and apatite.

Most of the granitoids are coarse grained, but thin sections suggest that some rocks classed as porphyritic in hand specimen may be misnamed. Some "phenocrysts" have been produced by partial cataclasis, others are composite grains in which late-formed microcline has enveloped early-formed plagioclase.

The textures of most rocks are hypidiomorphic to xenomorphic granular: but some, such as granodiorite MJ, are cumulate; and others, such as diorite MG, granodiorites P and CC and adamellite CA are, at least in part, granophyric.

Some samples from most types show incipient development of mylonite, and fine-grained groundmass (0.01 - 0.1 mm grain size) may be either primary or the product of crushing. In more extremely

TABLE 1. ROCK TYPES AND SYMBOLS

Map symbol	Microcline %	K ₂ O/Na ₂ O	Rock type
Northern migmatite complex			
MA	20+	0.92	granodiorite
MB	15+	1.2	adamellite
MC	20+	0.91	granodiorite
MD	15+	1.2	granodiorite- adamellite
ME	10+	0.90	granodiorite
MF	40	0.89	syenite
MG	0-5	0.41	diorite
MH	20-40	11.5	epidotized granitoid
MH2	20-40	14.2	epidotized granitoid
MI	< 5	0.48	tonalite
MJ	5-10	0.64	granodiorite
D	< 10	0.55	granodiorite
T	< 5	0.38	tonalite
Warrery Gap			
MW	10-20	0.73	granodiorite
Porphyritic granitoids			
P	25+	0.86	granodiorite
PA	30+	1.3	adamellite
PB	20+	1.0	adamellite
Mondana Adamellite			
C	30+	1.2	adamellite
Southwestern complex			
CC	5-15	0.57	granodiorite
CB	20	0.85	granodiorite
CA	30+	1.3	adamellite
CD	20+	1.3	adamellite
All fresh samples			
Average		0.95	granodiorite

affected samples (not considered chemically fresh), proto-mylonite shear zones retain their crush structure and, in some cases, include stringers of pseudotachylite. In other cases these crush zones have been recrystallized into a mass of equant polygonal grains. Some crush zones cut rocks containing epidote and other metamorphic minerals, but some epidote is found in the recrystallized polygonal grains.

METAMORPHISM

All of the rocks have been subjected to low-grade metamorphism. Three different metamorphic styles have been detected:

- chlorite-epidote
- prehnite-pumpellyite
- cataclastic

The cataclastic metamorphism is the latest, but the relative ages of the chlorite-epidote and the prehnite-pumpellyite metamorphism have not been determined.

The chlorite-epidote alteration is universal. It is expressed by initial saussuritization and seri-

cization of plagioclase, followed in some instances, by development of larger grains of clinozoisite or epidote from the saussurite and secondary muscovite from the sericite. This is accompanied by partial chloritization of biotite and amphibole. The presence of clinozoisite as well as epidote indicates lower greenschist facies (Winkler, 1979).

Prehnite-pumpellyite alteration is not visible in every thin section. Prehnite is mainly present within the altered biotite, and appears to have formed at its expense. Pumpellyite is rare and has only been identified in veins. Neither mineral has been found in the rocks of the southwest complex or the Mondana Adamellite. Saussurite, epidote, and chlorite, are normally present in rocks containing prehnite and pumpellyite. Prehnite and pumpellyite are not uncommon in the Marble Bar area (Hickman and Lipple, 1978; Barley, 1982). Smith and others (1982, Fig. 2) suggested that a gradational boundary between a prehnite-pumpellyite zone and a prehnite-pumpellyite-epidote zone runs north-south through the batholith. Observations made during this study suggest that most of the

TABLE 2. COMPOSITIONS OF ALL ROCK TYPES AND BATHOLITH AS A WHOLE.

(See Table 1 for description of rock types)

	MA (10 samples)			MB (30 samples)			MC (9 samples)		
	Range	Mean	Std. Dev.	Range	Mean	Std. Dev.	Range	Mean	Std. Dev.
Percentage									
SiO ₂	68.3 - 72.2	69.9	1.4	69.5 - 75.6	73.4	1.6	68.2 - 72.5	69.8	1.5
Al ₂ O ₃	13.1 - 14.8	13.9	0.66	12.1 - 14.3	13.3	0.62	12.5 - 14.7	14.0	0.66
Fe ₂ O ₃	2.5 - 4.2	3.6	0.78	0.9 - 3.6	2.0	0.63	2.8 - 5.0	3.7	0.73
MgO	0.32 - 1.3	0.80	0.33	0.07 - 0.65	0.30	0.16	0.80 - 1.4	1.1	0.21
CaO	1.2 - 2.8	2.2	0.57	0.27 - 2.2	1.3	0.52	1.1 - 3.1	2.3	0.58
Na ₂ O	3.1 - 4.4	3.6	0.40	2.3 - 4.2	3.5	0.48	3.2 - 4.0	3.5	0.23
K ₂ O	2.3 - 4.4	3.3	0.67	3.3 - 6.0	4.1	0.76	2.3 - 3.7	3.2	0.43
LOI	0.22 - 2.5	1.2	0.66	0.25 - 1.4	0.81	0.64	0.60 - 1.6	1.2	0.38
TiO ₂	0.20 - 0.48	0.37	0.10	<0.01 - 0.31	0.13	0.08	0.27 - 0.63	0.39	0.11
P ₂ O ₅	<0.01 - 0.18	0.03	0.05	<0.01 - 0.07	0.01	0.01	<0.01 - 0.10	0.04	0.03
MnO	0.01 - 0.08	0.04	0.02	<0.01 - 0.05	<0.01		0.02 - 0.06	0.04	0.01
Parts per million									
Ba	450 - 2000	989	538	120 - 1200	598	277	400 - 1600	617	402
Be (b)	1 - 2	-	-	<1 - 3	-	-	1 - 2	-	-
B (b)	1 - 6	-	-	<1 - 10	-	-	3 - 7	-	-
Ce	65 - 220	127	54	10 - 95	51	22	35 - 160	66	39
Co	5 - 13	10	3	<5 - 14	6	3	5 - 13	10	3
Cu	13 - 134	47	42	7 - 73	21	15	8 - 18	13	3
F	220 - 880	428	206	50 - 620	248	155	240 - 760	349	161
Ga	12 - 18	15	2	10 - 18	15	2	14 - 18	16	2
La	40 - 140	74	31	<10 - 60	34	15	10 - 100	36	29
Pb	15 - 25	19	3	7 - 70	20	11	12 - 22	16	3
Li	12 - 40	24	7	6 - 58	26	17	10 - 29	22	6
Mn	250 - 600	381	96	81 - 397	213	105	237 - 483	361	78
Mo	- 1	1	-	- 1	1	-	- 1	1	-
Ni	10 - 20	15	3	5 - 17	10	4	7 - 18	13	3
Nb	<5 - 15	9	5	<5 - 15	(a) 7	(a) 4	<5 - 10	-	-
Rb	65 - 130	98	20	75 - 210	144	36	80 - 150	113	26
Sr	130 - 240	184	48	35 - 210	112	36	140 - 300	202	44
Th	5 - 50	13	5	<5 - 20	11	6	<5 - 10	6	4
Sn	<2 - 16	3	5	<2 - 35	4	6	<2 - 4	<2	-
U	<1 - 2	<1	-	<1 - 8	2	2	<1 - 1	-	-
V	10 - 40	27	10	<10 - 20	<10	-	10 - 50	34	16
Y	10 - 40	28	10	6 - 40	23	10	15 - 40	23	8
Zn	38 - 95	52	8	14 - 54	35	13	24 - 64	47	12
Zr	160 - 250	205	33	70 - 220	140	43	120 - 250	161	45
CaO/TiO ₂		6.0			10.0			5.0	
K (%)		2.74			3.40			2.66	

(a) Approximate values only. (b) Fewer than stated number of samples. (c) Mean of seven samples. (d) Mean of four samples.

TABLE 2. CONTINUED.

	MD (22 samples)			ME (1 sample)	MF (2 samples)		MG (1 sample)	MH (2 samples)	
	Range	Mean	Std. Dev.		Range	Mean		Range	Mean
Percentage									
SiO ₂	63.1 - 76.1	72.1	3.7	70.5	61.7 - 65.4	63.5	56.3	62.0 - 66.0	64.0
Al ₂ O ₃	11.8 - 15.9	13.2	1.1	14.1	16.3 - 17.1	16.7	15.1	14.2 - 15.6	14.9
Fe ₂ O ₃	1.1 - 5.9	2.7	1.2	3.2	2.6 - 3.1	2.8	9.1	3.9 - 5.3	4.6
MgO	0.12 - 1.3	0.53	0.35	0.65	0.46 - 0.65	0.55	3.3	- 0.08	0.08
CaO	0.42 - 2.8	1.5	0.72	2.3	1.5 - 2.8	2.1	6.9	8.8 - 10.6	9.7
Na ₂ O	2.3 - 4.5	3.4	0.60	3.0	5.2 - 5.7	5.7	3.2	0.30 - 0.38	0.34
K ₂ O	2.8 - 5.5	4.0	0.79	2.7	5.1 - 5.2	5.1	1.3	3.8 - 4.1	3.9
LOI	0.44 - 2.6	1.1	0.52	0.97	0.92 - 3.0	2.0	1.2	1.1 - 1.6	1.3
TiO ₂	<0.01 - 0.63	0.24	0.16	0.23	0.19 - 0.25	0.22	1.1	0.33 - 0.34	0.33
P ₂ O ₅	<0.01 - 0.12	0.04	0.03	0.06	0.02 - 0.03	0.02	0.08	0.05 - 0.07	0.06
MnO	<0.01 - 0.06	0.01	-	0.04	0.02 - 0.03	0.02	0.10	0.04 - 0.06	0.05
Parts per million									
Ba	220 - 8000	1443	2062	700	450 - 600	525	220	- 800	800
Be	1 - 2	-	-	-	1 - 2	1	-	- -	-
B	<1 - 10	-	-	-	<1 - 15	7	-	- -	-
Ce	10 - 280	113	77	80	- 80	80	30	110 - 130	120
Co	<5 - 15	7	3	8	5 - 10	7	17	5 - 10	7
Cu	10 - 191	26	38	8	5 - 40	22	42	12 - 68	40
F	50 - 900	286	200	290	60 - 140	100	340	330 - 2100	1215
Ga	10 - 18	14	2	14	- 15	15	18	26 - 30	28
La	<10 - 180	70	51	50	40 - 60	50	30	60 - 90	75
Pb	10 - 30	16	4	8	- 10	10	15	12 - 30	21
Li	8 - 77	23	16	27	17 - 32	22	21	12 - 17	14
Mn	28 - 520	206	142	242	200 - 290	245	850	395 - 451	423
Ni	7 - 17	10	3	5	5 - 10	7	28	5 - 12	8
Nb	<5 - 20	8	5	10	- <5	<5	10	5 - 10	7
Rb	45 - 260	124	47	110	140 - 200	170	60	130 - 140	135
Sr	40 - 400	137	74	180	85 - 170	127	220	480 - 750	615
Th	<5 - 30	11	6	10	20 - 30	25	<5	5 - 10	7
Sn	<2 - 16	3	4	2	<2 - 2	<2	2	2 - 4	3
U	<1 - 5	-	-	<1	- <1	<1	<1	<1 - 1	-
V	<10 - 40	12	10	10	- 10	100	10	- 10	10
Y	6 - 60	26	15	21	15 - 20	17	24	30 - 35	17
Zn	12 - 81	37	20	43	17 - 45	31	109	8 - 42	25
Zr	80 - 400	185	80	220	150 - 180	165	120	180 - 240	210
CaO/TiO ₂		6.3		10.0		9.6	6.3		29.4
K (%)		3.32		2.24		4.23	1.08		3.24

(a) Approximate values only. (b) Fewer than stated number of samples. (c) Mean of seven samples. (d) Mean of four samples.

TABLE 2. CONTINUED.

	MH2 (2 samples)		MI (2 samples)		MJ (1 sample)	MW (2 samples)	
	Range	Mean	Range	Mean		Range	Mean
	Percentage						
SiO ₂	63.4 - 65.8	64.6	65.3 - 65.4	65.3	65.6	72.0 - 72.6	72.3
Al ₂ O ₃	13.0 - 14.9	13.9	14.2 - 14.5	14.3	19.2	13.2 - 13.5	13.3
Fe ₂ O ₃	5.0 - 6.2	5.6	5.1 - 5.2	5.1	1.2	2.6 - 2.8	2.7
MgO	- 0.05	0.05	0.92 - 1.1	1.0	0.23	0.80 - 0.83	0.81
CaO	8.1 - 10.7	9.4	3.4 - 3.5	3.4	1.9	1.8 - 1.9	1.8
Na ₂ O	0.10 - 0.43	0.26	4.0 - 4.3	4.1	4.4	3.5 - 4.0	3.7
K ₂ O	3.0 - 4.5	3.7	1.9 - 2.5	2.2	2.8	2.7 - 2.8	2.7
LOI	0.86 - 1.3	1.1	0.73 - 1.2	0.97	1.1	1.1 - 1.2	1.1
TiO ₂	0.28 - 0.34	0.31	0.55 - 0.56	0.55	0.09	0.22 - 0.25	0.23
P ₂ O ₅	0.03 - 0.08	0.05	0.06 - 0.07	0.06	0.08	0.03 - 0.05	0.04
	Parts per million						
Ba	450 - 600	525	- 500	500	350	500 - 600	550
Be	2 - 3	2	- 3	3	-	- -	-
B	- 3	3	- 1	1	-	- 6	6
Ce	120 - 130	125	100 - 130	115	15	60 - 80	70
Co	<5 - 5	<5	- 7	7	10	10 - 12	11
Cu	10 - 17	13	35 - 46	40	20	13 - 17	15
F	150 - 230	190	- 810	810	250	250 - 260	255
Ga	30 - 32	31	- 18	18	20	14 - 16	15
La	70 - 80	75	60 - 70	65	<10	- 40	40
Pb	10 - 32	21	18 - 20	19	10	12 - 27	19
Li	3 - 6	4	29 - 40	34	21	37 - 54	45
Mn	280 - 583	431	584 - 649	616	105	279 - 287	283
Ni	- 5	5	23 - 28	25	10	7 - 12	9
Nb	- 10	- 10	10 - 15	12	<5	5 - 10	7
Rb	80 - 170	125	90 - 110	100	140	- 80	80
Sr	1100 - 1300	1200	190 - 240	215	340	140 - 15	0145
Th	- 10	10	10 - 15	12	5	5 - 10	7
Sn	<2 - 4	-	2 - 4	3	<2	<2 - 2	-
U	- <1	<1	- 2	2	<1	- <1	<1
V	20 - 40	30	40 - 50	45	10	- 20	20
Y	20 - 24	22	- 45	45	12	21 - 30	25
Zn	6 - 17	11	73 - 76	74	23	33 - 34	33
Zr	195 - 200	197	240 - 250	245	70	140 - 160	150
CaO/TiO ₂		30.3		6.2	21.1		7.9
K (%)		3.1		1.8	2.3		2.2

(a) Approximate values only. (b) Fewer than stated number of samples. (c) Mean of seven samples. (c) Mean of four samples.

TABLE 2. CONTINUED.

	D (10 samples)			T (11 samples)			P (8 samples)		
	Range	Mean	Std. Dev.	Range	Mean	Std. Dev.	Range	Mean	Std. Dev.
Percentage									
SiO ₂	64.4 - 69.5	66.0	1.4	63.3 - 74.4	67.1	3.0	65.9 - 70.8	68.3	1.6
Al ₂ O ₃	17.5 - 15.8	15.1	0.40	14.2 - 15.6	14.9	0.58	13.1 - 14.3	13.8	0.41
Fe ₂ O ₃	3.3 - 5.3	4.7	0.57	2.6 - 6.9	4.6	1.3	3.4 - 5.0	4.2	0.53
MgO	0.87 - 1.7	1.5	0.24	0.58 - 1.9	1.4	0.51	0.78 - 1.7	0.96	0.32
CaO	2.5 - 4.0	3.4	0.52	2.2 - 4.3	3.3	0.62	2.2 - 3.1	2.6	0.33
Na ₂ O	3.6 - 4.7	4.2	0.34	3.2 - 4.9	4.2	0.46	2.7 - 4.1	3.6	0.43
K ₂ O	1.9 - 2.9	2.3	0.38	1.1 - 2.0	1.6	0.26	2.5 - 3.5	3.1	0.32
LOI	0.73 - 1.8	1.4	0.34	1.2 - 2.5	1.9	0.43	0.43 - 2.3	1.0	0.58
TiO ₂	0.31 - 0.57	0.50	0.08	0.20 - 0.83	0.50	0.16	0.36 - 0.54	0.44	0.06
P ₂ O ₅	0.05 - 0.12	0.09	0.02	<0.01 - 0.33	0.08	0.09	0.04 - 0.08	0.05	0.01
Parts per million									
Ba	300 - 500	415	82	220 - 800	401	178	350 - 600	456	78
Be	2 - 3	-	-	1 - 2	-	-	2 - 3	-	-
B	3 - 7	-	-	4 - 10	-	-	2 - 10	-	-
Ce	25 - 60	40	11	40 - 160	74	36	60 - 120	96	21
Co	7 - 13	10	2	7 - 20	12	4	6 - 20	11	4
Cu	10 - 43	23	9	10 - 110	29	29	17 - 46	24	10
F	280 - 530	425	67	180 - 740	383	102	340 - 840	668	146
Ga	16 - 18	17	1	14 - 21	17	2	16 - 18	17	1
La	<10 - 40	22	12	<20 - 120	42	32	40 - 70	49	11
Pb	10 - 17	15	2	10 - 70	21	18	18 - 37	23	6
Li	12 - 40	29	12	21 - 70	27	6	24 - 60	39	16
Mn	382 - 579	488	62	201 - 900	455	160	310 - 549	462	71
Ni	12 - 25	16	4	7 - 40	14	5	10 - 28	20	6
Nb	<5 - 10	-	-	<5 - 18	7	3	<5 - 15	10	3
Rb	70 - 140	97	24	65 - 100	78	15	95 - 170	129	27
Sr	220 - 320	260	35	210 - 360	284	44	140 - 220	176	32
Th	<5 - 10	-	-	<5 - 20	7	3	10 - 20	14	4
Sn	<2 - 30	(a)6	(a)9	<2 - 8	2	2	2 - 8	5	2
U	<1 - 2	1	1	<1 - 1	-	-	<1 - 6	3	2
V	40 - 60	55	7	<10 - 80	45	24	20 - 60	33	13
Y	15 - 45	24	8	6 - 30	21	8	25 - 45	36	6
Zn	51 - 64	59	4	27 - 165	67	37	48 - 136	69	28
Zr	140 - 200	171	23	150 - 300	215	53	165 - 240	206	30
CaO/TiO ₂		6.8			6.6			5.9	
K (%)		1.91			1.33			2.57	

(a) Approximate values only. (b) Fewer than stated number of samples. (c) Mean of seven samples. (d) Mean of four samples.

TABLE 2. CONTINUED.

	PA (13 samples)			PB (8 samples)			C (10 samples)		
	Range	Mean	Std. Dev.	Range	Mean	Std. Dev.	Range	Mean	Std. Dev.
				Percentage					
SiO ₂	66.8 - 76.8	73.1	2.7	69.6 - 72.4	70.8	0.98	73.2 - 75.9	75.0	0.97
Al ₂ O ₃	10.9 - 14.0	12.7	0.93	12.6 - 14.0	13.3	0.47	12.2 - 12.8	12.5	0.23
Fe ₂ O ₃	1.5 - 5.5	2.5	1.1	2.3 - 3.6	3.0	0.51	1.2 - 1.9	1.6	0.27
MgO	0.13 - 0.82	0.42	0.21	0.45 - 0.92	0.69	0.17	0.07 - 0.30	0.19	0.09
CaO	0.54 - 3.1	1.3	0.71	1.1 - 2.5	1.9	0.43	0.22 - 1.4	0.76	0.38
Na ₂ O	2.8 - 3.8	3.2	0.34	3.5 - 4.0	3.8	0.21	3.1 - 4.4	3.5	0.41
K ₂ O	3.2 - 5.2	4.1	0.53	3.3 - 4.3	3.8	0.34	3.6 - 4.8	4.3	0.36
LOI	0.40 - 0.98	0.63	0.18	0.62 - 1.3	1.0	0.23	0.52 - 0.64	0.58	0.04
TiO ₂	0.05 - 0.67	0.21	0.16	0.19 - 0.38	0.29	0.07	0.03 - 0.14	0.08	0.04
P ₂ O ₅	<0.01 - 0.11	0.03	0.04	0.03 - 0.06	0.04	0.01	<0.01 - 0.02	<0.01	-
				Parts per million					
Ba	100 - 600	299	157	500 - 900	(c)642	162	60 - 400	157	116
Be	2 - 3	-	-	2 - 3	-	-	2 - 5	-	-
B	1 - 10	-	-	<1 - 7	-	-	<1 - 11	-	-
Ce	40 - 140	81	40	70 - 120	(c)101	20	15 - 65	44	15
Co	3 - 17	7	4	7 - 14	10	2	<5 - 12	7	3
Cr	7 - 30	16	6	13 - 20	16	2	5 - 25	13	6
F	160 - 930	511	243	180 - 780	454	237	70 - 1860	629	593
Ga	12 - 18	15	2	12 - 16	(c) 15	2	12 - 18	15	2
La	10 - 70	38	20	40 - 80	(c) 60	17	<10 - 30	-	-
Pb	10 - 32	20	7	10 - 30	23	6	12 - 32	26	6
Li	17 - 56	27	12	13 - 44	21	10	7 - 53	24	14
Mn	103 - 601	260	145	180 - 500	350	122	66 - 320	181	72
Ni	4 - 28	9	6	5 - 20	13	5	5 - 15	10	4
Nb	<5 - 15	10	4	<5 - 15	-	-	5 - 15	11	4
Rb	110 - 230	178	40	90 - 180	151	25	180 - 260	227	25
Sr	50 - 160	88	37	130 - 240	(c)181	36	5 - 95	51	30
Th	10 - 30	22	6	10 - 20	(c) 14	4	10 - 25	19	5
Sn	2 - 8	4	2	<2 - 6	(c) 3	2	<2 - 8	3	2
U	<1 - 6	4	2	1 - 4	3	1	<1 - 5	3	2
V	<10 - 30	-	-	<10 - 30	(c) 18	8	<10 - 10	-	-
Y	15 - 50	30	11	25 - 35	(c) 32	4	21 - 60	34	13
Zn	24 - 102	47	25	35 - 56	42	7	17 - 44	28	10
Zr	80 - 250	157	52	160 - 200	(c)172	15	70 - 140	104	21
CaO/TiO ₂		6.2			6.6			9.5	
K(%)		3.40			3.15			3.57	

(a) Approximate values only. (b) Fewer than stated number of samples. (c) Mean of seven samples. (d) Mean of four samples.

TABLE 2. CONTINUED.

	CA (5 samples)			CB (4 samples)			CC (11 samples)		
	Range	Mean	Std. Dev.	Range	Mean	Std. Dev.	Range	Mean	Std. Dev.
	Percentage								
SiO ₂	73.3 - 76.6	74.8	1.6	69.9 - 71.2	70.4	0.64	64.3 - 71.1	67.4	2.2
Al ₂ O ₃	12.3 - 13.0	12.6	0.31	14.0 - 14.7	14.4	0.29	13.8 - 15.4	14.6	0.58
Fe ₂ O ₃	1.0 - 2.5	1.7	0.64	2.4 - 3.6	3.0	0.49	3.2 - 5.4	4.2	0.71
MgO	0.10 - 0.75	0.37	0.29	0.72 - 1.1	0.86	0.17	0.90 - 1.8	1.3	0.28
CaO	0.17 - 1.4	0.82	0.55	2.2 - 2.7	2.3	0.26	2.2 - 3.9	3.0	0.53
Na ₂ O	2.4 - 3.8	3.3	0.53	3.8 - 4.3	4.0	0.20	3.9 - 4.5	4.2	0.16
K ₂ O	3.9 - 5.5	4.6	0.62	3.4 - 3.5	3.4	0.05	2.0 - 2.9	2.4	0.30
LOI	0.20 - 0.87	0.54	0.24	0.39 - 1.2	0.74	0.34	0.24 - 1.7	0.83	0.52
TiO ₂	0.01 - 0.24	0.13	0.10	0.22 - 0.39	0.30	0.07	0.29 - 0.61	0.45	0.10
P ₂ O ₅	<0.01 - 0.03	0.02	0.01	0.04 - 0.11	0.06	0.04	0.03 - 0.13	0.07	0.03
	Parts per million								
Ba	50 - 1600	542	636	300 - 800	488	218	300 - 800	542	165
Be	2 - 3	-	-	- -	-	-	2 - 3	-	-
B	2 - 4	-	-	- -	-	-	2 - 8	-	-
Ce	25 - 140	78	41	50 - 70	59	8	55 - 110	80	13
Co	<5 - 8	(d) 7	3	8 - 15	-	-	8 - 15	11	2
Cu	10 - 27	15	7	17 - 51	27	16	17 - 50	25	10
F	40 - 340	198	119	270 - 510	395	114	400 - 770	509	113
Ga	- 14	-	-	- 14	14	-	16 - 18	17	1
La	20 - 80	(d) 53	21	- 30	30	-	30 - 55	41	8
Pb	10 - 28	17	7	13 - 17	16	2	10 - 17	13	3
Li	<2 - 27	14	11	23 - 44	34	9	21 - 53	38	11
Mn	<20 - 302	158	134	300 - 500	393	83	327 - 639	472	89
Ni	7 - 15	10	4	7 - 20	12	6	13 - 23	18	3
Nb	<5 - 12	8	4	5 - 8	6	2	<5 - 15	8	4
Rb	130 - 210	149	33	95 - 130	116	15	80 - 110	95	10
Sr	15 - 160	88	69	200 - 220	213	10	180 - 320	259	52
Th	10 - 30	19	9	5 - 10	9	3	<10 - 15	(a)8	(a)3
Sn	<2 - 2	-	-	2 - 6	3	2	<2 - 4	(a)2	(a)1
U	<1 - 4	(a) 2	(a) 1	<1 - 2	<2	-	<1 - 6	-	-
V	<10 - 30	(a) 13	(a) 12	20 - 40	28	10	20 - 80	48	16
Y	12 - 30	(d) 22	8	18 - 21	-	-	18 - 35	25	5
Zn	15 - 32	24	8	37 - 60	45	10	44 - 71	57	8
Zr	100 - 140	(d)125	19	- 120	120	-	160 - 200	176	15
CaO/TiO ₂		6.3			7.7			6.7	
K (%)		3.82			2.82			1.99	

(a) Approximate values only. (b) Fewer than stated number of samples. (c) Mean of seven samples. (d) Mean of four samples.

TABLE 2. CONTINUED.

	CD (5 samples)			All (164 samples)		
	Range	Mean	Std. Dev.	Mean	Std. Dev.	
Percentage						
SiO ₂	71.1 - 77.3	75.2	2.5	70.8	3.8	
Al ₂ O ₃	11.7 - 13.3	12.5	0.59	13.7	1.2	
Fe ₂ O ₃	0.7 - 1.9	1.3	0.49	3.0	1.4	
MgO	0.10 - 0.58	0.28	0.20	0.72	0.53	
CaO	0.3 - 1.4	0.71	0.48	2.0	1.1	
Na ₂ O	2.6 - 3.7	3.3	0.44	3.7	0.56	
K ₂ O	4.0 - 4.9	4.4	0.34	3.5	1.0	
H ₂ O+	0.53 - 1.5	0.98	0.43	1.0	0.57	
TiO ₂	<0.01 - 0.20	0.09	0.08	0.29	0.19	
P ₂ O ₅	<0.01 - 0.02	<0.01		0.04	0.04	
Parts per million						
Ba	20 - 600	180	240	634	890	
Be	2 - 3	-	-	-	-	
B	3 - 5	-	-	-	-	
Ce	5 - 40	26	16	74	47	
Co	5 - 13	9	3	9	4	
Cu	10 - 38	19	11	23	22	
F	40 - 420	212	151	387	253	
Ga	14 - 16	15	1	15	2	
La	<10 - 20	<20		42	31	
Pb	10 - 30	22	8	19	9	
Li	8 - 37	22	13	27	14	
Mn	56 - 260	169	98	311	164	
Ni	5 - 12	9	3	12	5	
Nb	<5 - 10	(b) 7	4	8	4	
Rb	140 - 280	208	55	133	50	
Sr	10 - 120	53	47	160	83	
Th	10 - 35	22	9	12	7	
Sn	<2 - 6	3	2	3	4	
U	<1 - 3	2	1	2	2	
V	<10 - 10	-	-	23	21	
Y	15 - 30	21	6	26	11	
Zn	13 - 33	27	8	45	22	
Zr	75 - 105	92	14	163	56	
CaO/TiO ₂		7.9		6.9		
K (%)		3.65		2.91		

(a) Approximate values only. (b) Fewer than stated number of samples. (c) Mean of seven samples. (d) Mean of four samples.

batholith lies in the latter zone, and there seems to be no fundamental reason for the absence of prehnite or pumpellyite from the southern part of the batholith.

Dynamic alteration is represented in many rocks by the thin crush zones. Large mylonite zones are present in the batholith, the largest trends northwesterly and separates adamellites PB and CA. The relationship of the small mylonitic zones to the larger has not been established; but they are assumed to have been generated by the same event. The later recrystallization may be a product of heat generated during the faulting, or belong to a later separate event: the former hypothesis is favoured.

CHEMICAL COMPOSITION

The composition of each sample analyzed is given in Appendix 3. Means, ranges, and standard deviations for the various rock types are given in Table 2, together with an average value for the rocks analyzed. Some Harker variation diagrams are given in Figure 2. The K₂O/Na₂O ratio of the average value suggests that the overall composition of the batholith may be granodioritic near the adamellite border (Table 1).

ELEMENTS OF ECONOMIC INTEREST

Values for elements of economic interest have been plotted on cumulative frequency probability curves as well as on contoured maps. Mean values,

TABLE 3. MEAN, STANDARD DEVIATION, AND THRESHOLD FOR ELEMENTS OF ECONOMIC INTEREST.

Element	Mean	Standard deviation	Threshold value	Samples above threshold
	(ppm)	(ppm)	(ppm)	(no.)
Cu	22	21	100	4
Pb	19	30	40	3
Zn	41	22	90	4
W	<<10		9	2
U	1.6	1.6	5	7
Mo	1	1	2	2
Sn	< 4		10	6
Li	25	14	60	4

NOTE: Samples which can be considered as anomalous are listed in Table 5.

standard deviations and threshold values estimated from these curves together with the number of samples which have values exceeding the threshold values, are given in Table 3.

Contoured plots for six of these elements: Cu, Pb, Sn, Th, U, and Zn, are given in Figs. 3A-F. Data for these plots have been obtained from altered granitoids, aplites, and mylonites, as well as from fresh granitoids.

RESULTS: ROCKS OF THE BATHOLITH
THE NORTHERN MIGMATITE COMPLEX

The present study suggests that there are at least five distinct larger granitoids (MA-MC, MB, MD, D, T), together with several smaller ones (Fig. 1B) in the northern complex. Of these, granodiorites MC and MA are separated solely on the basis of their petrography. Samples from granodiorite MC have undergone a greater degree of cataclasis than those of MA; but they are very similar chemically (Tables 1, 2). The overall compositions of granodiorite MB and granodiorite-adamellite MD are also similar; however, MB is more homogeneous in composition than MD, and feldspar grains are more nearly idiomorphic in MB than in MD. Granodiorite west of Warrery Gap (Fig. 1A) is texturally and compositionally similar to MD and is only classed separately (as MW) because it is a discrete outcrop.

High values of Ba, Ce, La, and Zr, found in certain samples near the margins of the batholith (samples 59201- 3, 59330-3) may reflect local contamination of the granitoids by incorporation of some pre-existing material rather than potential mineralization.

Two tonalites (T and MI) appear to intrude the migmatite complex, though both are deformed and the latter contains almost enough K₂O to qualify as granodiorite. Granodiorite gneiss D is compositionally close to both diorite and tonalite and

differs from tonalites T and MI by virtue of lower SiO₂ and higher K₂O. The only ferro-magnesian mineral in tonalite T is biotite; in tonalite MI, biotite is accompanied by small amounts of amphibole; and in granodiorite D, both amphibole and biotite are common. Granodiorite D is a true orthogneiss, and contains no metamorphic mineral segregations; tonalites T and MI are foliated and contain metamorphic mineral segregations.

PORPHYRITIC GRANITOIDS

Hickman and Lipple (1978) ascribed all porphyritic granitoids to the Carvana Pool Adamellite. This study allows three types (P, PA, PB)—of which PA represents the original Carvana Pool Adamellite—to be distinguished.

There is a clear two-fold division into granodiorite P and adamellite PA and PB. Adamellite PB is distinguished from PA by its different composition (Table 2) and by a greater degree of cataclasis.

A major shear zone separates PB from the newly recognized southwestern complex; there may have been metasomatism or alteration associated with this shear to produce some redistribution of the components of PB. In general, the compositions of PA and PB change from adamellite near granodiorite close to the shear zone, to a more potassic adamellite further to the northeast.

THE MONTANA ADAMELLITE

The Montana Adamellite (C) is now known to be restricted to the eastern part of the outcrop shown by Hickman and Lipple (1978). The rock has well-defined margins, clearly visible on aerial photographs, and is intrusive into the adjacent porphyritic granitoids. It is also intrusive into the adjacent southwestern complex.

THE SOUTHWESTERN COMPLEX

Rocks southwest of Budjan Creek (Figs 1A, 1B), described by Hickman and Lipple (1978) as part of the Montana Adamellite, are now recognized as a separate complex, probably older than the Montana Adamellite (C), but possibly younger than the northern migmatite complex since they lack those rocks' distinctive foliations.

The most mafic rock (CC), a hornblende-biotite granodiorite near tonalite, occupies the core of the complex, and is fringed on its southern side by a cusped outcrop of biotite-(hornblende) granodiorite (CB). The outermost rocks are the adamellites CA and CD.

These two adamellites have different spectral images on Landsat images. They are very different from the spectral image of the now more restricted Montana Adamellite. The major—component

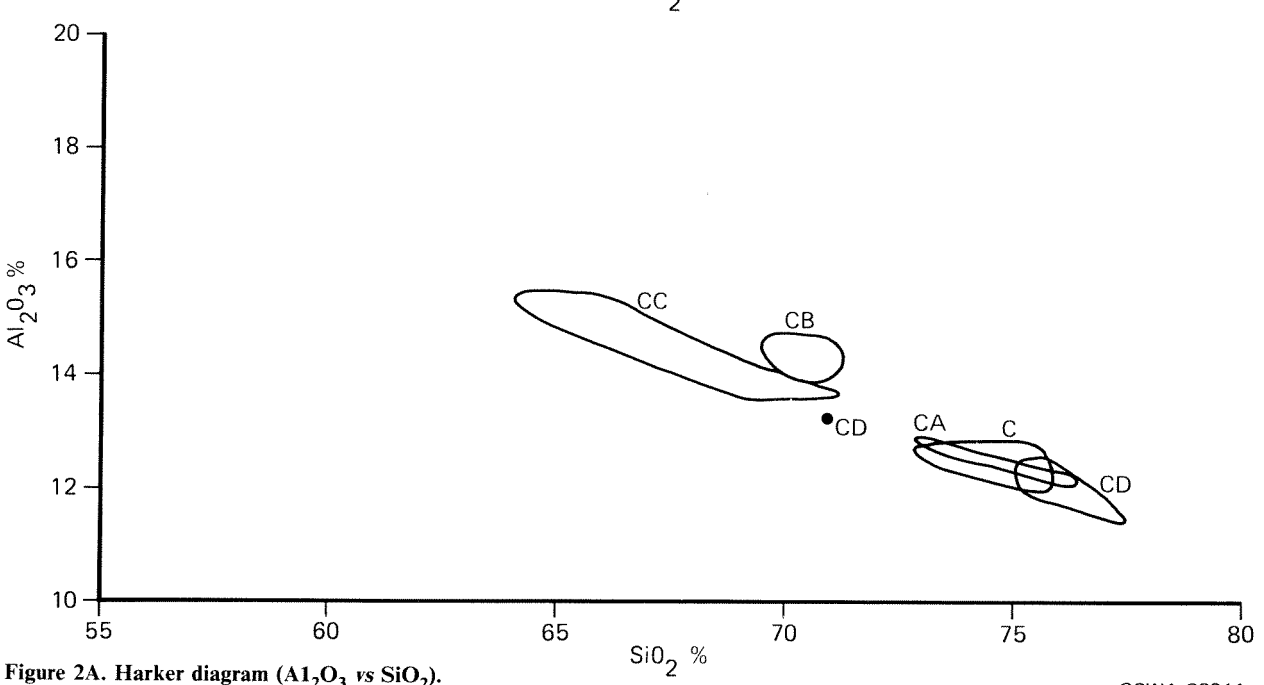
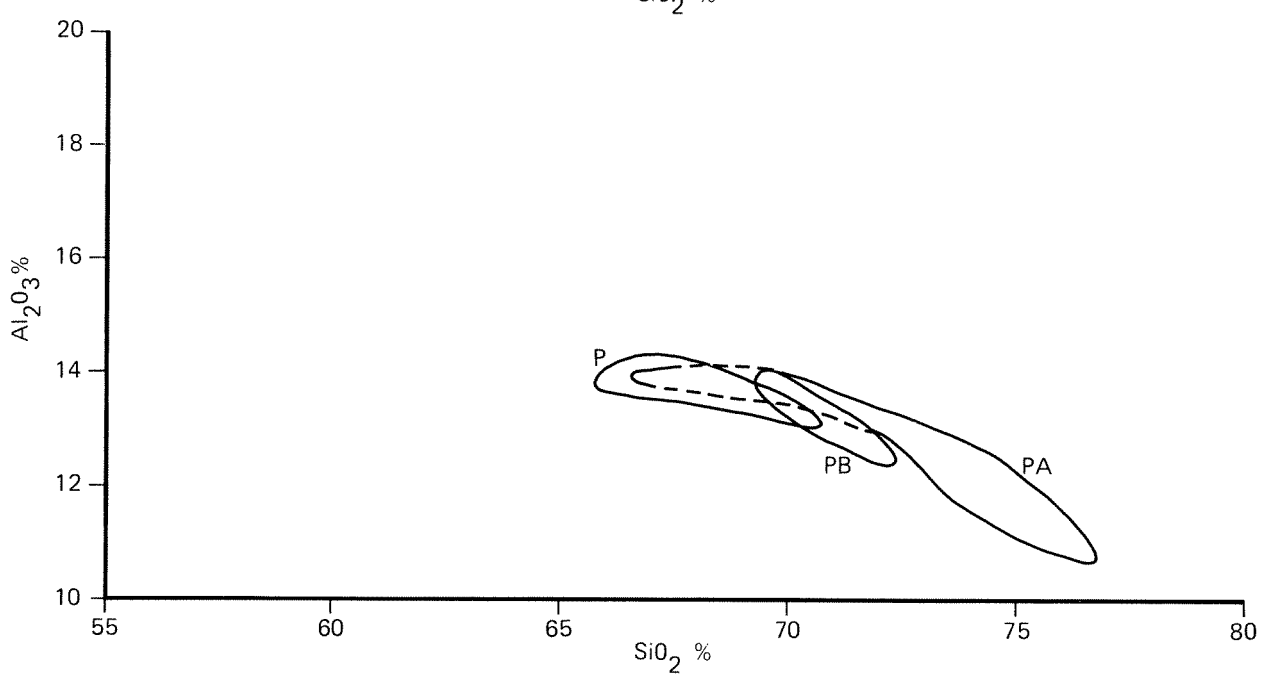
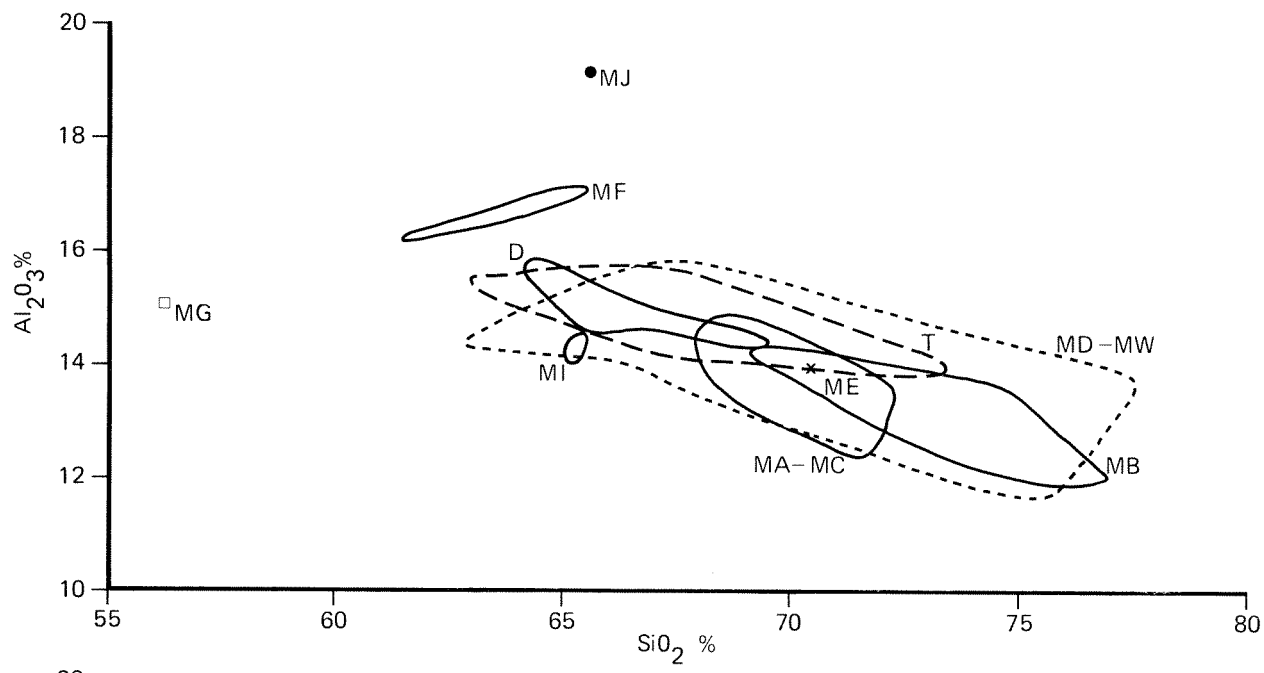
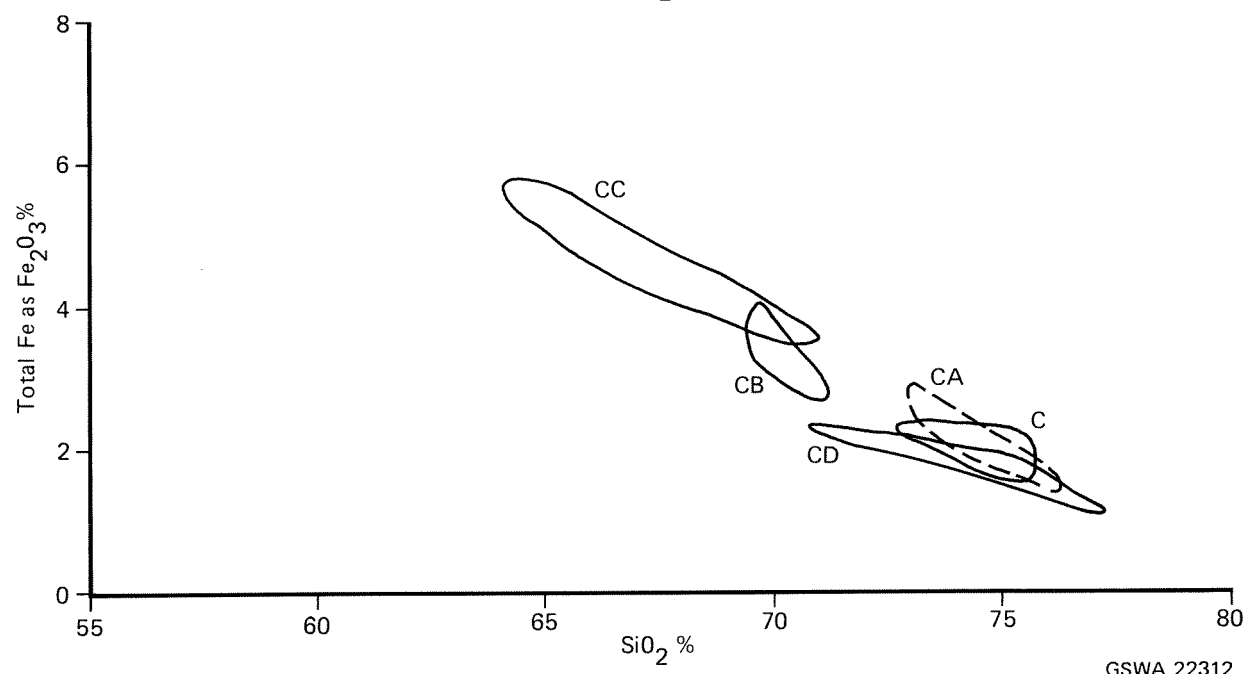
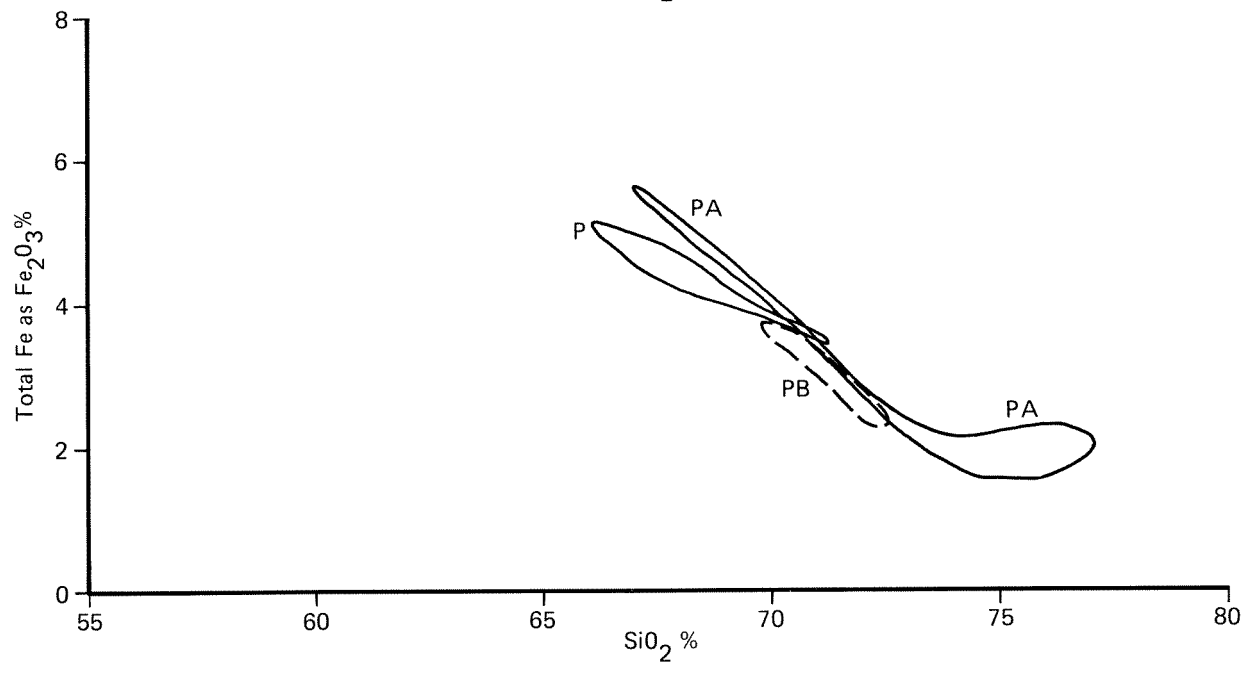
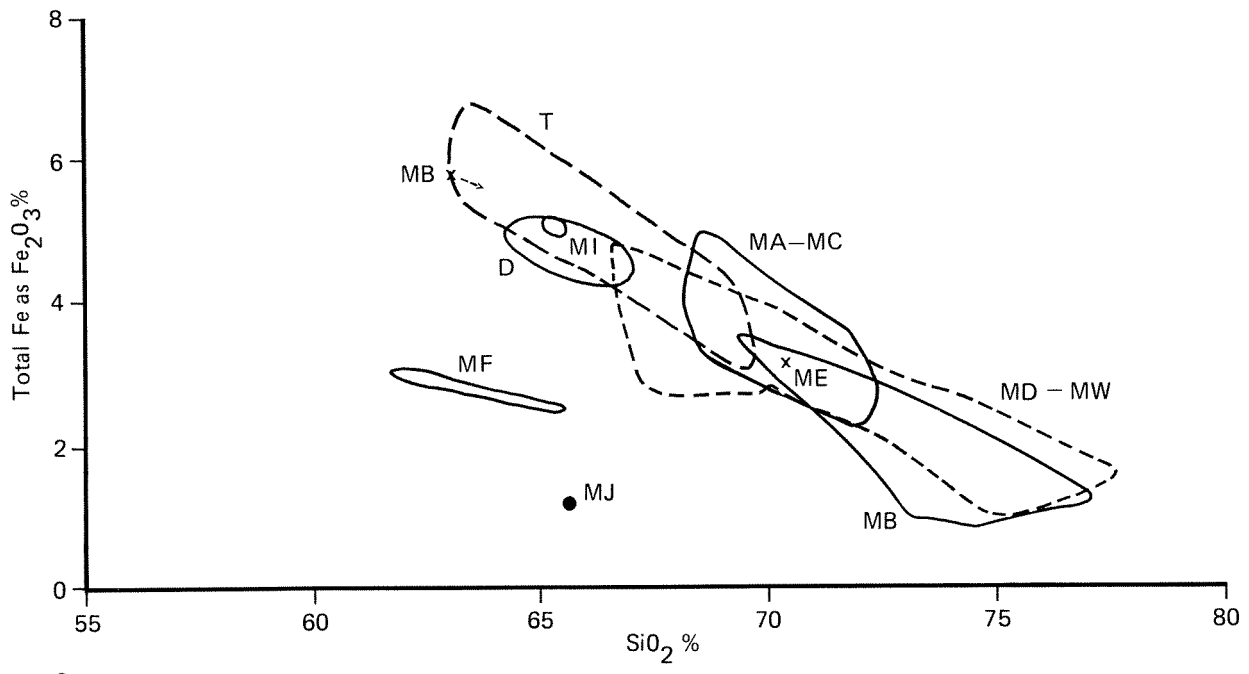


Figure 2A. Harker diagram (Al_2O_3 vs SiO_2).

□ MG



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Figure 2B. Harker diagram (total Fe as Fe_2O_3 vs SiO_2).

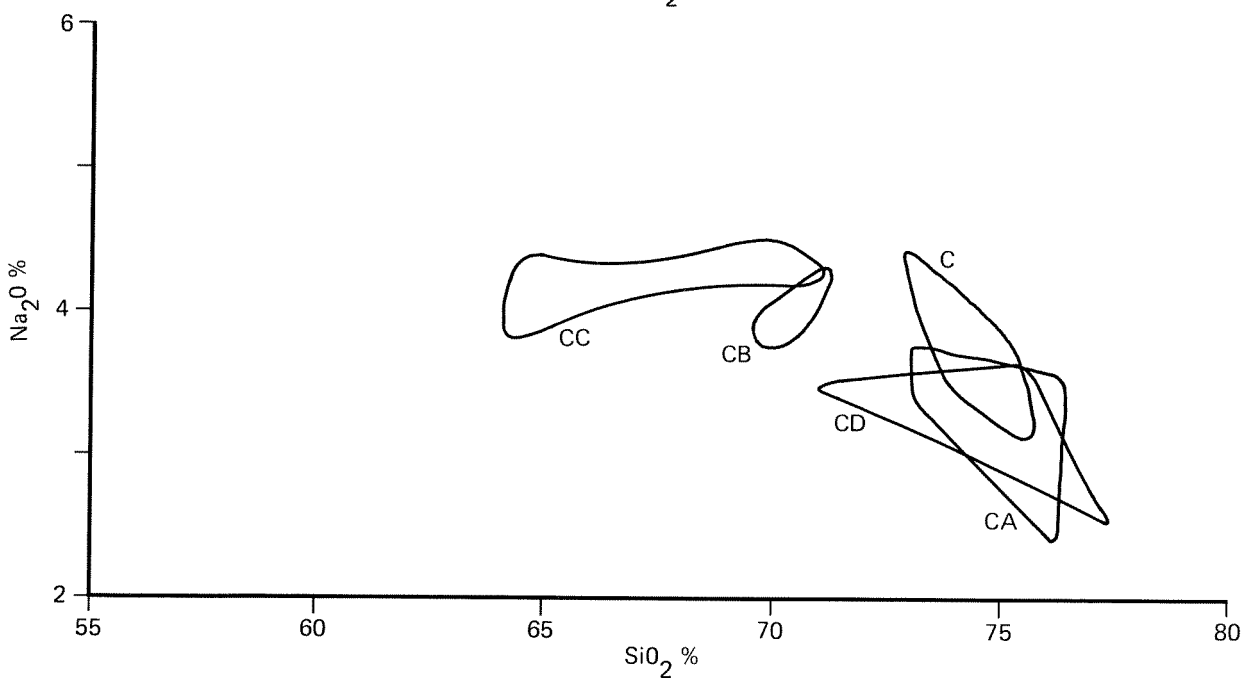
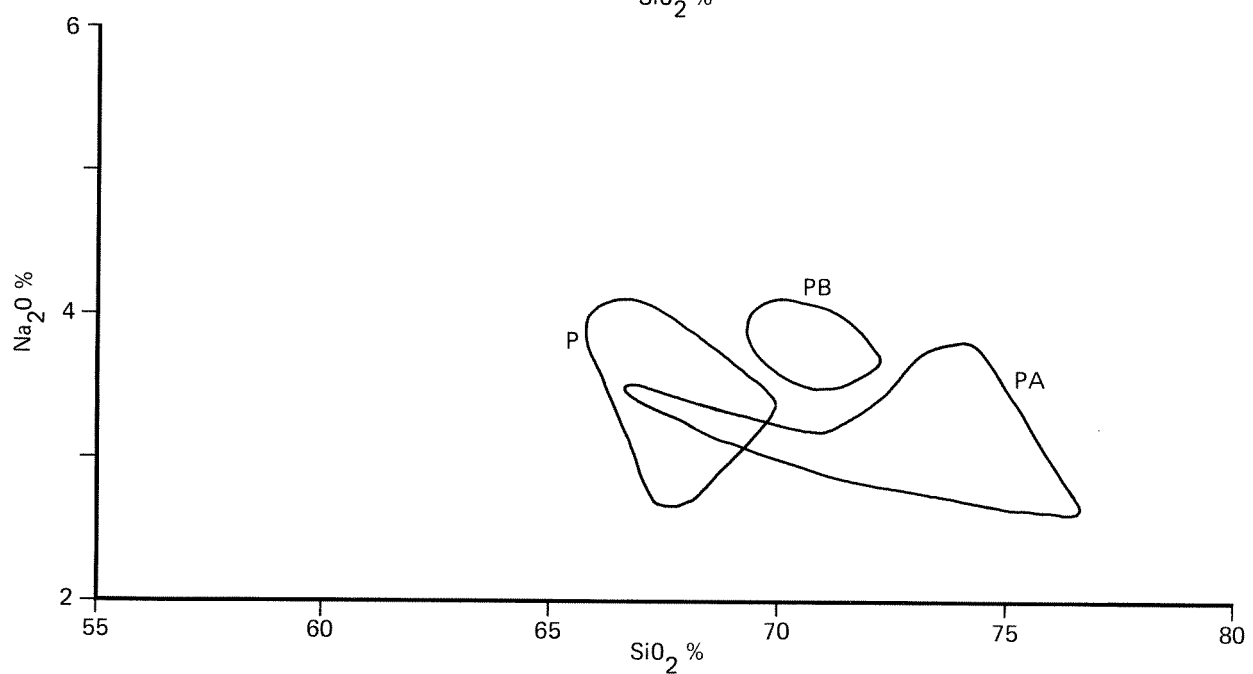
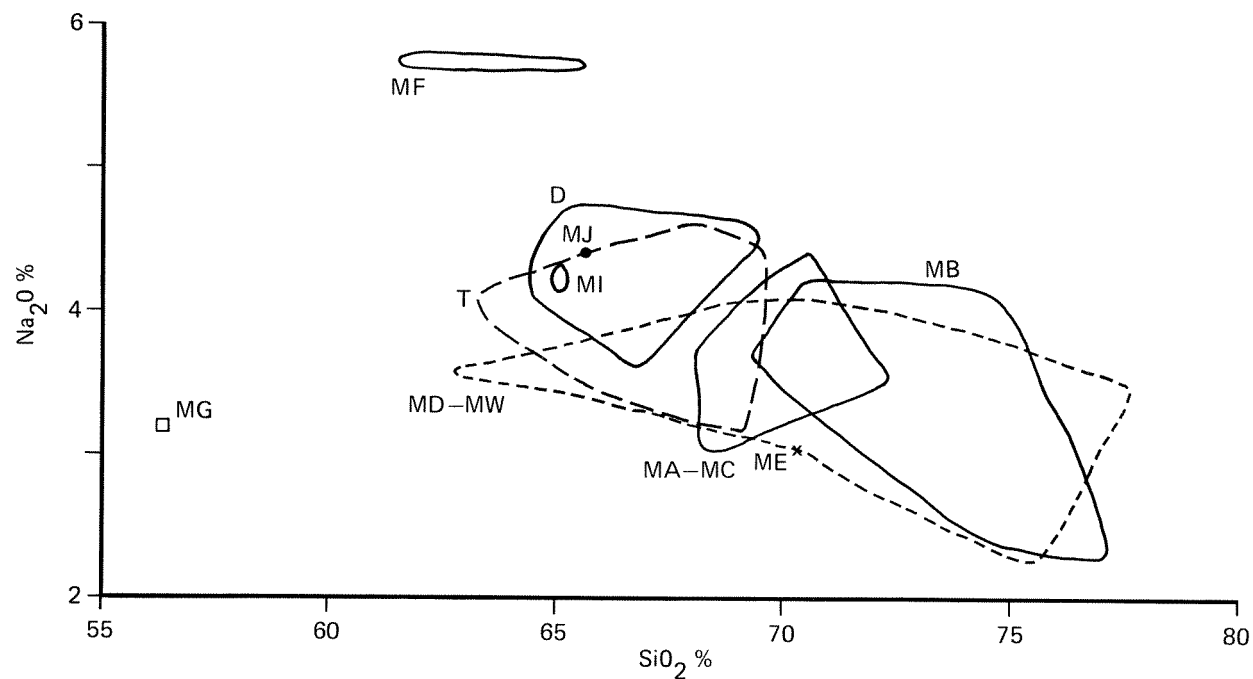


Figure 2C. Harker diagram (Na₂O vs SiO₂).

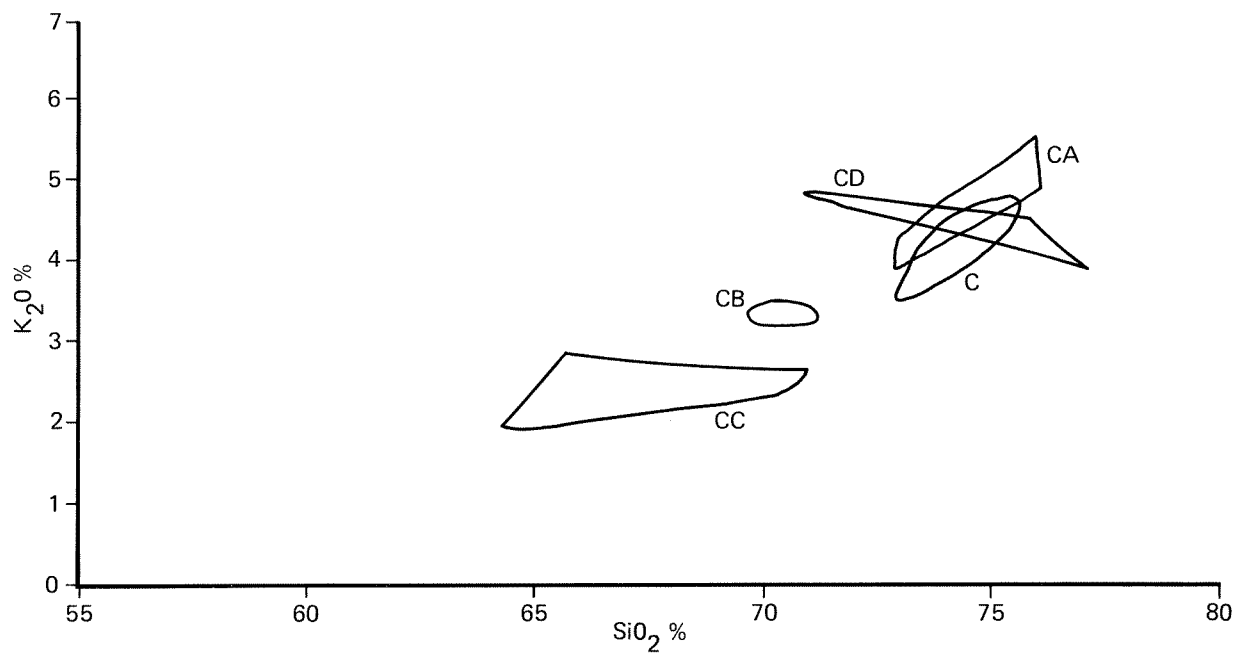
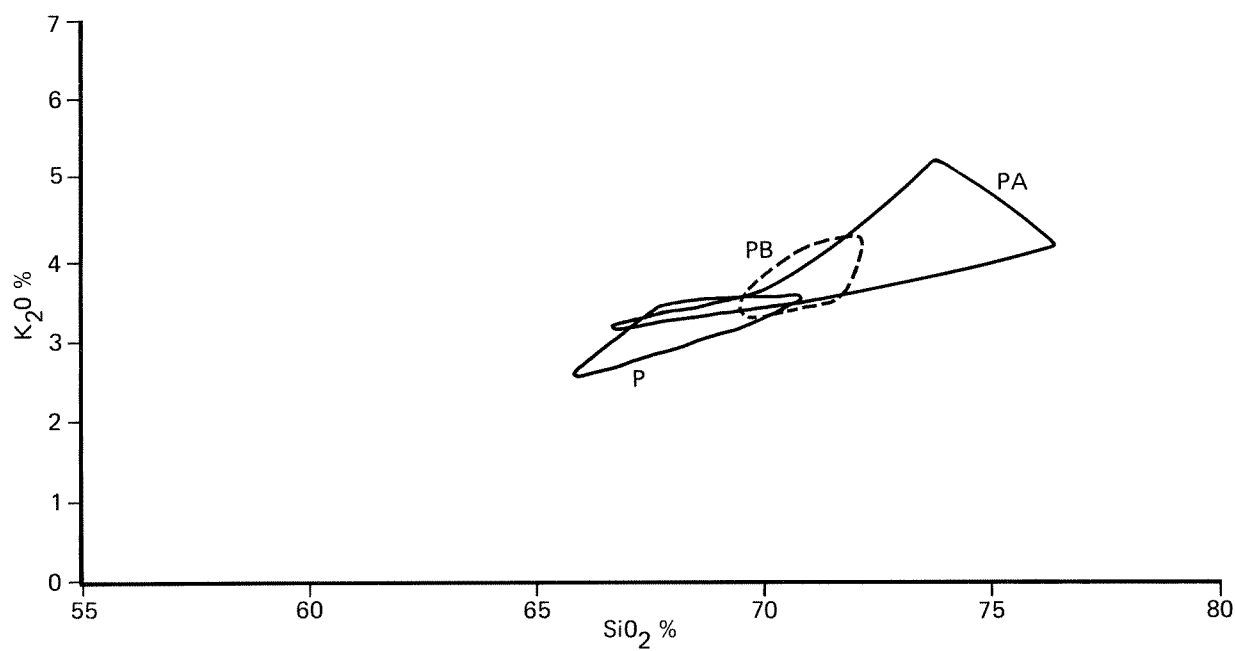
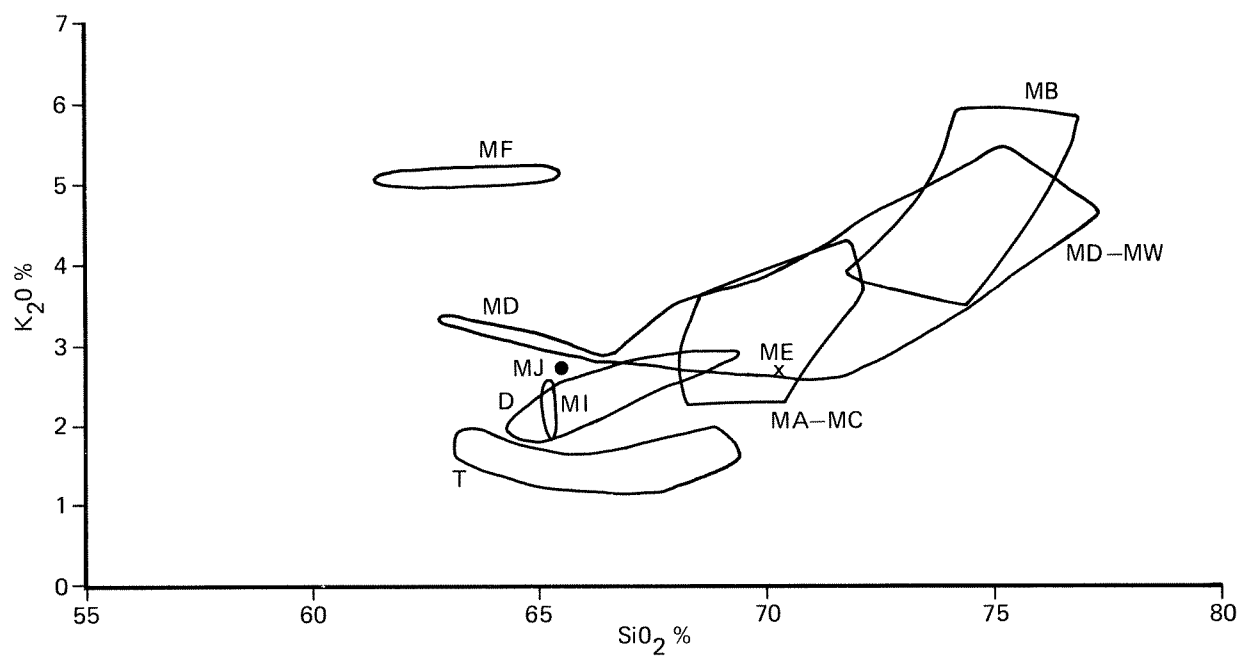


Figure 2D. Harker diagram (K_2O vs SiO_2).

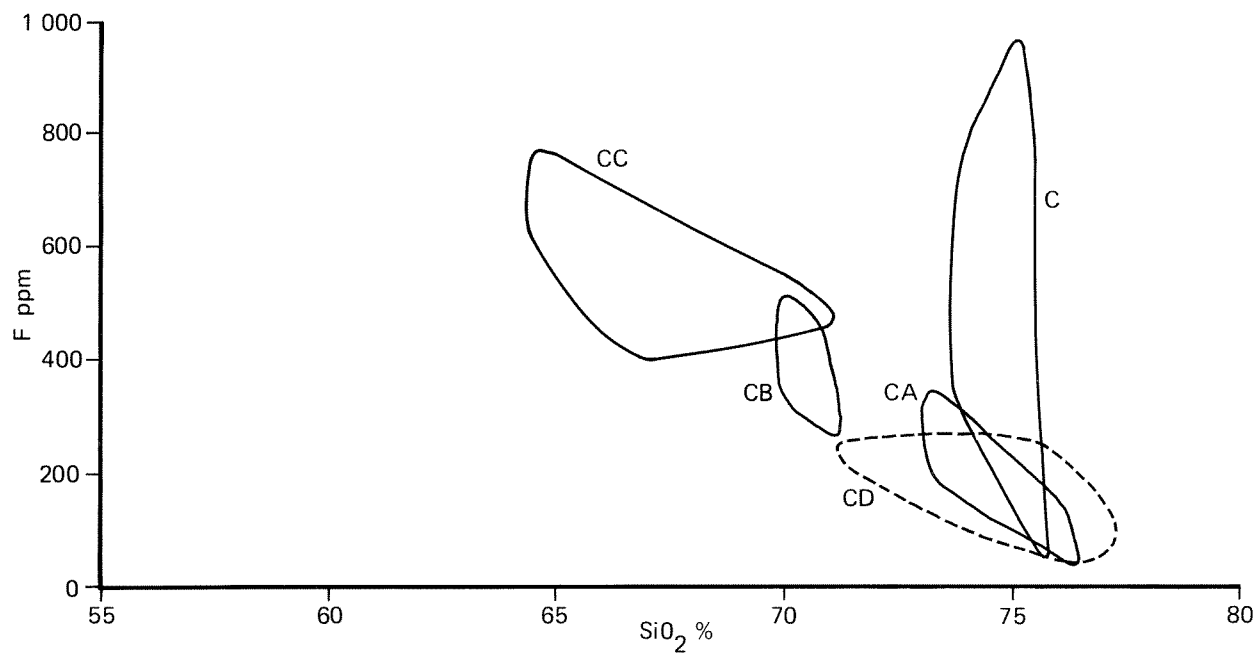
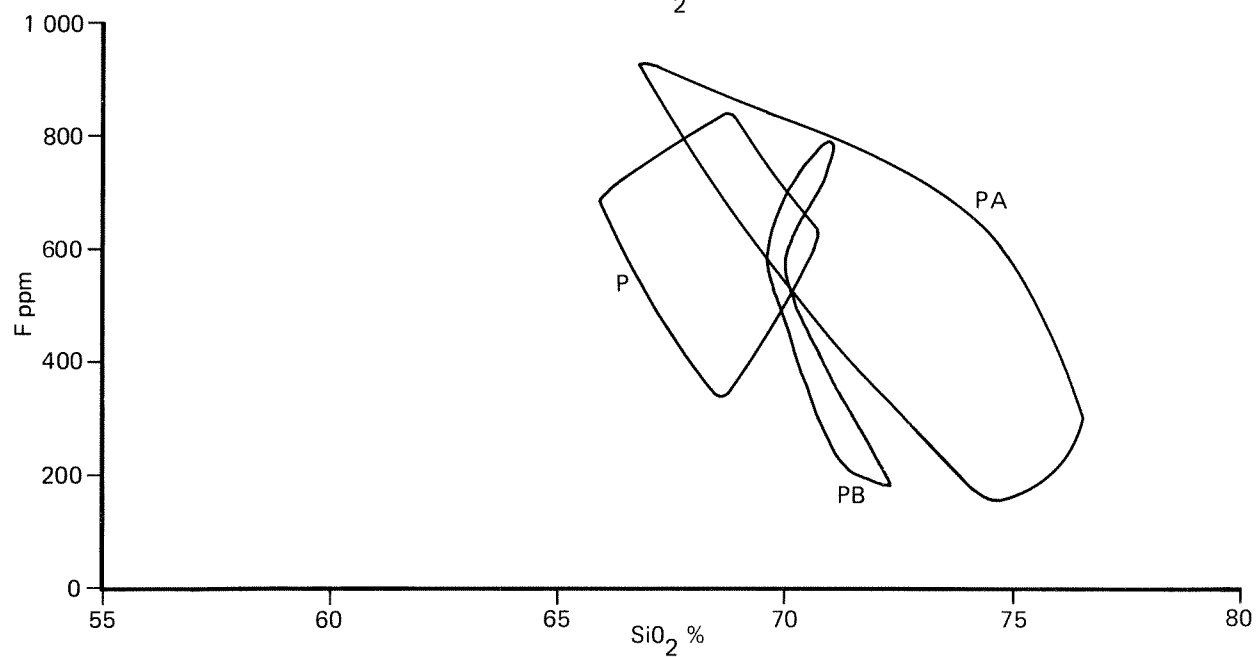
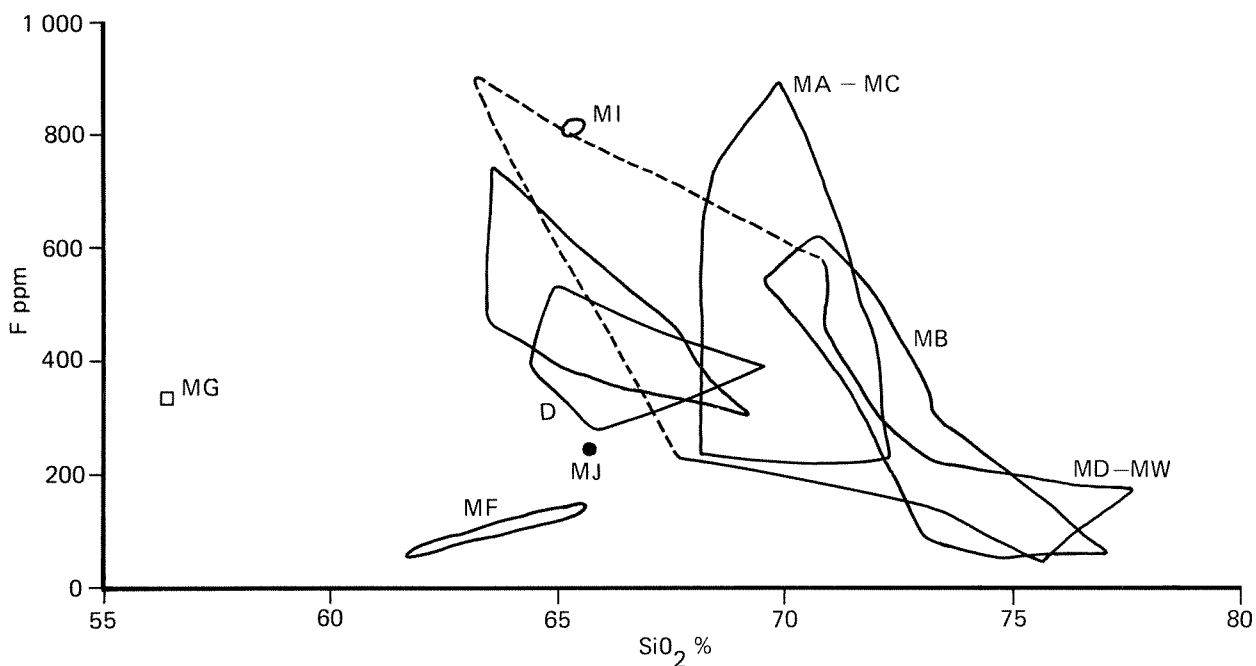


Figure 2E. Harker diagram (F vs SiO₂).

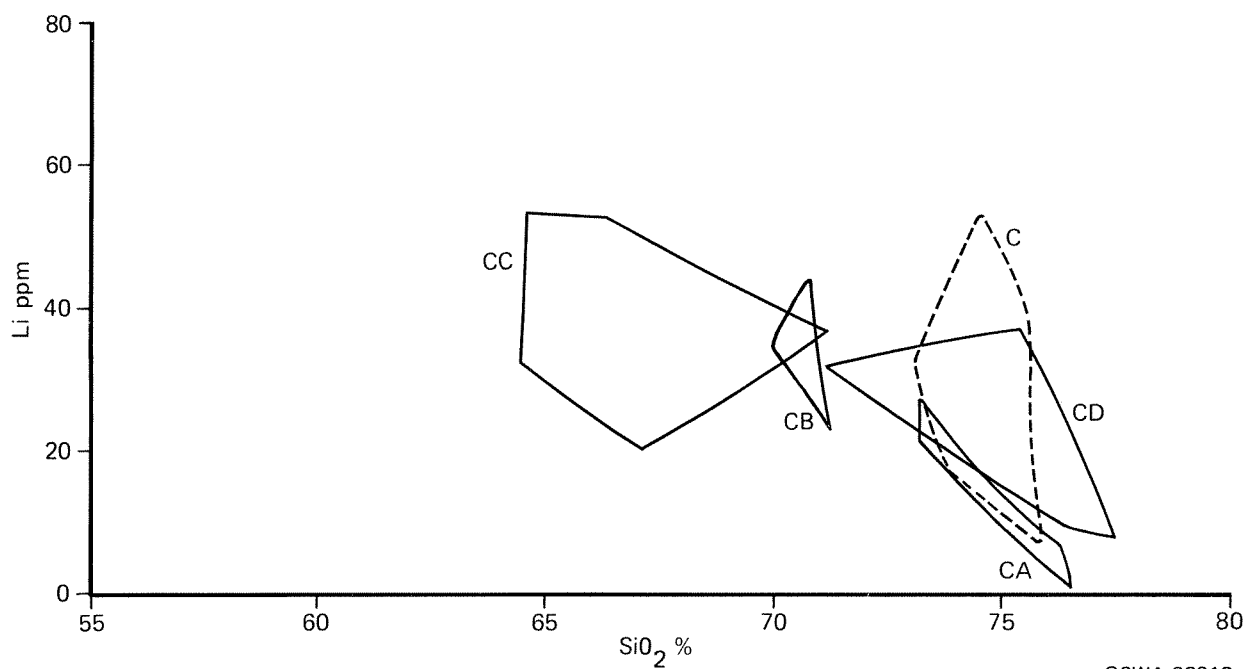
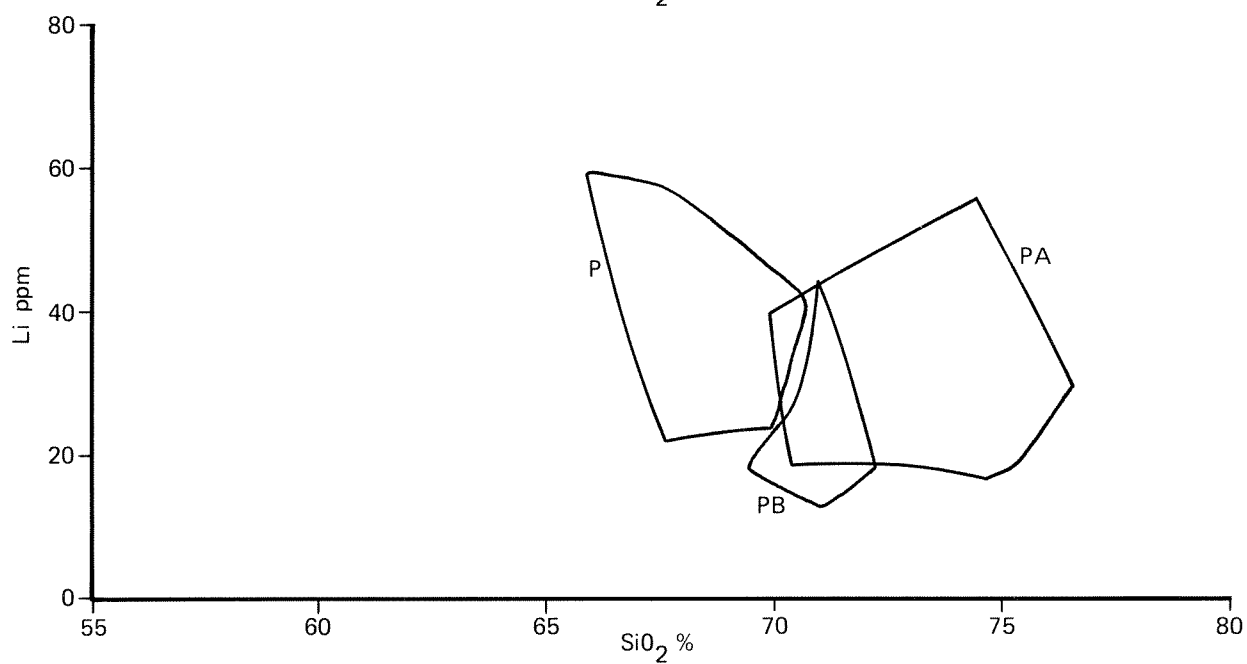
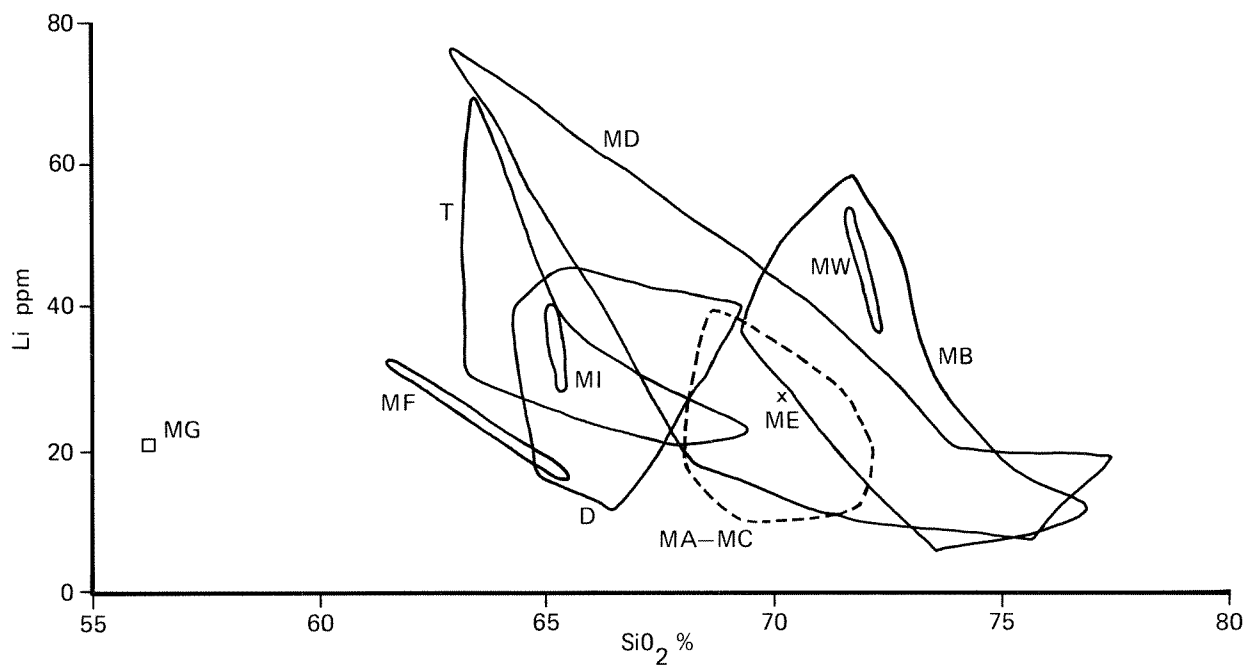


Figure 2F. Harker diagram (Li vs SiO₂).

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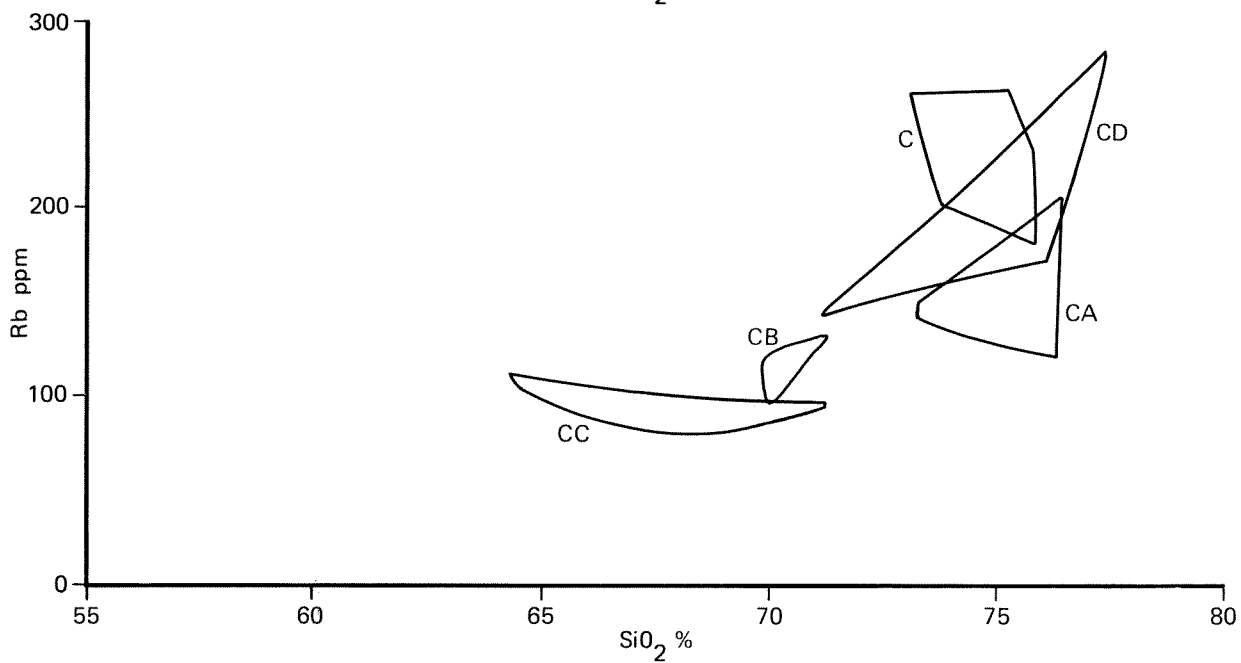
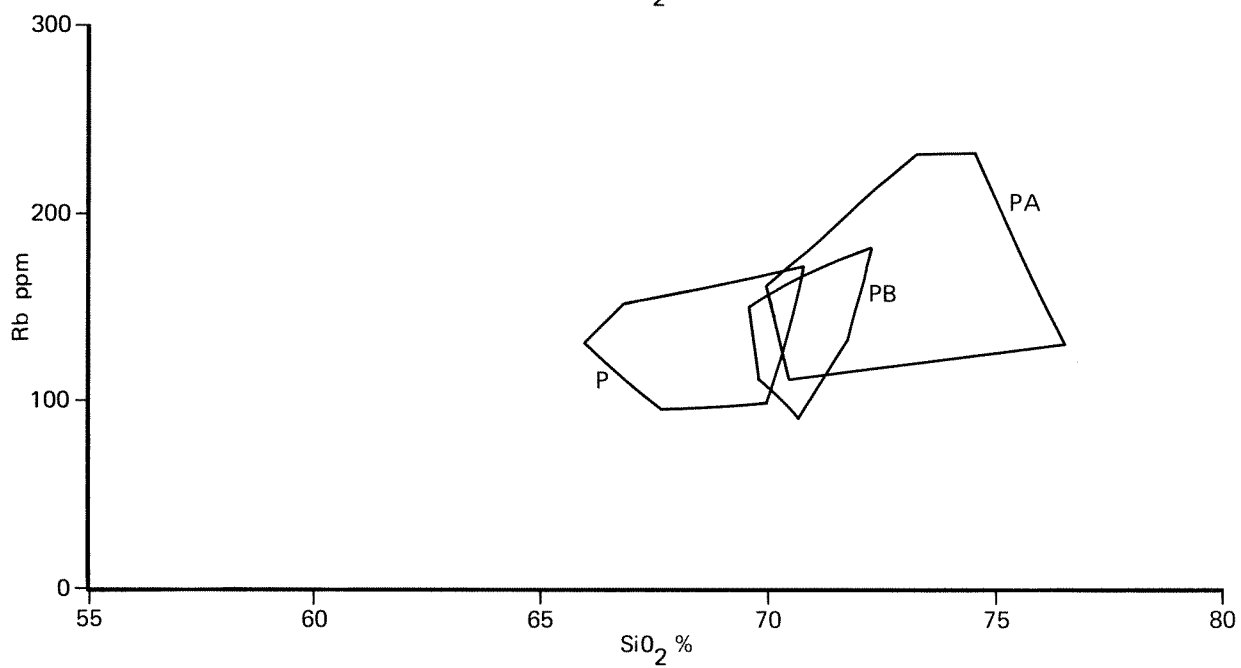
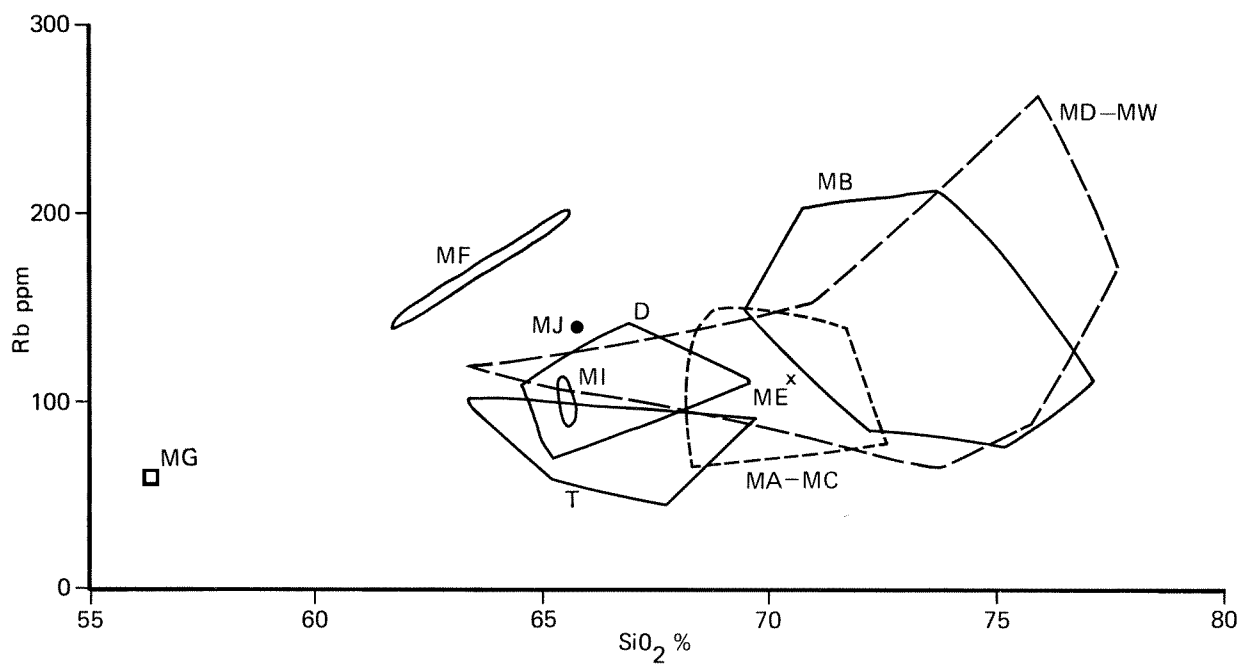


Figure 2G. Harker diagram (Rb vs SiO₂).

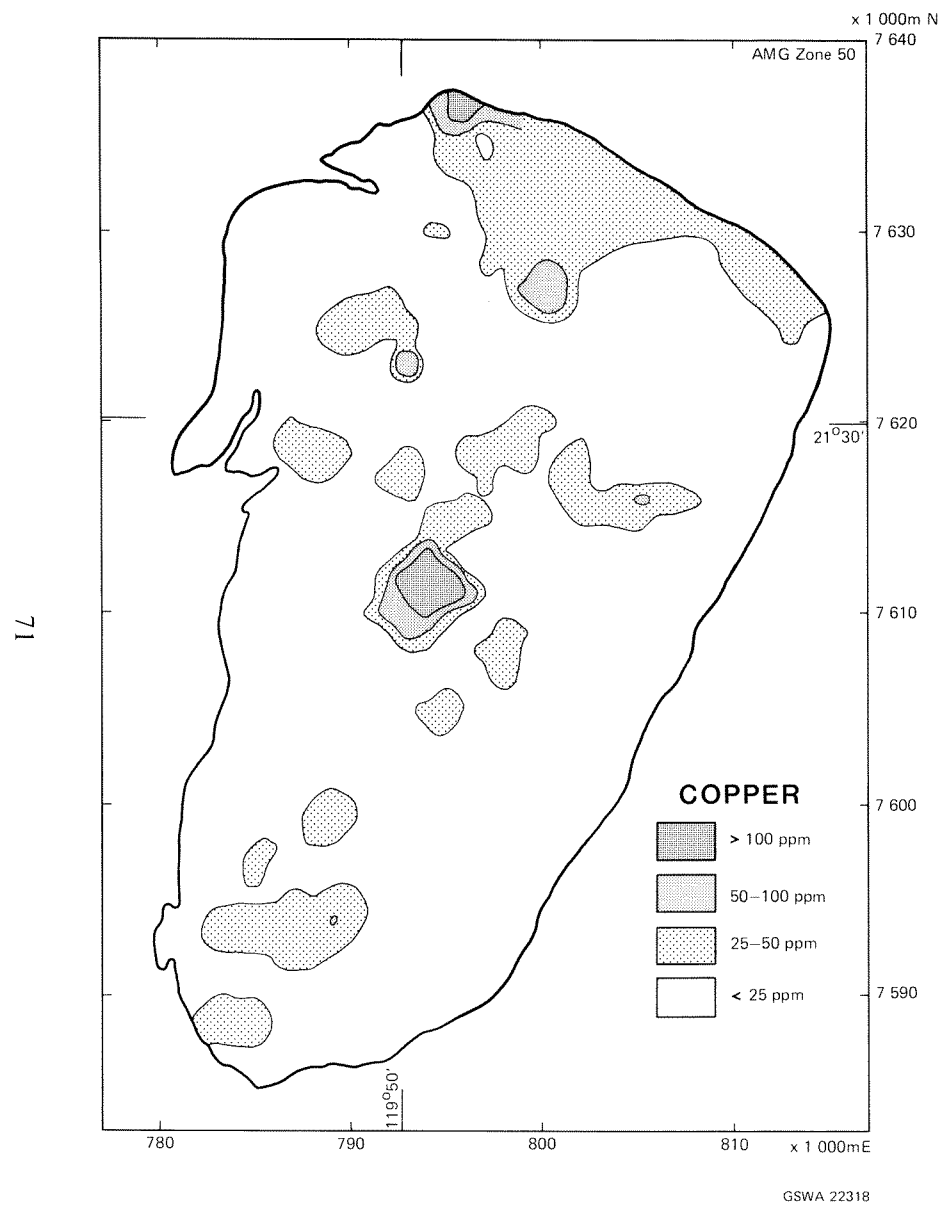


Figure 3A. Copper isopleths.

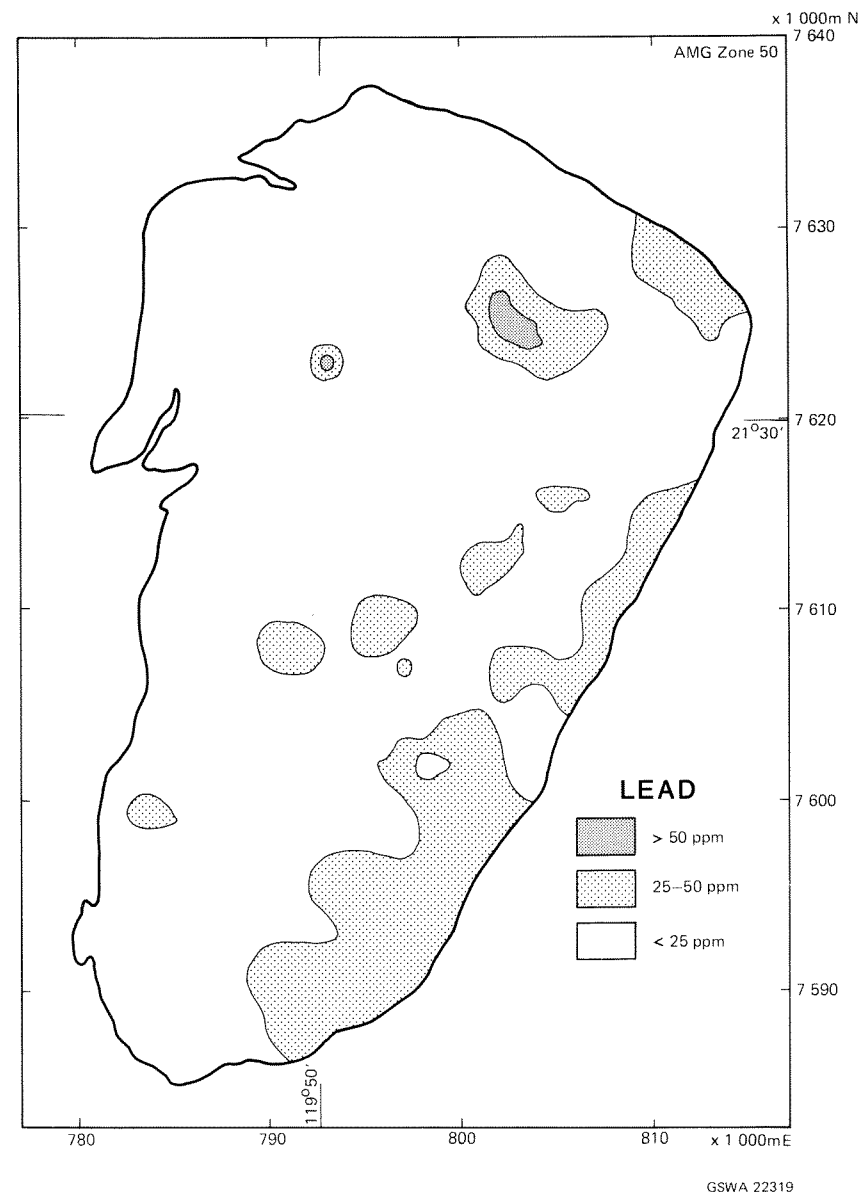


Figure 3B. Lead isopleths.

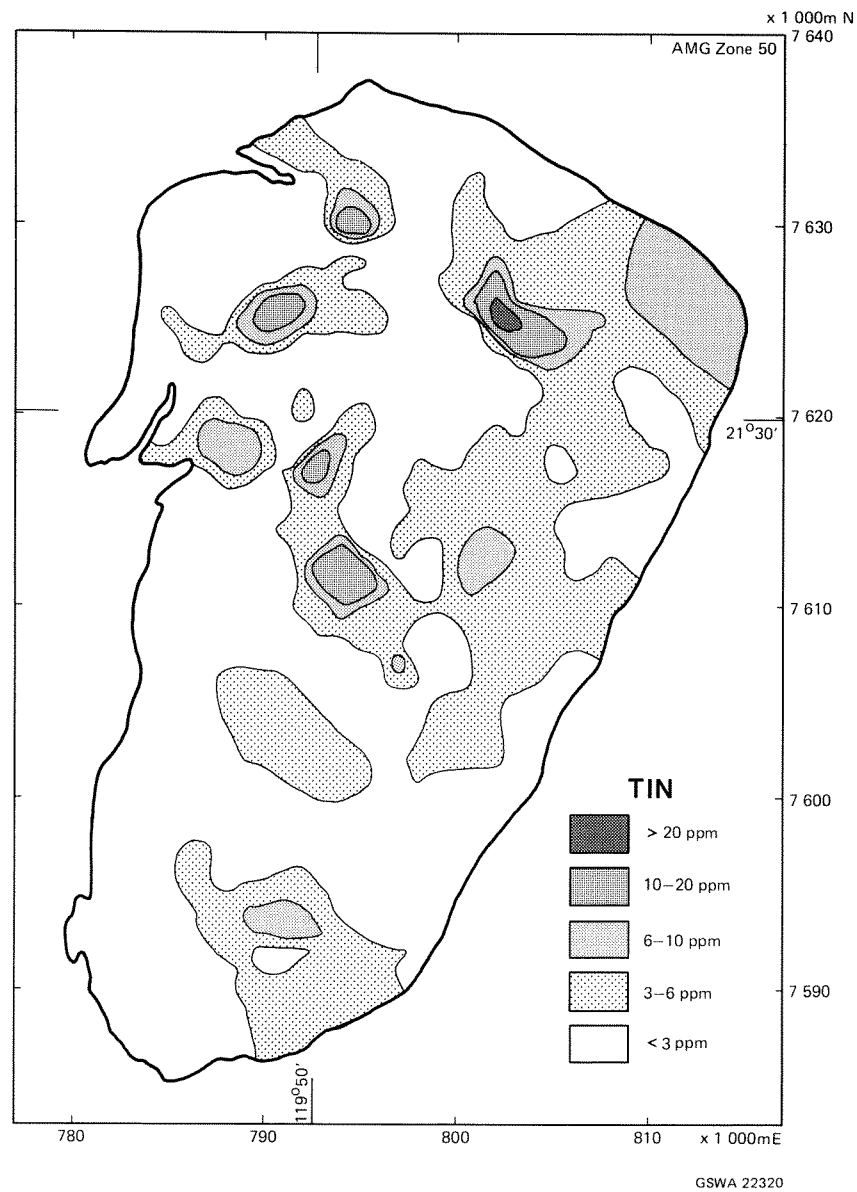


Figure 3C. Tin isopleths.

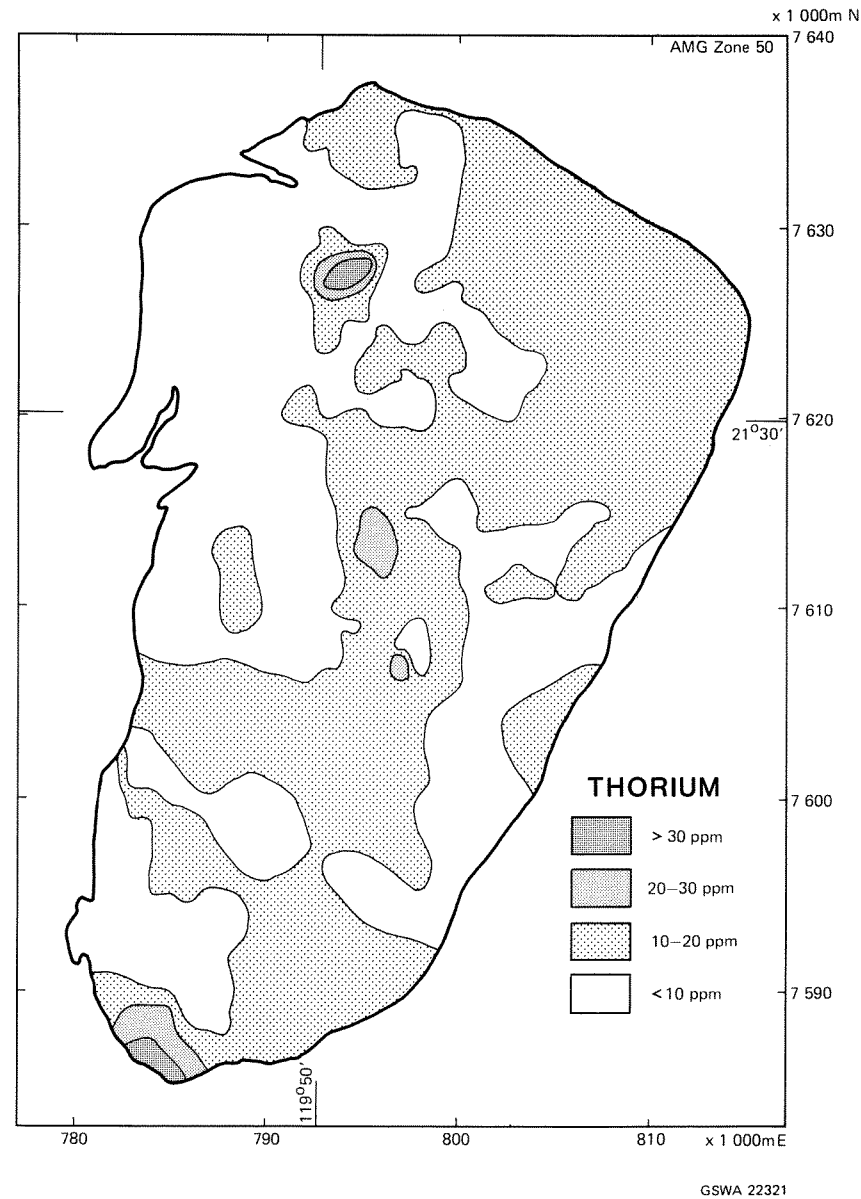


Figure 3D. Thorium isopleths.

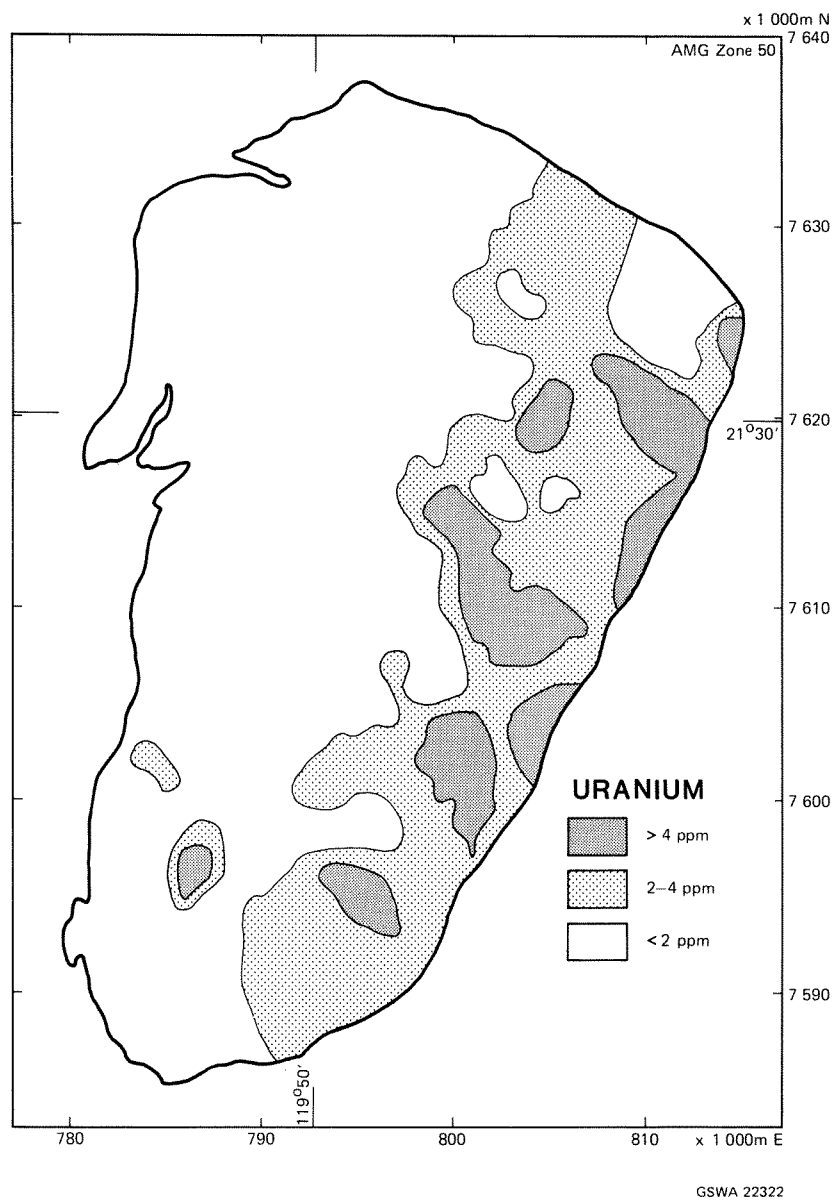


Figure 3E. Uranium isopleths.

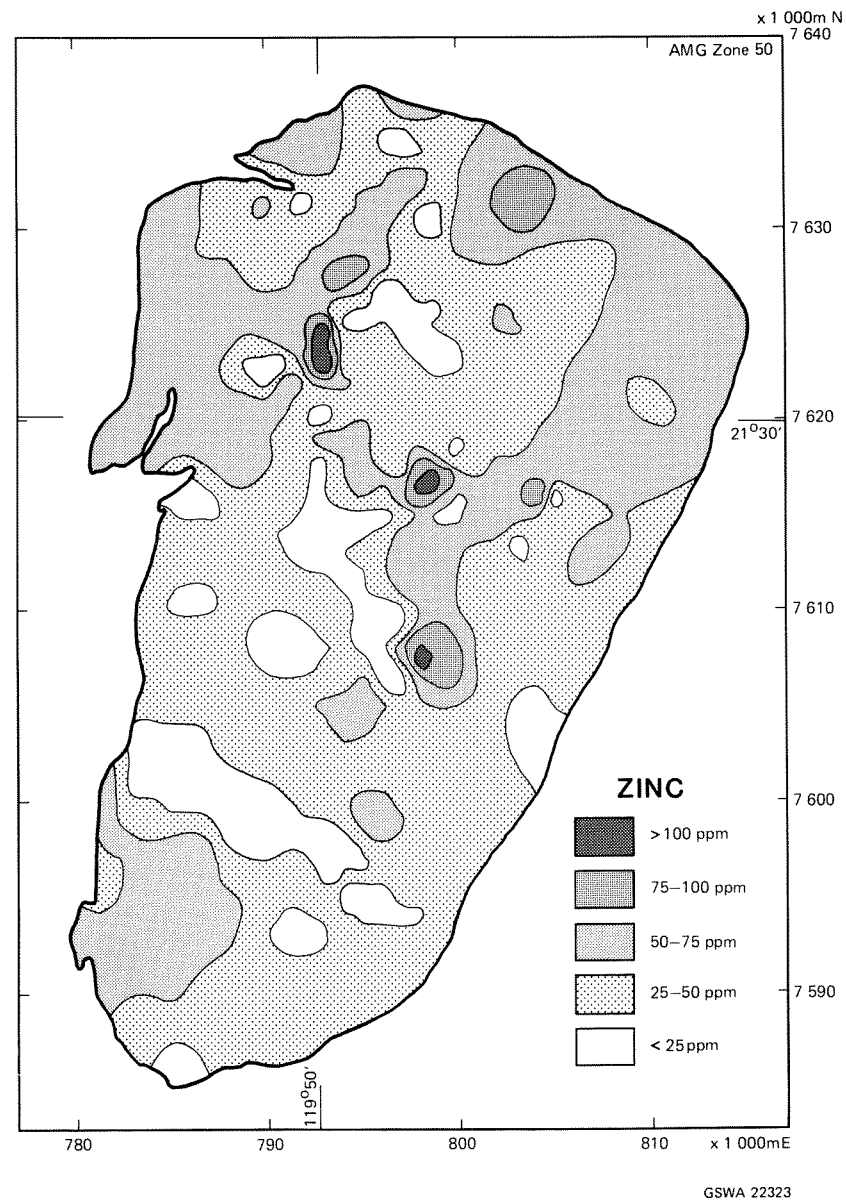


Figure 3F. Zinc isopleths.

composition of the two adamellites is similar, but they appear to differ in Ba, Ce, La, Rb, Zr, and possibly Sr, although the scatter, represented by the standard deviation, is high (Table 2). Adamellite CA differs from adamellite CD in that it is partly granophyric; it is not as coarse as CD and contains more microcline (Appendix 2). The Montana Adamellite also has similar major-component composition. Its trace-element composition is very close to that of adamellite CD except for F and Y (Table 2, Figs 2F-H). However, the Montana Adamellite is different texturally and is intrusive into the southwest complex.

MINOR GRANITOID INTRUSIONS

Possible Proterozoic plug

The small outcrop of granodiorite (MJ) located within granitoid MD, is unusual compositionally and texturally. It is very highly aluminous (19.2% Al_2O_3), has a cumulate texture, and, as such, is different from any other sample collected (Fig. 2A).

It is thought to be a plug, and may be related to Proterozoic felsic volcanic and subvolcanic rocks found elsewhere in the Pilbara Block region. The composition is unlike either felsic dykes described from the Mount Edgar Batholith (Lewis and Davy, 1981) or felsic volcanic rocks of Archaean age (Glikson and Hickman, 1981).

Syenite

A syenitic rock (MF), collected from two outcrops a kilometre apart, occurs within granitoid MD. The syenite contains high (>5%), approximately equal, amounts of Na_2O and K_2O , and is more aluminous (16.7% Al_2O_3) than its host. It contains almost 10% quartz; the feldspars are microcline (some concentrically zoned) and albite-oligoclase. The contact with MD is concealed, but the syenite MF is presumed to be intrusive. Harker diagrams (Figs 2B-E,) indicate that the composition is quite distinct from the majority of the granitoids of the batholith.

Other minor granitoid intrusions

Other small patches of distinctive granitoid outcrop within rocks of granodiorite-adamellite MD (Fig 1B). The most significant of these is MG, which is a diorite and contains very little quartz; it is characterized by low SiO_2 (56.3%) and by the presence of pyroxene. It appears to be intrusive into the adjacent MD but no contact phenomena were noticed in the nearest outcrop of adamellite PA (approximately 1 km to the southeast). Granitoids to the west (MH2) are variably but strongly epidotized.

A small exposure of granodiorite ME displays flow-aligned feldspars. The texture is unlike any other sample and this outcrop may represent a sub-volcanic plug or stock.

Epidotized granitoids

Epidotized granitoids MH and MH2 outcrop west of the diorite MG (Fig. 1B). Both are characterized by high CaO and K_2O , and by very low Na_2O and MgO (Table 2). Distinction between them is made on the basis of differing amounts of F, Sr, V and possibly Ba (Table 2). Whether the distinction is real or not (there is wide compositional scatter), these two areas have been subject to extreme metasomatism. The epidotized granitoid, MH2, may conceivably be the product of some kind of contact phenomenon associated with the intrusion of diorite MG, but the extent of the epidotization suggests that some other, outside, source is involved.

Mylonites, dyke rocks, and aplites

No felsic dykes of the types found on the Mount Edgar batholith (Lewis and Davy, 1981) have been found in the Corunna Downs batholith. Rocks which resembled silicified felsic dykes in outcrop proved to be mylonites. There is abundant evidence of elemental mobility in these rocks, and the few samples analyzed show marked compositional differences from their enclosing granitoids.

The only dykes recognized were north-northwest-trending dolerites; a typical analysis is sample 59388D (Appendix 3). Contact effects were detected within the granitoids for some 50-100 m from the dykes; and affected rocks have been excluded from data summaries.

No pegmatites were observed in the batholith; but most granitoids contain patches or dyke-like bodies of microgranite or aplite. The composition of microgranite appears to be similar to that of its enclosing coarser granitoid, and analyses are normally included within the granitoid class in which they are found. Aplites have a slightly more distinctive composition, mainly adamellite; they have not been included in the discussion except as far as their composition includes anomalous trace elements of possible economic interest. The largest number of aplites occurs within granodiorite-adamellite MD.

DISCUSSION

THE COMPOSITION OF THE BATHOLITH

The outstanding feature of this batholith is its low Na_2O content. Most Archaean granitoids and felsic gneisses, in particular those of Western Australia, are considered to have high Na_2O ; and many contain in excess of 4% Na_2O . In this batholith, whilst

certain types (MF, MI, MJ, D, T, CB, and CC) average at least this value, and individual samples of other types contain over 4% Na₂O, most of the samples analyzed have values in the range 3.2-4.0%. The mean value for all the granitoid samples analyzed is 3.7% which indicates that the Corunna Downs rocks, at least those exposed at the surface, must be considered low-soda rocks in comparison with other Archaean granitic complexes.

Comparison of the data with summary data for igneous rocks provided by Nockolds (1954) and Le Maitre (1976) confirms that the analyses are close to the expected value for biotite-rich granitoids. In many cases, the average values of the individual classes fall between the averages for the muscovite-biotite granitoids and biotite granitoids of Nockolds (1954). Although the Corunna Downs rocks are characteristically low in Al₂O₃ and P₂O₅, and, for some types, MgO, K₂O, and TiO₂ as well, silica tends to be higher than Nockolds' averages for the respective types. A similar pattern is shown in comparison with Le Maitre's (1976) data: the Corunna Downs adamellites fall in general between

"granites" and "adamellites" but contain more SiO₂ and less Al₂O₃, Fe₂O₃, MgO, CaO, TiO₂, and P₂O₅, than these rocks. Granodiorites P and CC are quite similar to Le Maitre's average granodiorite; other Corunna Downs granodiorites are intermediate in composition (except for high SiO₂) between Le Maitre's granodiorites and adamellites.

Much less comparative information is available for trace elements. In general, values for Be, B, Ce, F, Li, Mn, Nb, Sr, U, V, and Y, are lower than for mean granitoid values estimated by Turekian and Wedepohl (1961), Vinogradov (1962), and Krauskopf (1979). No trace element in the Corunna Downs granitoids has values significantly higher than the mean values suggested by these authors.

The granitoids of this study do not readily fit either of the currently favoured (S,I,A, or ilmenite/magnetite) classification schemes. All groups have been assessed for a possible S, "sedimentary", I, "igneous", or A, "apical" origin, using the criteria of Chappell and White (1974), White and Chappell (1977), and Collins and others (1982). Neither the

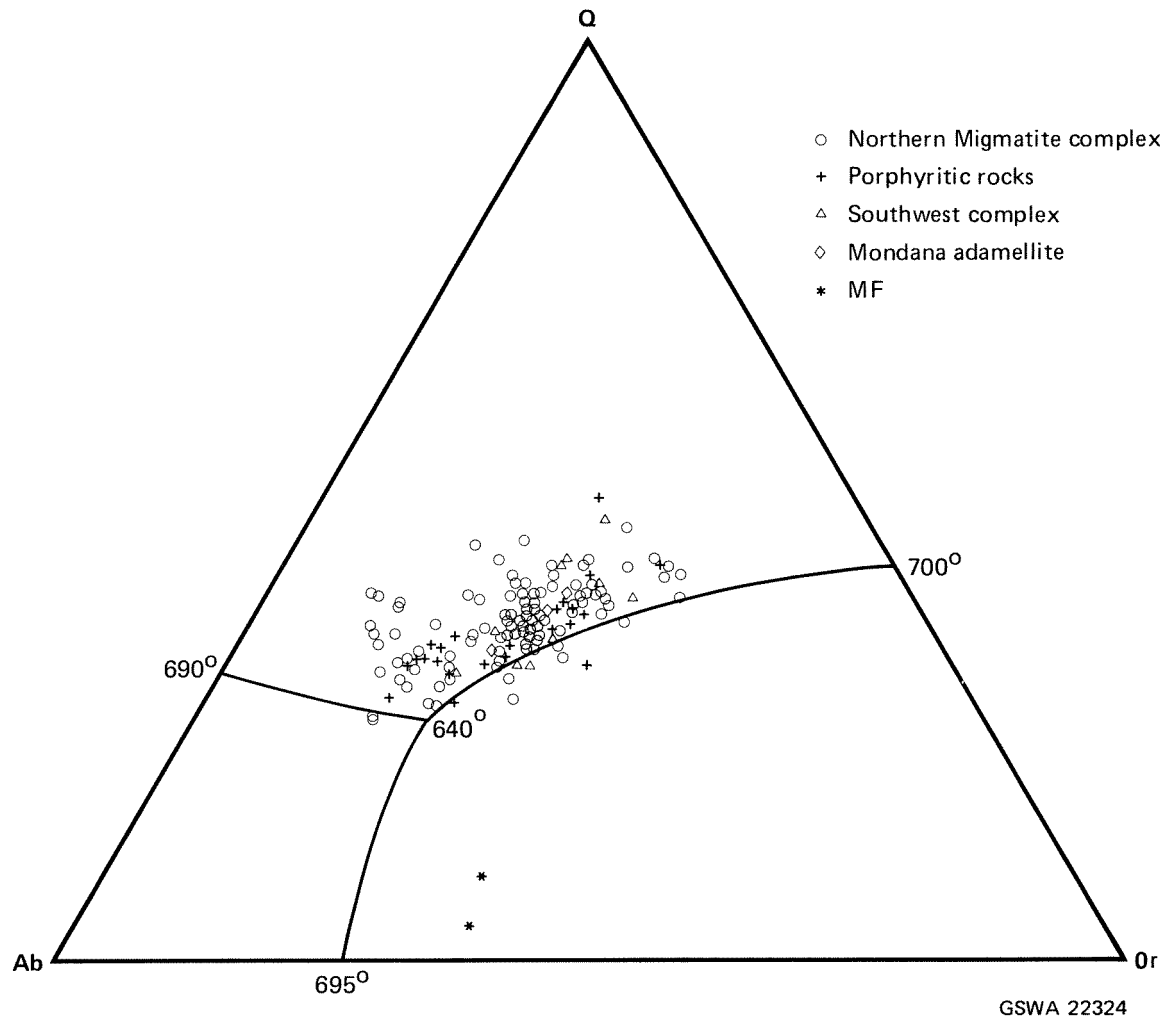


Figure 4. Normative Q-Ab-Or.

granitoids of the Mount Edgar batholith (Davy and Lewis, 1986) nor the various types of Corunna Downs rocks conform exactly to any of these criteria.

Features which relate more to S granitoids include a restricted SiO_2 range, a generally high $\text{K}_2\text{O}:\text{Na}_2\text{O}$ ratio (excludes MG, MI, T, and D) and low Ca and Sr. Granodiorite MJ has a very high $\text{Al}_2\text{O}_3:(\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO})$ molecular ratio of 1.4:1.

Features suggesting an I derivation include the presence of abundant sphene, and hornblende and biotite as the main ferromagnesian minerals (and the absence of primary muscovite). Most granitoids in this study have $\text{Al}_2\text{O}_3:(\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO})$ ratios of $1.1 \pm 0.2:1$ (i.e., midway between I and S types); however, P, PB, CB, CC, D, and MG, have ratios consistently below 1.1:1.

The Corunna Downs granitoids have none of the distinctive features of the A granitoids of Collins and others (1982). Similarly, they do not fall easily into either the ilmenite or the magnetite series of Ishihara (1980). Features which suggest they belong

to the ilmenite series are the presence of ilmenite itself, a low total proportion of opaques, an increase of the $\text{Fe}:(\text{Fe} + \text{Mg})$ ratio with increasing silica, an increase of Rb with increasing SiO_2 (Fig. 2G) and (where measured) an $\text{Fe}_2\text{O}_3:\text{FeO}$ ratio less than or equal to 0.5. Features which favour classification in the magnetite series include the widespread presence of sphene and epidote minerals (though many of the latter may be of metamorphic origin), the virtual absence of monazite and garnet, the presence of pyrite casts, and the lack of variation of trace elements such as F and Li with SiO_2 (Figs 2E,F).

On balance, it is concluded that the rocks would probably fall in the ilmenite series of Ishihara, or in the I type of Chappell and White (1974), but that neither classification is entirely suitable. Most would fall into the sphene-allanite type of barren granites suggested by Ivanova and Butuzova (1968).

A plot of normative Q-Ab-Or (Fig. 4) indicates a general concentration of compositions in the vicinity of eutectic troughs originally defined by Tuttle and Bowen (1958) and extended in Winkler (1979).

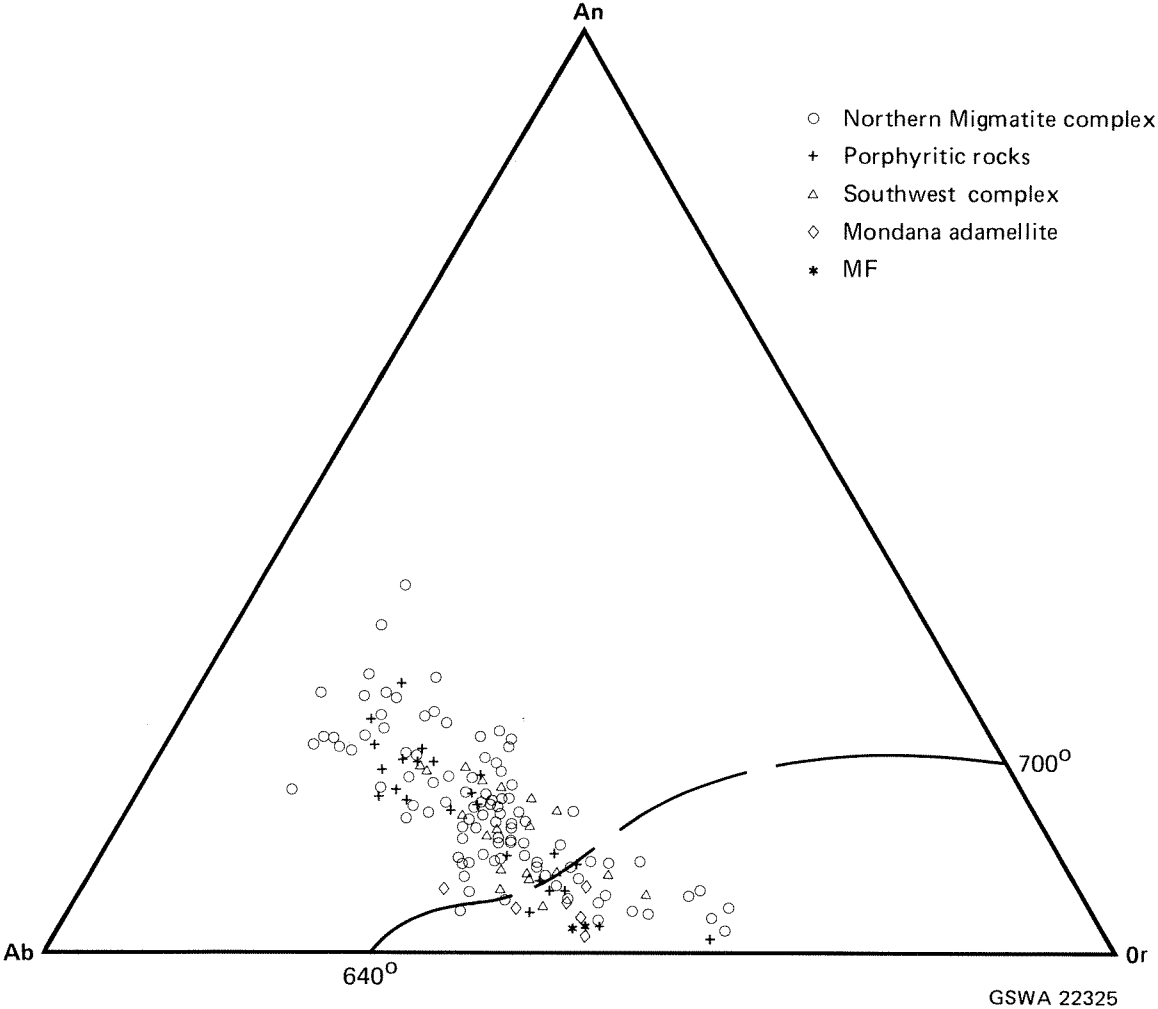


Figure 5. Normative Ab-An-Or.

TABLE 4. COMPARISON OF THE SHAW, CORUNNA DOWNS AND MOUNT EDGAR, BATHOLITHS

	Shaw	Corunna Downs	Mount Edgar
Intrusive felsic dykes	Present	Not recognized	Present
Pegmatites	Present	Not recognized	Present
Mean composition of older granitoids	Granodiorite near tonalite	Granodiorite near adamellite	Granodiorite near tonalite
Mean Na ₂ O content	(a) > 4%	< 4%	> 4%
Rocks of clear sedimentary origin	Present	Not recognized	Not recognized(b)
Late dynamic stress		Present	Minimal
Location	West of Corunna Downs	—	Northeast of Corunna Downs

(a) Limited data.
(b) Schistose xenoliths may be of sedimentary origin.

SOURCES: Shaw Batholith—Bickle and others (1980), Bettenay and others (1981), Bickle and others (1983). Mount Edgar Batholith—Davy and Lewis (1981, 1986), Hickman (1983).

Granodiorite D lies close to the ternary eutectics on the Q/Ab/Or diagrams of Winkler (1979, p.303, 304). Most other classes plot close to the binary eutectic between Q and Or at temperatures rather higher than the ternary minimum. However T, MW, ME, and MF plot well away from any eutectic line. Moreover, a normative An-Ab-Or diagram (Fig. 5) indicates that few samples lie on a true eutectic; most types, if ever wholly molten, must have formed at temperatures above the minimum defined by the eutectics.

The Harker diagrams, in general, support the idea of non-minimum melts. Regression lines, drawn for those components which correlate negatively with SiO₂, commonly intersect the SiO₂ axis with higher values of SiO₂ than has been predicted by Chappell and White for minimum melts (76% SiO₂). The Harker diagrams indicate that several distinctly different magmas may be involved, some of which may have evolved? along similar paths, others of which may not have evolved significantly at all.

COMPARISON WITH OTHER PILBARA GRANITOIDS

A substantial body of data is available for the Mount Edgar Batholith (Davy and Lewis, 1981,

1986) and for the Shaw Batholith (Bettenay and others, 1981, Bickle and others 1980, 1983), the batholiths closest to the Corunna Downs Batholith to the northeast and west respectively. Some comparisons, many not directly compositional, between the rocks of these three batholiths are given in Table 4.

Pre- and syntectonic granitoids

Pre- and syntectonic granitoids include all granitoids described from the Corunna Downs batholith except the Mondana Adamellite and the possible sub-volcanic plugs ME and MJ.

Many samples of the older granitoids are compositionally similar to samples from either the Shaw or Mount Edgar Batholiths or other Pilbara granitoids (Bickle and others, 1983, Table 5). An AFM diagram (Fig. 6) suggests that the rocks from Corunna Downs are calc-alkaline, as are those from the other batholiths (Davy and Lewis, 1986, Appendix D; Blockley, 1980, Tables 45,46; Hickman, 1983, Appendix B). However, the Corunna Downs granitoids, in general, appear to be more potassic and less sodic than those from other batholiths: this reflects the apparent larger proportion of adamellites in the Corunna Downs batholith.

Hickman (1983) in his Appendix B shows that the porphyritic granitoids are more consistently potassic (granodiorite-adamellite) than the older more foliated granitoids. The porphyritic rocks of Corunna Downs show a similar pattern.

Figure 7 shows the envelope of data for all the granitoids other than the Mondana Adamellite on a K₂O/Na₂O/CaO diagram. Superimposed on this diagram are data from Hickman (1983, Fig. 39), which include data from Lambert and others (1976). The Corunna Downs granitoids have compositions which are similar to those of the Archaean Rhodesian (Zimbabwe) Kaapvaal, East Greenland, and Scottish (Laxfordian) granitoids, but are far more sodic than the Amitsoq gneiss of Greenland.

The Mondana Adamellite, a post-tectonic granitoid?

This rock has been described by Blockley (1980, p.57) as “a granite of the younger type”. Its composition and petrography have been compared with Pilbara post-tectonic granitoids reported by Blockley (1980), Davy and Lewis (1981), and Hickman (1983). Chemical comparisons given in Table 6 show that the Mondana Adamellite has less K₂O, Na₂O, Ce, F, Li, Nb, Rb, Th, Sn, and Zn, than most other post-tectonic granitoids. It is also different mineralogically. The dominant ferromagnesian mineral in the Mondana Adamellite is biotite and there is accessory amphibole; there is no primary muscovite. In contrast, most of the other post-

tectonic granitoids are two-mica rocks with prominent primary muscovite; most contain no amphibole.

Hickman (1983) notes that established “tin-granites” of the Pilbara have an Rb:Sr ratio greater than 5. The same ratio for Corunna Downs granitoids, including the Mondana Adamellite, varies from 0.5 to 4.5. Figure 8 illustrates the relationships of K and Rb for the Corunna Downs granitoids together with the field suggested by Hickman (1983, Fig. 33) occupied by tin granites. Though many Pilbara granitoids contain the requisite amount of K_2O , none contains 300 ppm Rb. All the Corunna Downs granitoids fall in the field suggested by Hickman as representing older (non-stanniferous) rocks. The Mondana Adamellite approaches the closest to the tin-granite field but is still some distance away.

The premise used for estimating the Corunna Downs rocks as potentially stanniferous was that “tin-granites” usually average in excess of 10 ppm Sn. The Moolyella Adamellite and the Cooglegong

Adamellite, known tin-bearing granitoids, average 10 ppm Sn and 7.7 ppm Sn respectively, (Davy and Lewis, 1981; Blockley, 1980). None of the Corunna Downs granitoids has an average value that approaches even 8 ppm Sn. It is, therefore, suggested that there is no primary association of any of the granitoids with Sn, even though Table 5 does indicate that isolated samples contain tin values above 10 ppm.

Hickman (1983) has already noted that the Mondana Adamellite falls outside the requisite Rb:Sr ratio for tin-granites. The conclusion reached here is that the Mondana Adamellite is not part of the post-tectonic Sn-mineralized suite of adamellites. The Mondana Adamellite may prove to be of different age, possibly older, than the tin granites.

COMPARISON WITH PILBARA FELSIC VOLCANIC ROCKS

The compositions of the Corunna Downs granitoids do not resemble those of felsic rocks of

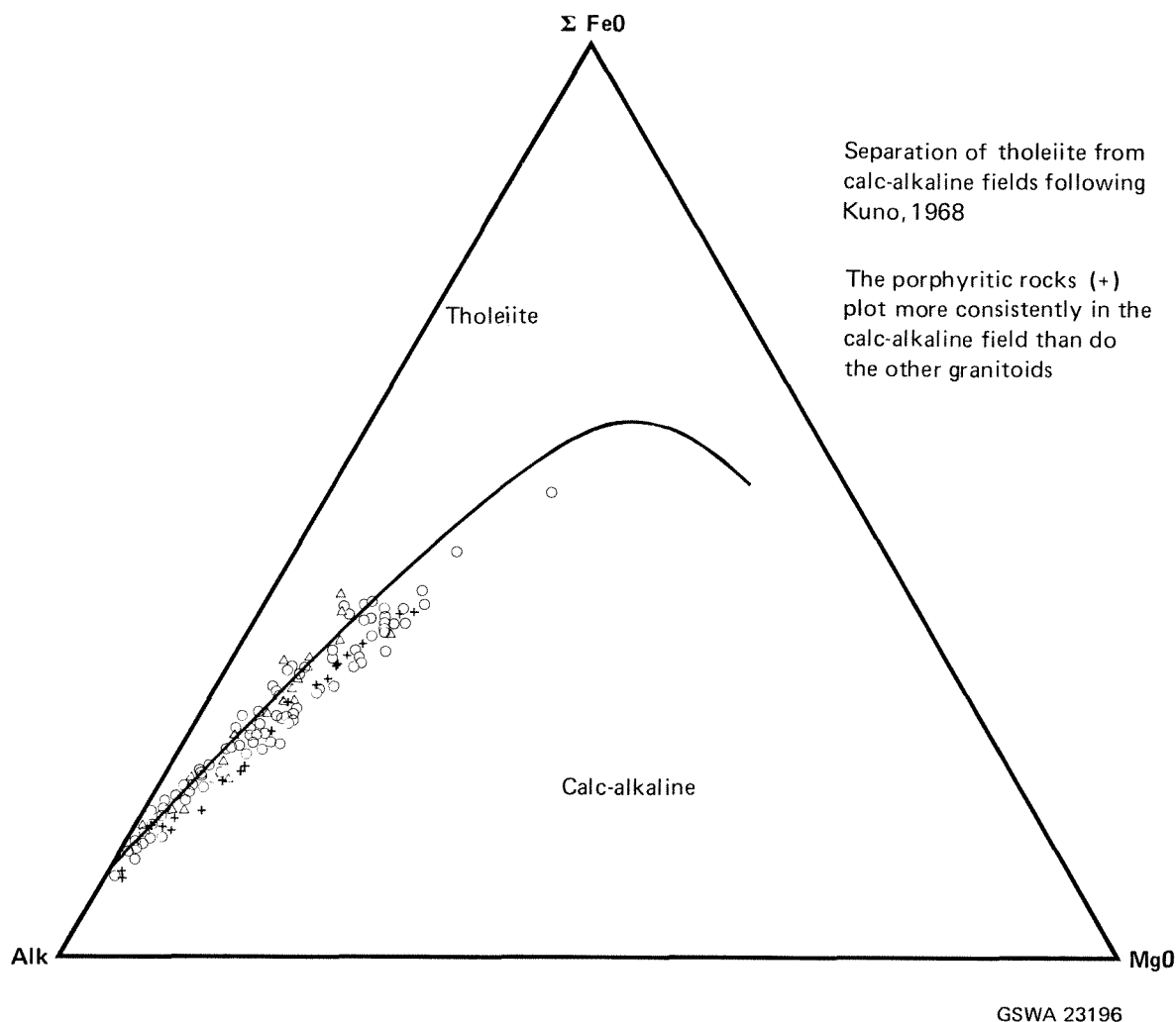


Figure 6. AFM diagram showing relationship of granitoids to calc-alkaline and tholeiite fields.

the North Star Basalt or the Wyman Formation of the Warrawoona Group (Glikson and Hickman, 1981, Table 6.16; Hickman, 1983, Appendix E). The major differences are that the granitoids contain too much SiO_2 , too little Al_2O_3 , and disparate amounts of Na_2O and K_2O , for the granitoids and the volcanic rocks to have been co-magmatic. However, certain of the MI and T tonalites have compositions quite close to dacites of the Duffer Formation of the Warrawoona Group (Hickman, 1983, Appendix D, column 36). Comparison of the dates of these granitoids with that of the Duffer Formation, which Pigeon (1978) has dated at 3452 ± 16 Ma by using the U/Pb method, is needed.

ORIGINS OF THE BATHOLITH

The maps produced by Hickman and Lipple (1978) and Hickman (1979, 1983) suggest a simple pattern within the batholith. An older complex in the north (including the tonalite) is bounded to the south by successively younger crescentic intrusions of essentially potassic granitoids. The picture pre-

sented here is substantially more complicated with the identification of many new separate classes and the recognition of an additional complex intrusion in the southwest corner of the batholith.

Hickman (1975) published a simplified structural plan of the batholith which indicated the position of trains of greenstone xenoliths in the two older phases of the granitoids and suggested two structural domes for the granitoids within these older rocks. The greenstone xenoliths have been ignored for this study but the pattern of distribution, particularly of MA-MC, MB, and MD, supports Hickman's concept of domical intrusions.

Granodiorites MA-MC represent the northern, and granodiorite MD the central dome recognized by Hickman (1975). The adamellite MB may reflect a third dome not recognized by Hickman. It is not clear where granodiorite D and tonalite T fit into these domical patterns. They, together with the minor intrusions ME-MJ, MF, MA, and MI, appear to intrude these domes. Hickman (1975) interpreted the greenstone xenoliths as remnant root-

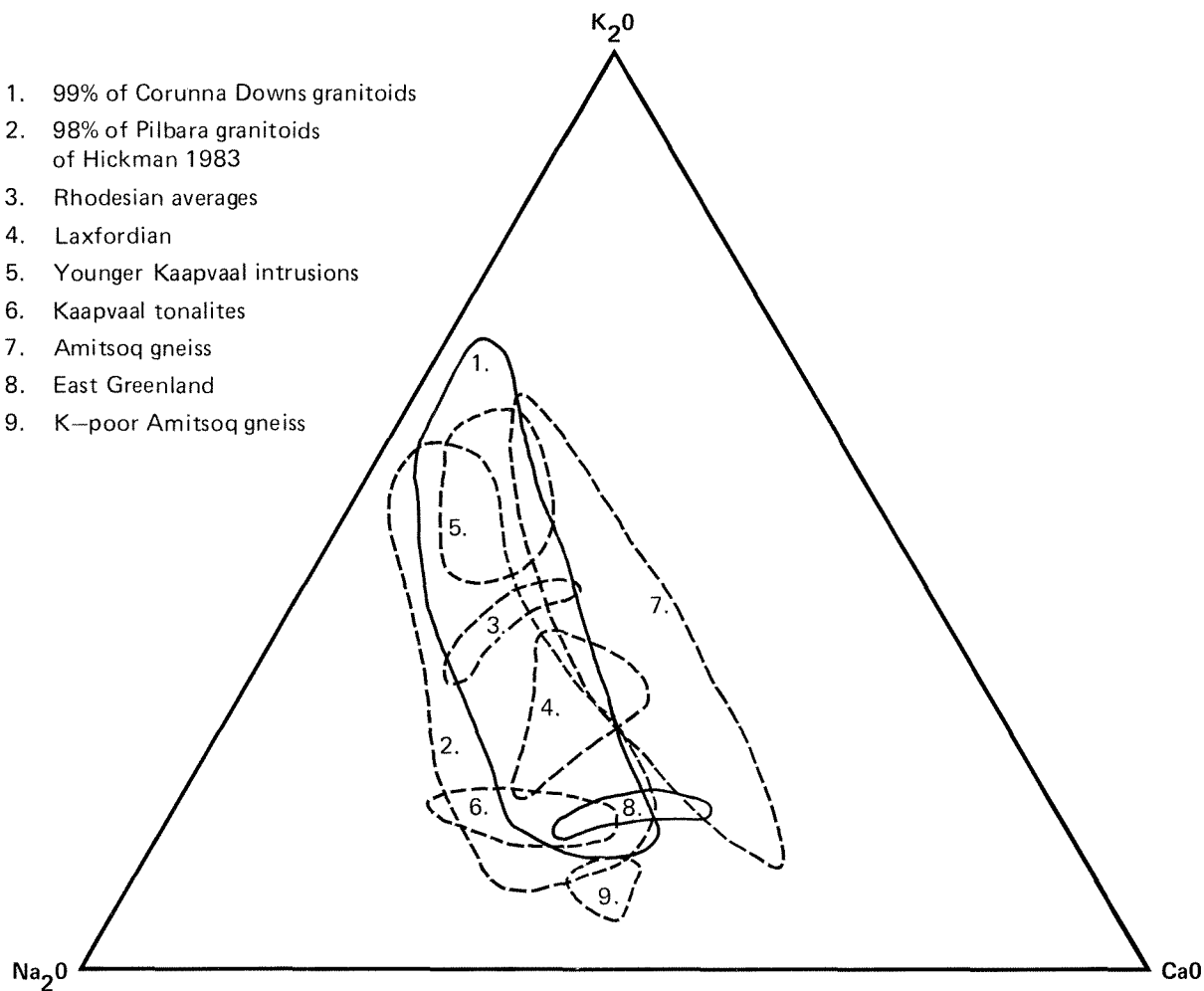


Figure 7. Comparison of Na_2O - K_2O - CaO data for Corunna Downs granitoids and gneisses with data of Hickman (1983) and Lambert and others (1976).

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TABLE 5. COMPARISON OF THE COMPOSITION OF THE MONDANA ADAMELLITE WITH PUBLISHED DATA FOR OTHER YOUNGER (ADAMELLITIC) GRANITOIDS

	Mondana		Moolyella				Cooglegong		Spear Hill	Coondina
	(10 samples)(a)		(11 samples)(b)		(11 samples)(c)		(13 samples)(c)		(3 samples)(c)	(2 samples)
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Mean
	Percentage									
SiO ₂	75.0	0.97	74.4	0.56	74.9	0.90	74.1	1.1	76.9	73.4
Al ₂ O ₃	12.5	0.23	13.4	0.30	13.4	0.34	13.2	0.51	12.5	13.6
Fe ₂ O ₃	1.6	0.27	1.5	0.13	1.2		1.8		1.0	1.8
MgO	0.19	0.09	0.13	0.02	0.11	0.02	0.22	0.11	0.07	0.31
CaO	0.76	0.38	0.72	0.15	0.78	0.12	0.94	0.29	0.68	1.01
Na ₂ O	3.5	0.41	3.9	0.18	4.08	0.14	3.76	0.32	4.12	3.87
K ₂ O	4.3	0.36	4.6	0.30	4.57	0.34	4.68	0.35	4.25	4.90
LOI	0.58	0.04	0.66	0.11	0.58	0.11	0.70	0.17	0.60	0.88
TiO ₂	0.08	0.04	0.05	0.03	0.07	0.01	0.17	0.09	0.08	0.23
P ₂ O ₅	<0.01	-	0.03	0.07	0.03	0.03	0.04	0.02	0.02	0.06
MnO	-	-	-	-	0.05	0.03	0.06	0.02	0.04	0.04
	Parts per million									
Ba	157	116	207	65	-	-	-	-	-	-
Be	< 5	-	5	1	6	3	6	2	6	5
B	<10	-	5	2	-	-	-	-	-	-
Ce	44	15	62	12	60	12	106	47	110	70
Co	7	3	-	-	-	-	-	-	-	-
Cu	13	6	14	16	4	3	13	19	2	7
F	629	593	738	205	1050	225	2380	2510	740	1360
Ga	15	2	23	3	-	-	-	-	-	-
La	<30	-	34	14	-	-	-	-	-	-
Pb	26	6	33	11	-	-	-	-	-	-
Li	24	14	155	94	185	90	95	115	95	80
Mn	181	72	380	165	-	-	-	-	-	-
Ni	10	4	<5	-	-	-	-	-	-	-
Nb	11	4	27	8	27	7	39	18	30	18
Rb	227	25	458	57	510	90	500	80	450	320
Sr	51	30	56	16	40	8	40	18	40	65
Th	19	5	32	9	35	11	44	10	27	70
Sn	3	2	11	5	9	7	8	7	6	3
U	3	2	11	5	15	8	7	6	14	40
V	<10	-	<10	-	-	-	-	-	-	-
Y	34	13	43	5	-	-	-	-	-	-
Zn	28	10	54	7	60	9	65	10	45	65
Zr	104	21	90	21	65	10	130	54	50	140

(a) This study. (b) Davy and Lewis (1986). (c) Blockley (1980).

NOTE: Davy and Lewis include in their samples of Moolyella Adamellite, three which were analysed separately.

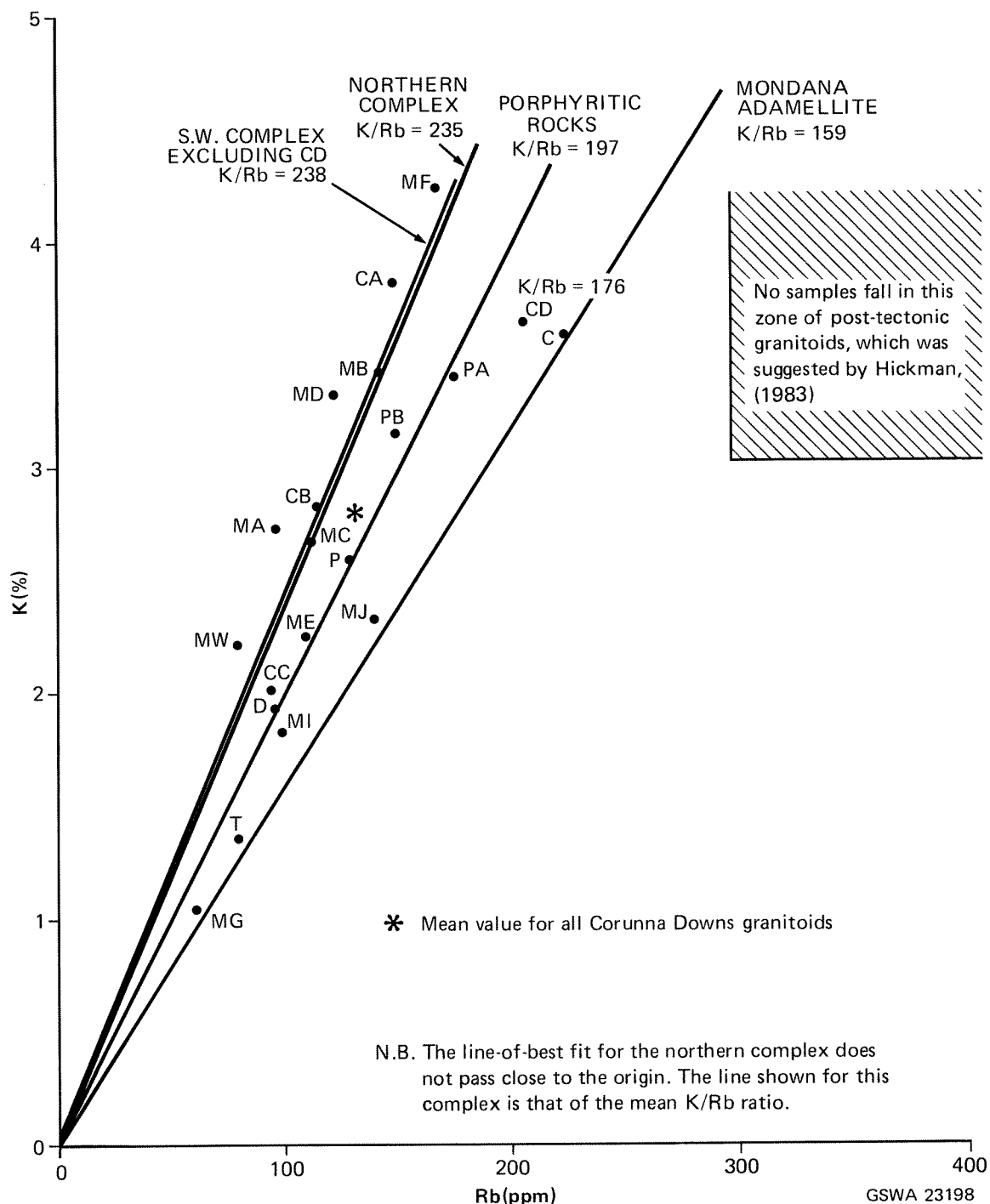


Figure 8. Potassium-rubidium ratios for each type of granitoid.

zones of greenstone belts. His Figure 36 suggests that there has been complex folding, and that the folds in the granitoids cross and refold synclinal structures in the greenstone remnants. There is some evidence of granitoid changes in the vicinity of these remnants. For example, certain qnessic rocks of granodiorite MA close to one such greenstone remnant (samples 59201-3) have high values for Ba, Ce, La, and Zn. The boundaries between granodiorite MA and adamellite MB and between granodiorite MD and adamellite PA also lie

close to such zones. These greenstone remnants may therefore represent genuine boundaries.

This study suggests that there are four main phases of granitoid intrusion which are not yet adequately dated. Compston and Arriens (1968) gave a Rb/Sr apparent age of $3\,050 \pm 180$ Ma for a sample from the northern part of the batholith. Cooper and others (1980, 1982) recently reported Rb/Sr dates from rocks in the vicinity of Warrery Gap. Granodiorite from an outlying pluton, west of the Gap and from an early dyke at the Gap itself

gave a result of $3\,270 \pm 22$ Ma ($R_i=0.701\,5 \pm 0.000\,3$). Scatter of other data from the same or nearby areas is such that the authors consider that this granodiorite has been contaminated, by slightly older (?greenstone) material. Adamellite from the main batholith 2 km south of Warrery Gap had an age of $3\,233 \pm 74$ Ma ($R_i=0.700\,9 \pm 0.001\,1$).

Microgranodiorite and adamellite at Gorge Well (equivalent to sample GSWA 59333) gave an isochron of $3\,235 \pm 36$ Ma ($R_i=0.703\,2 \pm 0.001\,1$). Rocks from these two areas appear to be of the same age but involve sources of at least two different initial ratios (Cooper and others, 1982, p.217). The "weighted mean" age is $3\,234 \pm 30$ Ma. Cooper and others (1980) refer to microgranodiorite 9 km east-northeast of Warrery Gap having an age of $3\,280 \pm 20$ Ma ($R_i=0.701\,4 \pm 0.002$).

Aplite from dykes at Warrery Gap suggests an age of $2\,989 \pm 26$ Ma ($R_i=0.742 \pm 0.101$) although two samples give younger model ages (Cooper and others 1982). A pink aplite, cutting adamellite 2 km South of Warrery Gap, gave an isochron of $2\,538 \pm 88$ Ma with $R_i=0.735 \pm 0.006$.

These results come from a small area of the batholith. In the terms of this report the granitoids involved belong to granodiorite-adamellite MD and granodiorite MW (the last has already been considered as an outlier of MD). The significance of the aplites' ages is not clear. However, the proximity of the sample site south of Warrery Gap to outcrops of adamellite PB might suggest some affinity of the aplite there with PB.

No other ages have been calculated for rocks of the batholith. The intrusion of most of the batholithic rocks is considered to post-date the crystallization of the magmas or crystal mushes which formed the primary granitoids. The foliated rocks of the batholith, and its overall shape, are now believed to be the product of solid-state diapirism (Hickman, 1983, 1984). Hickman (1984) argues that most of the granitoids formed 3 270 Ma ago (the dates obtained by Cooper and others, 1982) and that diapirism took place between approximately that time and 2 950 Ma ago.

The Mondana Adamellite is considered to be a post-diapirism intrusion. The relative age of the southwestern complex is not known. It is clear that additional age determinations are needed to resolve some of the problems still remaining within the batholith.

The relationships of small plutons within the outcrop area of granodiorite-adamellite MD are not fully established. These small plutons, except for diorite MG, seem to be distributed throughout MD rather than near its borders (*cf.* the pattern in the

Mount Edgar batholith, Davy and Lewis, 1981, Fig. 1). The absence of metamorphic foliations suggests late intrusion of small pockets of magma.

The potassic nature of many of the granitoids suggests that the present erosional level may be near the top of the batholith. However, the foliation dips which were taken by Hickman and Lipple (1978) are all steep ($>70^\circ$), and the granite-greenstone contacts appear to be close to vertical: Hickman (1984) suggested that the present erosion surface may be as much as 10 km below the former top of the granitic rocks, but much more structural investigation is needed to clarify this point.

On the basis of seismic studies, Drummond (1979, 1981) has postulated a boundary between upper and lower crust; it is about 10 km deep at Goldsworthy (150 km north of Corunna Downs), 16 km deep at Newman, and probably, therefore, 12-13 km beneath the Corunna Downs Batholith. The upper crust includes both granitoids and greenstones, but the seismic velocities of the lower crust suggest felsic (acid to intermediate) granulite. If this interpretation is correct, then there is insufficient mafic-ultramafic crustal material for the granitoids to have been generated either by fractionation or by partial melting. A probable source of the granitic material is the felsic granulite.

ECONOMIC POTENTIAL

The survey has shown no economic potential for the batholith.

The tin-bearing potential of the Mondana Adamellite has been considered earlier. None of the granitoids examined for this study can be considered a "tin granite", in the sense usually applied to other Pilbara granitoids, but isolated anomalous values for tin were found in the northern migmatite complex. In this, the Corunna Downs Batholith shows affinity with the Mount Edgar Batholith where anomalous values of Sn have been determined within the older granitoids and well away from known mineralization (Davy and Lewis, 1981, 1985). There may be enough tin in rocks of the migmatite complex to account for the Sn values in alluvium over these rocks that were reported by Campana (1963); however, no specific source has been identified.

No obviously mineralized rock has been identified. Table 6 indicates that the isolated high values of elements of economic interest are largely contained in aplites and mylonites within the northern migmatite complex. Two anomalous samples were found in the porphyritic rocks, but none in either the southwest complex or the Mondana Adamellite.

TABLE 6 SAMPLES WITH POSSIBLY ANOMALOUS VALUES

Sample and type		Cu	Pb	Zn	Sn	U (Values in ppm)	Mo	W	Ba	Li
59202	MA	134	-	-	-	-	-	-	-	-
216	MB	-	70	-	35	-	-	-	-	-
222	MB	-	-	-	-	8	-	-	-	-
227	mylonite	-	-	-	-	-	-	10	-	-
231	mylonite	-	100	-	-	-	3	180	-	-
234	P	-	-	136	-	-	-	-	-	-
240D	aplite	-	-	-	-	7	-	-	-	-
248A	aplite	-	-	-	-	9	-	-	-	-
257	MD	191	-	-	16	-	-	-	-	-
259	aplite	290	-	-	14	-	13	-	-	-
310D	mylonite	-	-	-	-	-	-	-	-	75
311	MD	-	-	-	-	-	-	-	6000	-
314	MD	-	-	-	-	-	-	-	8000	-
317	MD	-	-	-	-	-	-	-	-	77
331	MD	-	-	-	-	-	-	-	5000	-
349	MG	-	-	109	-	-	-	-	-	-
354	PA	-	-	102	-	-	-	-	-	-
357A	aplite	-	-	-	24	-	-	-	-	-
377	D	-	-	-	30	-	-	-	-	-
56295	MA	-	-	-	16	-	-	-	-	-
56297	T	110	70	165	-	-	-	-	-	-

NOTE: Sample locations in Appendix 3.

The two tungsten-bearing samples (Table 5) came from the eastern margin of the batholith, and several other anomalous samples were collected close to the margins of the batholith. If any further prospecting is considered warranted, it should be restricted to the northern migmatite complex and, perhaps, marginal areas of the batholith.

CONCLUSIONS

- (1) Some 22 different granitoids have been identified in the batholith.
- (2) A previously unrecognized intrusive complex has been identified in the south-west part of the batholith: the Mondana Adamellite is of more restricted extent than has been previously reported.
- (3) The Na₂O content (and the proportion of tonalite) is substantially lower than in most other described Archaean granitoid complexes.
- (4) The granitoids do not fit neatly into any of the more recent classifications of the origins or types of granitoids. On balance they appear to be of igneous origin (I type) and to belong to the ilmenite series of Ishihara (1980).
- (5) The metamorphic history of the batholith has been complex; three metamorphic events have been identified, in probable order:
 - (a) Chlorite-epidote (greenschist facies) regional metamorphism.
 - (b) Prehnite-pumpellyite metamorphism.
 - (c) Cataclastic metamorphism.

- (6) The overall composition of the batholith appears to be granodiorite near the adamellite border.
- (7) The batholith is unlike other granitoid batholiths of the Pilbara in that it is:
 - (a) More potassic and less sodic.
 - (b) Lacking in pegmatites.
 - (c) Lacking felsic dykes.
 - (d) Lacking rocks of clear sedimentary origin.
- (8) There is no obvious economic potential.

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APPENDICES

Appendices 1, 2, and 3, are on microfiche and will be found inside back cover.

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THE TRANSITION BETWEEN THE HAMERSLEY AND FORTESCUE GROUPS AS EVIDENCED IN A DRILL CORE

by Richard Davy and A. H. Hickman

ABSTRACT

Mineralogical and chemical examination of core from DDH 186 has shown that there was no complete break of deposition at the contact between the Marra Mamba Iron Formation (Hamersley Group) and the underlying Roy Hill Shale Member of the Jeerinah Formation (Fortescue Group). The Roy Hill Shale Member includes a zone of incipient iron-formation 9-16 m below its upper contact, and a shale component can be recognized in the Marra Mamba Iron Formation for approximately 49 m above its base. The results suggest that the Roy Hill Member Shale should possibly lie within the Hamersley Group rather than in the Fortescue Group as presently defined.

Shale units within the Roy Hill Shale Member contain abundant free carbon, iron sulphides, and potash; the last locally exceeds 9%. These units contain trace minor Zn (<0.2%) and Cu (<0.04%) mineralization as sulphide. The present composition may be the result of some combination of the following three factors: the reaction of sea water with felsic volcanic ash (and cationic replacement of Na₂O by K₂O); the product of dilution of an ultrapotassic volcanic ash with organic remains and diagenetic sulphide; and the product of hydrothermal brines acting on underlying rocks.

The chert-carbonate unit within the Roy Hill Shale Member contains, on average, 16.0% Fe and is therefore technically iron-formation. It contains no magnetite, but otherwise has mineralogy similar to that of the Marra Mamba Iron Formation.

The lowest part of the Marra Mamba Iron Formation is also chert-carbonate with an admixture of shale. Magnetite is absent from the lowest 9 m of the formation and only becomes prominent about 30 m above the base. Other main iron minerals are stilpnomelane, minnesotaite and ferrodolomite; and the formation comprises mixed oxide-silicate-carbonate facies. A detrital component, represented by Al₂O₃, K₂O, Na₂O, TiO₂, Ba, Rb, and Zr, correlates strongly with stilpnomelane (some of which replaces tuff) and may be of conventional felsic volcanic (rhyolite or rhyodacite) origin.

INTRODUCTION

The Marra Mamba Iron Formation has been arbitrarily defined as the lowest unit of the Precambrian Hamersley Group in the Pilbara District of Western Australia (MacLeod and others, 1963). It overlies, conformably, the Roy Hill Shale Member of the Jeerinah Formation, which is, therefore, the uppermost formation of the Fortescue Group (Table 1).

The status of the Jeerinah Formation, however, is open to some doubt. Suggestions have been made by Kriewaldt (1964), on lithological grounds, and by Trendall and Blockley (1970), on the basis of its pattern of distribution, that it should really belong to the Hamersley Group. However, no detailed study of the boundary has yet been made. This paper is intended to partly redress this deficiency.

In 1977, Hamersley Exploration Pty Ltd, as part of a major prospecting program, drilled the Marra Mamba Iron Formation in many places. Examination of one of their cores, DDH 186, which intersected the lower part of the Marra Mamba Iron Formation and the upper part of the Roy Hill Shale Member, forms the basis for this paper. The location of the core is shown in Figure 1; it is sited at 117°55'E and 22°24'S (AMG SF50, 594600E and 7522600N). The core was drilled to 207.5 m normal

to the bedding, but the study was restricted to the interval where fresh rock was available, between 54.0 m and 207.5 m (Fig. 1).

A detailed study of the sampling methods, the chemical composition, and the mineralogy of the core, is presented elsewhere (Davy, 1986). Chemical and mineralogical determinations were made by

TABLE 1. SUMMARY OF STRATIGRAPHY OF THE JEERINAH FORMATION AND THE HAMERSLEY GROUP

Hamersley Group	Boolgeeda Iron Formation Woongarra Volcanics Weeli Wolli Formation Brockman Iron Formation Yandicoogina Shale Member Joffre Member Whaleback Shale Member Dales Gorge Member Mount McRae Shale Mount Sylvia Formation Wittenoom Dolomite Marra Mamba Iron Formation (no unconformity)	
Fortescue Group	Jeerinah Formation Roy Hill Shale Member Warrie Member Woodiana Sandstone Member Maddina Basalt Kiruna Siltstone Nymerina Basalt Tumbiana Formation Kylena Basalt Hardey Sandstone Mount Roe Basalt	Mount Jope Volcanics

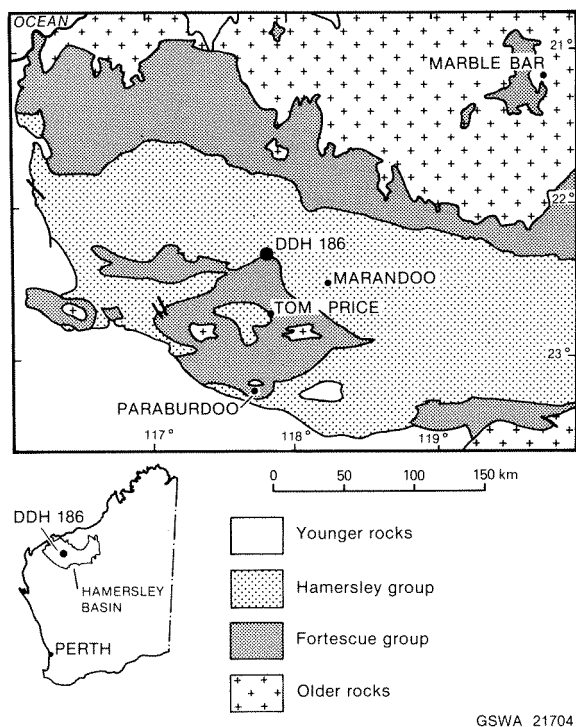


Figure 1. Location of DDH 186 in relation to contact of Hamersley and Fortescue Group rocks.

the W.A. Government Chemical Laboratories. Petrographic studies were made at the Geological Survey.

BRIEF DESCRIPTION OF THE CORE

The studied part of the core comprises Marra Mamba Iron Formation from 54.0 m to 141.95 m and Jeerinah Formation, Roy Hill Shale Member, from 141.95 m to 207.5 m.

The latter, informally called the Roy Hill Shale, can be divided into three units in the core:

upper black shale	141.95 - 150.95 m
chert-carbonate	150.95 - 157.9 m
lower black shale	157.9 - 207.5 m

A detailed log of the core is given in Davy (1986). An abbreviated log is included as an appendix to this paper.

The mineralogy and the chemical composition of the four units, determined by bulk analysis, are reported in Tables 2 and 3.

Roy Hill Shale

The shale units of the Roy Hill Shale are black, and thinly laminated with layers of massive sulphide up to 2 cm thick. A clastic, silt- to sand-sized component with clasts of quartz, chert, carbonate, and volcanic rocks is present in the lower shale below about 188.8 m. This "coarse" detritus is rare above 188.8 m, but isolated clasts, for example of K-feldspar, are present in the upper shale. Most

TABLE 2. OVERALL COMPOSITION OF THE UNITS DETERMINED BY X-RAY DIFFRACTION ANALYSIS

GSWA No.	Class	Density (tm ⁻³)	From (m)	To (m)	Dolom (%)	Sider (%)	Magnet (%)	Kspar (%)	Pyrite (%)	Q (%)	Chlorite (%)	Stilp (%)	Mica (%)	Minn (%)
70101	MM	3.00	54.00	141.95	5-10	10	5-10	50-55	10-15	25-30	10-15	15-20	TR	30-35
70102	RH1	2.79	141.95	150.95	<5	<5		<5	TR	10-15	10-15	<5	TR	TR
70103	RH2	3.00	150.95	157.9	15-20	25-30				35-40	10-15		TR	
70104	RH3	2.78	157.9	207.5	<5			30-35	15-20	15-20	10		10-15	

For analyses, see Table 3. Graphite is poorly crystalline and is not included in this table, it may be estimated from "Free C" in Table 3.

MM	=	Marra Mamba Iron Formation	Dolom	=	dolomite	Chlorit	=	chlorite
RH1	=	Upper shale unit	Sider	=	siderite	Stilp	=	stilpnomelane
RH2	=	Chert-carbonate unit	Magnet	=	magnetite	Mica	=	muscovite plus biotite
RH3	=	Lower shale unit	Kspar	=	potassium feldspar	Minn	=	minnesotaite
			Q	=	quartz (chert)	SG	=	specific gravity
						TR	=	trace

shale above 190 m—of both units—contains little visible clastic material: isolated curved grains suggest the presence of tuffaceous material and are more common in the lower shale. A large part of these units is petrographically opaque.

The mineralogy, determined by X-ray diffraction, is given in Table 2. It is similar for both shale units except that the lower shale contains abundant mica, a mineral almost absent from the upper shale.

These shale units contain sub-economic Zn mineralization together with anomalous Cu (Table 3). Other base-metal contents are not unusually high for black shales.

Both units have similar chemical compositions. The K₂O content and the K₂O/Na₂O ratio are very high. Potash locally reaches 9.9% in the lower shale (in the interval 193.5-193.7 m) and exceeds 9% over the interval 145.0-150.1 m in the upper shale.

The main differences in chemical composition lie in CaO, Na₂O, B, Ce, F, Th, and Sr. The lower shale contains the larger amounts of CaO, Na₂O, B, F, Sr, and Tk while the upper shale contains the larger amount of Ce. Sodium oxide, B, and F seem to be related to the mica content, while CaO and Sr appear to be related to a differing composition of the carbonate present.

The shales are separated by a unit in which chert (quartz) and carbonate (siderite and dolomite) are the dominant minerals. The contacts are not sharp, but are transitional, both above and below, over distances of about 1.7 m. The bulk mineralogy is given in Table 2. The mineral assemblage is similar to that of the Marra Mamba Iron Formation, except that chlorite is relatively abundant and there is no magnetite.

The main part of the chert-carbonate unit consists of a laminated interleaving of green (chlorite-rich), white (chert-carbonate rich), and black (“shaly”) layers. The transition zones above and below (150.1-152.9 m and 156.15-157.9 m respectively) comprise a mixture of this type of material and black shale. The boundaries of this unit are defined where the chert-carbonate component exceeds the shale component.

Roy Hill Shale - Marra Mamba Iron Formation contact

The contact between the Roy Hill Shale and Marra Mamba Iron Formation is marked by a carbonate-rich zone overlying the black shale. A transition zone (139.5-141.95 m), consisting of veined and fractured black shale with chert and carbonate, is included within the Marra Mamba Iron Formation because of its higher Fe content (14.9% Fe) and the absence of K-feldspar in contrast with the shale below.

TABLE 3. COMPOSITION OF THE UNITS ANALYZED

	GSWA Sample number			
	70101	70102	70103	70104
	percent			
SiO ₂	51.1	48.0	44.9	48.2
Al ₂ O ₃	1.2	11.6	2.1	11.5
Fe ₂ O ₃	5.2	7.0	<0.1	8.5
FeO	23.4	6.77	20.7	3.39
MnO	0.07	0.06	0.26	0.14
MgO	4.25	2.51	5.31	2.30
CaO	1.86	1.02	4.59	1.96
Na ₂ O	0.19	0.05	0.02	0.19
K ₂ O	0.41	7.43	0.62	5.56
TiO ₂	0.06	0.66	0.12	0.67
P ₂ O ₅	0.11	0.09	0.10	0.11
H ₂ O+	2.86	2.14	0.56	2.05
H ₂ O-	0.21	0.06	0.02	0.14
CO ₂	6.47	2.36	18.4	2.74
Free C	2.10	5.14	1.04	6.79
S	0.70	6.52	1.14	6.67
	parts per million			
Ag	<0.5	1.0	<0.5	1.0
As	3	56	5	47
B	11	14	4	48
Ba	30	265	24	277
Be	1	2	<1	4
Cd	2	2	2	2
Ce	23	71	<10	47
Cl	64	87	65	87
Co	5	50	25	55
Cr	10	151	21	163
Cu	10	330	75	320
F	340	452	154	927
Ga	<5	16	<5	18
La	16	29	<10	29
Li	2	16	2	20
Mo	<1	3	1	5
Nb	<5	9	5	7
Ni	<5	85	<5	100
Pb	<10	60	<5	50
Rb	20	176	13	148
Sr	14	18	17	30
Th	<5	<5	<5	9
U	<1	<1	<1	<1
V	19	108	29	116
Y	7	23	8	27
Zn	30	1750	235	850
Zr	16	129	26	138

For details of samples see Table 2.

Marra Mamba Iron Formation

The Marra Mamba Iron Formation is banded, but the banding is not entirely regular, and the rock varies from laminated to massive. Subdivision of the formation depends more on the differences in proportions of the minerals present (represented visually by colour differences) than on totally different lithologies. There are no “macrobands” of radically different composition.

Nonetheless, there are variations in composition. Black shaly zones are present from the base of the formation up to 96.3 m; their frequency and general thickness decrease upwards. Magnetite is absent in the lowest 9 m and is not common in the lowest 29 m of the formation.

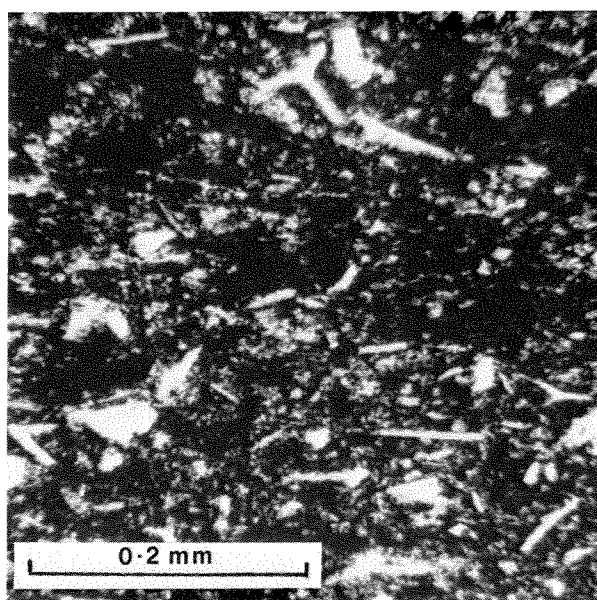
Individual layers vary in thickness from about 1 mm to over 20 cm in thickness, but larger compound units extend to several metres. Assemblages common in these individual layers ("mesobands") include:

chert-carbonate(-stilpnomelane)
minnesotaite-carbonate
magnetite-chert(-carbonate)
magnetite-minnesotaite
magnetite-stilpnomelane
stilpnomelane(-chlorite-carbon)
chert(quartz)-minnesotaite(-carbonate)
carbonate

These assemblages are not exclusive and may grade into one another.

Carbonaceous material may be present with any assemblage below 96.5 m, though it is less common in magnetite-rich assemblages.

Some stilpnomelane-rich layers are clearly tuffaceous with relic shards (Fig. 2). Other primary sedimentary features include auto-breccias, and rare indications of slumping, scouring, and possible cross-bedding. However, in most layers many of the primary structures have been modified or destroyed by diagenetic recrystallization. Consequently, for example, most stilpnomelane-rich layers are featureless.



GSWA 21705

Figure 2. Photomicrograph of tuff band at 113.3 m within the Marra Mamba Iron Formation—now almost wholly stilpnomelane.

Although sulphides (pyrite and pyrrhotite) are common accessory minerals, the rock belongs within a mixed oxide-silicate-carbonate facies of iron-formation.

Diagenesis and metamorphism

The succession has been affected by diagenesis and, though the effects are less obvious, by burial metamorphism.

The main diagenetic changes may be summarized as:

- (a) Recrystallization of most primary minerals
- (b) Formation of totally new minerals such as minnesotaite and sulphides
- (c) Blastic multi-stage growth of carbonates
- (d) Development of stylolites
- (e) Production of many nodular features
- (f) Syneresis cracks in sulphide and some stilpnomelane-rich layers

Most of the rock is undisturbed, but there has been post-depositional differential movement in the transition zones at the base of the Marra Mamba Iron Formation and on either side of the chert-carbonate unit. This is shown by brecciation (with carbonate-rich vein/fracture infillings) and by local variation in the attitude of the bedding. The timing of this movement relative to diagenesis or metamorphism is not clear; but, as there is little disturbance elsewhere, it may be related to a dewatering diagenetic stage.

There are no clear metamorphic effects. However, reference to Smith and others (1982) suggests that there is a weak metamorphism of prehnite-pumpellyite-epidote subfacies. None of these diagnostic minerals have been recognized but the observed assemblages are consistent with expected temperatures of 200-300°C and a maximum burial pressure of about 120 MPa (approximately equivalent to 4 km of overburden).

TRANSITIONAL CHANGES BETWEEN THE TWO FORMATIONS

The above description of the core carries with it the implication that changes were, in many respects, transitional although punctuated by clear breaks.

These clear sedimentation breaks lie between the Marra Mamba Iron Formation and the underlying shale, and between the chert-carbonate unit and the enclosing shale, even though there are 1-2 m of transitional material at each of these contacts.

Most changes may be related to changing depositional conditions. Different depositional mechanisms contribute different species to the

sediments and vie with each other for supremacy. Within the major depositional units there are additional, less obvious, distinctions.

Iron

There is a gradual increase of the iron content in the black shales from a value of about 7.5% Fe_2O_3 -equivalent close to 190-195 m (Fig. 3A). The iron content at the top of the lower shale has risen to about 12-14% Fe_2O_3 -equivalent. The upper shale contains slightly more iron, on average, than the lower shale (Table 4).

TABLE 4 MEAN IRON CONTENT OF THE ANALYZED UNITS

	Total Fe (as % Fe_2O_3)	Fe (%)
Marra Mamba Iron Formation	30.9	21.6
Roy Hill Shale Member:		
upper shale	14.5	10.2
chert-carbonate unit	22.8	16.0
lower shale	12.2	8.5

In between the shales, the chert-carbonate unit has appreciably more iron, though this is lower than that in the Marra Mamba Iron Formation. Recent definitions (James, 1966) suggest that a sedimentary rock may be called iron-formation if its overall primary iron content exceeds 15%. By this definition the chert-carbonate unit (but not the black shales) can be considered true iron-formation (Table 4). The mineralogy of this unit closely resembles that of the Marra Mamba Iron Formation—in particular, that of the lower part of the iron-formation. The unit may, therefore, be seen as a precursor of the main iron-formation, even though it is located within the Roy Hill Shale.

Within the Marra Mamba Iron Formation there are also changes in composition with respect to iron. Figure 3A shows that the iron content rises to its "normal" iron-formation level over about 10 m. There is a corresponding change in iron mineralogy from siderite-stilpnomelane to minnesotaite-stilpnomelane(-siderite-ferrodolomite-magnetite); magnetite is not abundant for a further 19 m.

Organic content

The organic content, represented by carbon, reaches a maximum in the upper part of the lower shale (157.9-185 m) (Fig. 3B). Apart from in the chert-carbonate unit, where it is low, carbon progressively decreases until it disappears at 92.6 m. The decrease in carbon in the Marra Mamba Iron Formation is paralleled by a similar gradual decrease in Cu, F, and S.

Boron

Boron is commonly high in detrital micas (illite), and reaches a maximum in the upper part of the lower shale (Fig. 3C). It drops almost to zero in the

chert-carbonate unit, then rises slightly in the upper shale, and drops again at the base of the Marra Mamba Iron Formation before rising slightly again.

Potash

Potash is subject to sharp fluctuations in concentration (Fig. 3D). In general, it increases in the shale units from the base of the core upwards, although it drops almost to nothing in the chert-carbonate unit. This component best illustrates the transitional zones above and below the chert-carbonate unit. Potash values drop abruptly but not completely at the top of the upper shale. Within the Marra Mamba Iron Formation, potash is highest where stilpnomelane is abundant.

In summary, the first major change takes place at the contact of the lower shale with the chert-carbonate unit; the last with the disappearance of free carbon in the Marra Mamba Iron Formation. There is thus some transition over at least 65 m (157.9-92.5 m).

FEATURES COMMON TO BOTH FORMATIONS

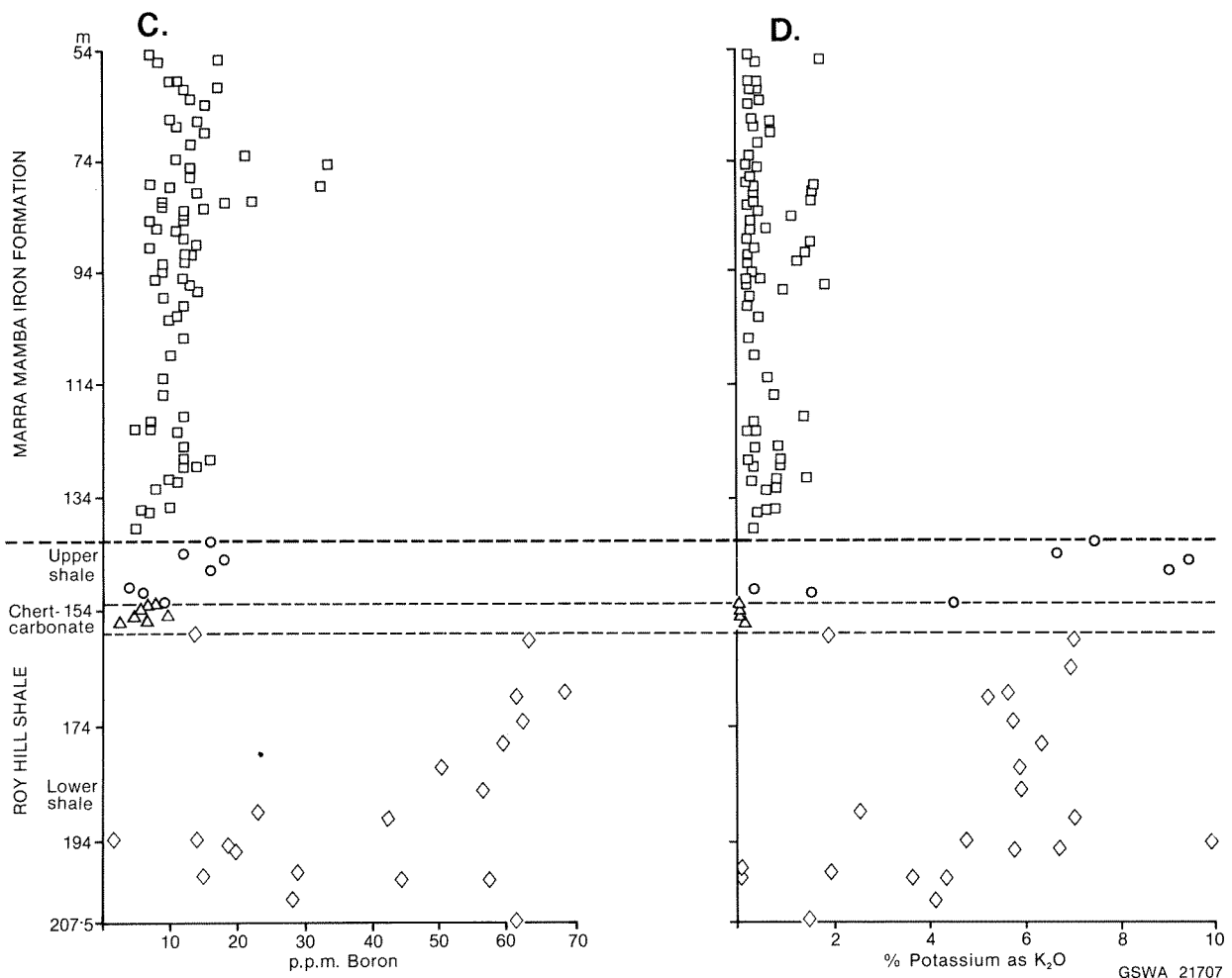
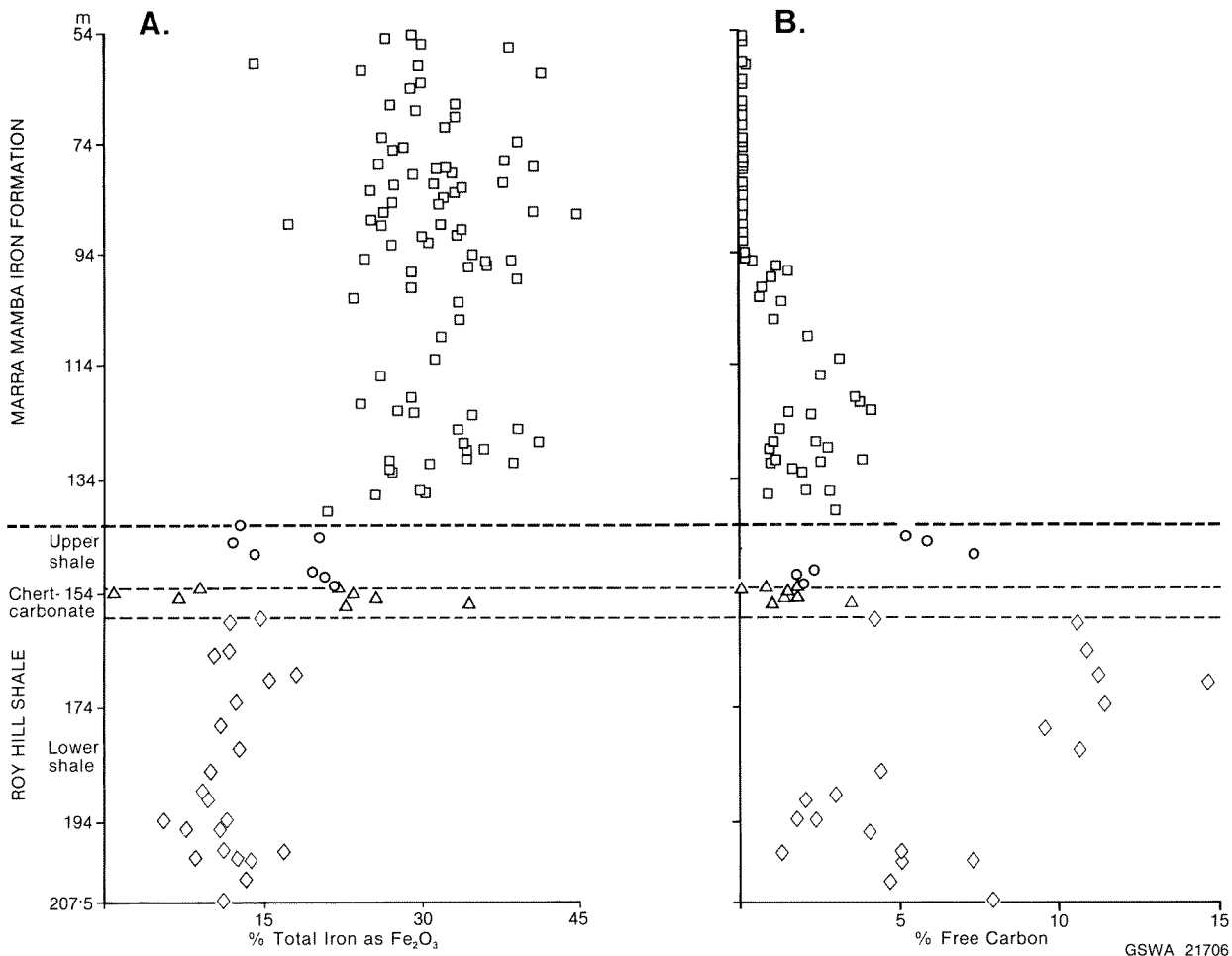
Features common to both formations in the whole length of the core are the presence of carbonate (implying some chemical deposition throughout the whole sequence) and volcanic material.

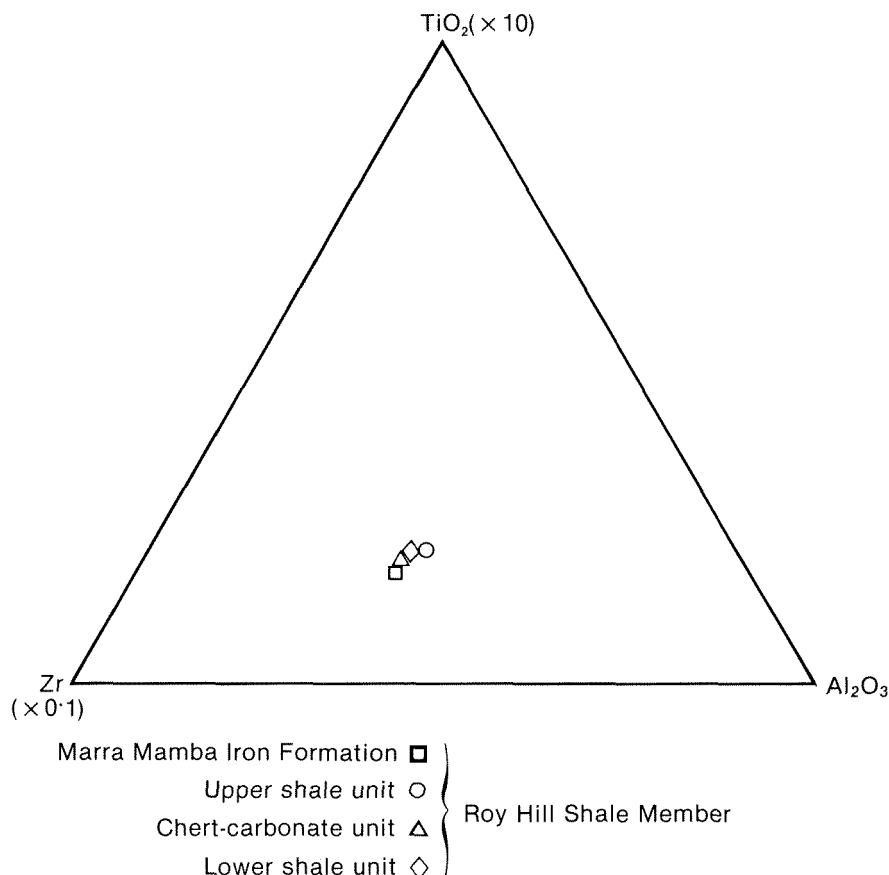
The carbonates are dolomite, ferrodolomite, and siderite (calcite is found only in veins). The carbonates normally occur in discrete layers, but rarely do any two of the three varieties co-exist. Some of the blastic grains are zoned, and reflect changing conditions during diagenesis.

Volcanic material is represented by a mixture of lithic and vitric tuffs in the Roy Hill Shale and by stilpnomelane tuff in the Marra Mamba Iron Formation. Much stilpnomelane in the Marra Mamba Iron Formation is recrystallized and is now featureless. Similar stilpnomelane-rich rocks in the Marra Mamba Iron Formation have already been recognized as possible tuffs by Trendall and Blockley (1970, p.82), and it seems likely that all stilpnomelane has been formed by diagenesis of tuffs. Supportive chemical data are adduced in the next section.

VOLCANIC INPUT

Volcanoclastic material is represented by lithic fragments and shards in the black shales, and by shards in the iron-formation. The exact proportion of volcanic material contributing to the various units cannot be determined, particularly for the shales. If all the stilpnomelane in the Marra Mamba Iron Formation represents volcanic ash, it must constitute 5-20% by volume of that formation.





GSWA 21731

Figure 4. Plot of Al₂O₃-TiO₂-Zr for the analyzed units.

Ewers and Morris (1981, p. 1937-1940) examined the relationships of the “immobile” components Al₂O₃, TiO₂, and Zr in “S”-macrobands of the Dales Gorge Member of the Brockman Iron Formation, and concluded that the components are “most probably volcanogenic” though a detrital clastic source was not totally ruled out. A triangular plot of these components for the units studied in DDH 186 shows that their ratios changed very little from the lower shale to the Marra Mamba Iron Formation (Fig. 4). Statistical analysis of the various units (not illustrated) showed that Al₂O₃, TiO₂, K₂O, Na₂O, Ba, Cr, Li, Rb, V and Zr are strongly correlated—particularly in the Marra Mamba Iron Formation, where they also correlated with stilpnomelane. Most of these components have been plotted against Al₂O₃; the plots for Na₂O and K₂O are given in Figures 5A and B. Similar plots for TiO₂ and Zr are given by Davy (1986).

On the assumption that the source was volcanic and that it originally contained some 15% Al₂O₃, extrapolation of the observed relationships suggests

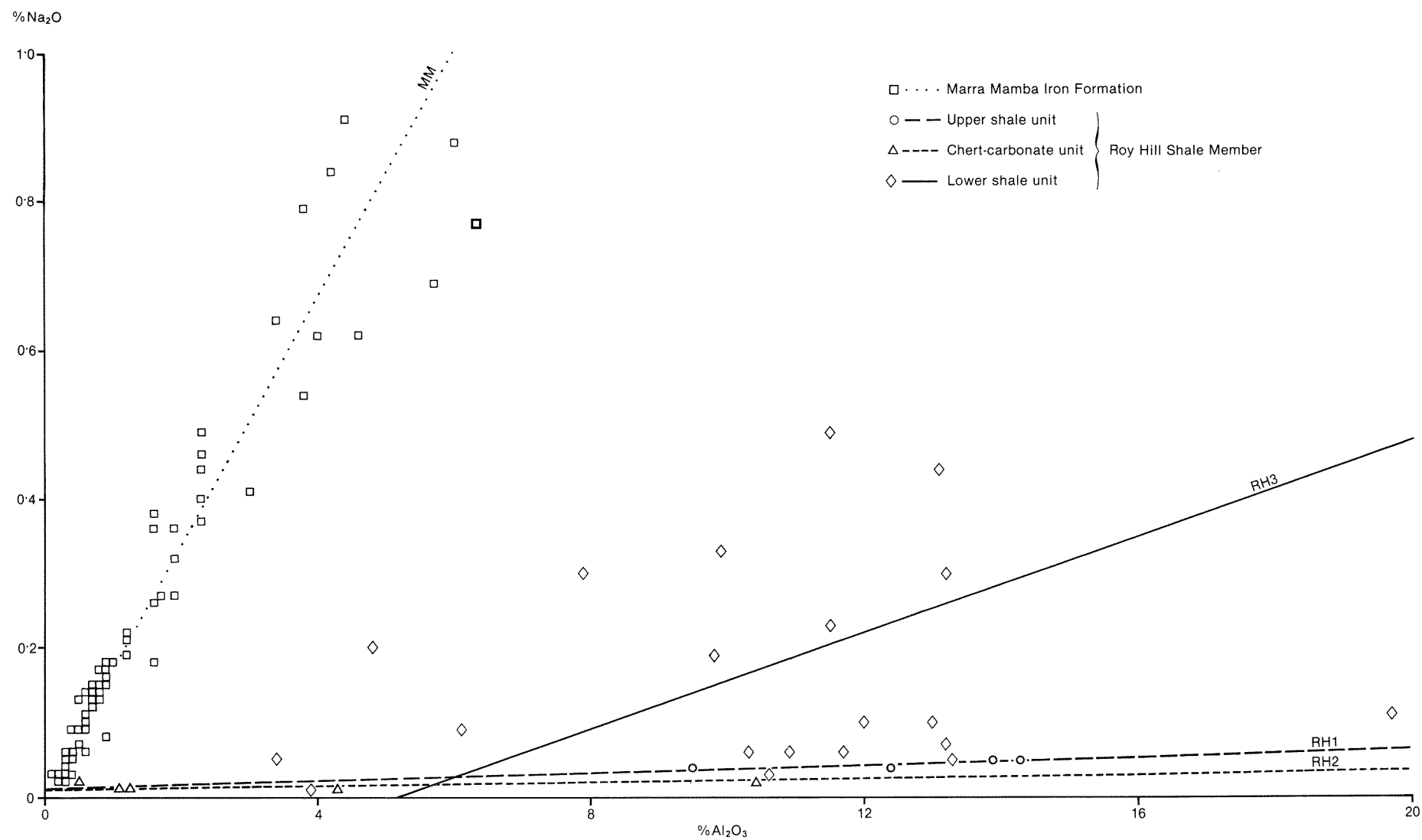
that the tuff contributing to the Marra Mamba Iron Formation may have contained 2.5% Na₂O, 4.5% K₂O, 0.75% TiO₂, and 125 ppm Zr. These data are consistent with an origin as rhyolite or rhyodacite. Similar values are not uncommon in clays and shales: such sediments are only excluded because of the visible, though limited, volcanic component.

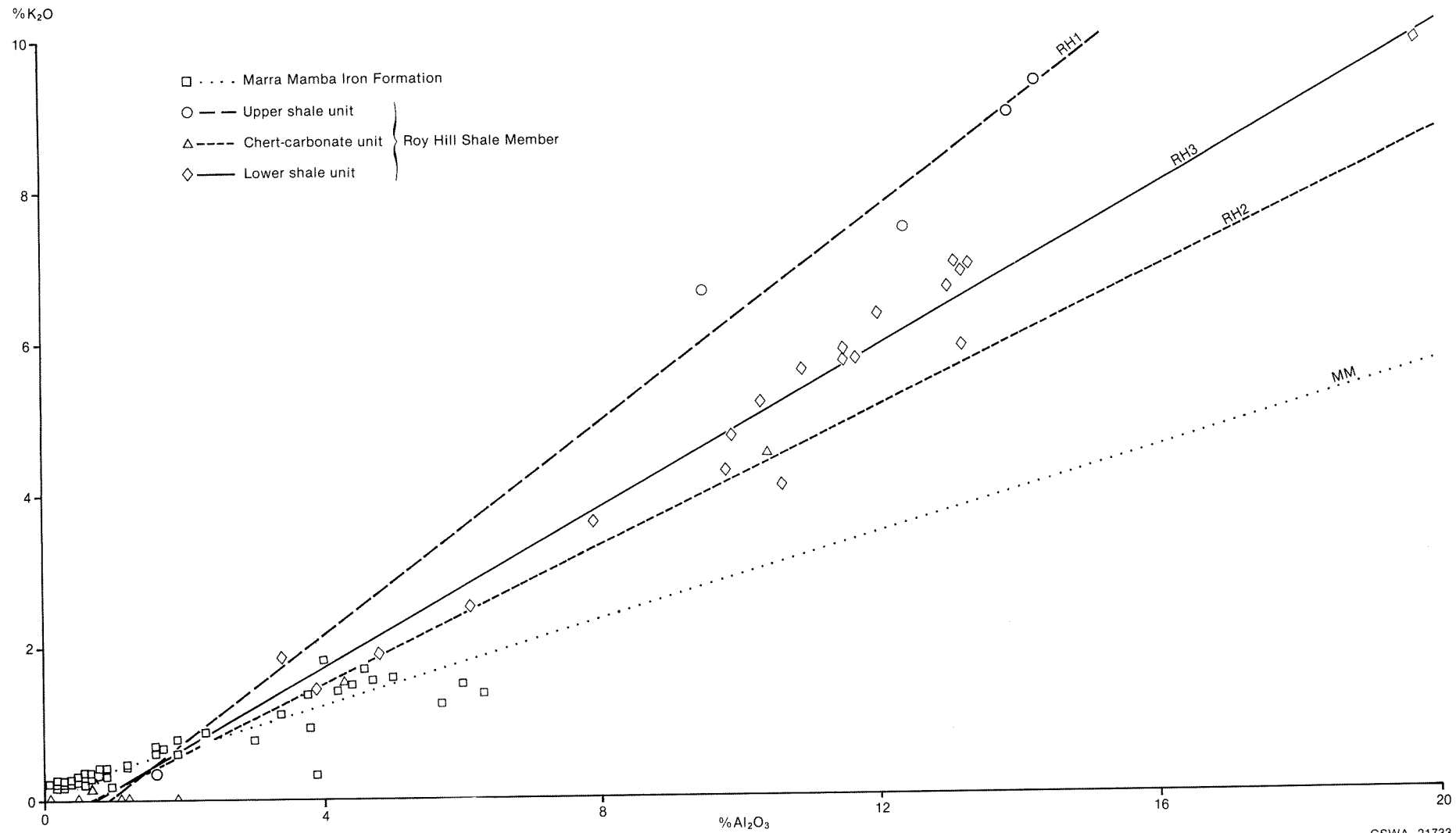
Volcanic debris, all probably intermediate to felsic in character, is known from other Hamersley Group rocks. The provenance of this debris is suggested by CSIRO workers to be volcanoes north of the Fortescue River Valley (Morris and Horwitz, 1983), though the specific volcanic centres have not yet been identified.

A similar argument applied to the shale units does not give as satisfactory a result. At an assumed Al₂O₃ content of 15%, the K₂O content is excessively high and the Na₂O content excessively low for a formal felsic volcanic source (Figure 5A and B). Nevertheless the identification of trachytic-textured fragments in the shales point to some volcanic input. Conventional interpretation of the very low levels of Na₂O and the high levels of K₂O ascribes the composition to diagenesis. Croxford (1965) reported that shales of similar composition

Figure 3. A - Plot of total iron (as Fe₂O₃) against depth in the core. B - Plot of free carbon against depth in the core. C - Plot of boron against depth in the core. D - Plot of potash against depth in the core.

Figure 5. A - Plot of Na_2O against Al_2O_3 .



B - Plot of K_2O against Al_2O_3 .

at Mount Isa, Queensland, were formed from volcanic glass and shards by reaction with potassium contained in connate waters. Other authors, for example Bowie and others (1966), consider that in alkaline environments potassium is fixed on montmorillonitic clays with release of sodium to sea water. The K-fixation sequence envisaged is:

- (a) glass;
- (b) montmorillonite;
- (c) illite(-stilpnomelane); and then

TABLE 5. COMPARISON OF THE BULK COMPOSITION OF THE UPPER SHALE, RECALCULATED FREE OF PYRITE AND CARBON, WITH LAMPROITE TUFFS AND A FRESH LAMPROITE FROM THE KIMBERLEY REGION, W.A.

	Upper shale unit	Big Spring Tuff (a) (71385)	Fishery Hill Tuff (a) (71881)	Fresh lamproite Oscar plug (71891)
	per cent			
SiO ₂	57.8	60.5	57.4	58.8
Al ₂ O ₃	14.0	15.1	13.2	8.3
Fe ₂ O ₃ (b)	8.3	3.2	9.3	7.3
MgO	3.0	1.27	1.78	2.24
CaO	1.2	1.76	0.78	1.65
Na ₂ O	0.06	0.10	0.09	0.33
K ₂ O	8.95	14.05	12.9	9.26
TiO ₂	0.08	0.62	0.67	5.33
P ₂ O ₅	0.11	0.09	0.61	0.96
MnO	0.07	0.01	0.13	0.05
CO ₂	2.8	0.43	0.03	0.01
	parts per million			
As	67	n.d.	4	1
B	19	28	13	7
Ba	319	6113	715	9905
Be	2	3	3	8
Ce	86	115	141	330
Cl	105	149	40	20
Co	60	10	20	21
Cr	182	79	68	460
Cu	400	30	48	53
F	545	1086	1380	1560
Ga	19	13	15	17
La	35	165	78	279
Li	19	11	14	8
Mo	3	1	<1	1
Nb	10	13	14	116
Ni	102	26	55	431
Pb	72	40	17	48
Rb	212	424	350	1123
Sr	22	82	90	942
V	130	97	121	183
Y	28	16	26	16
Zn	2100	68	75	75
Zr	155	186	180	1033

n.d. not determined

(a) Country rock is shale with the addition of fluids and ash from lamproites (J. D. Lewis, pers comm); numbers are GSWA sample numbers. (b) Total iron.

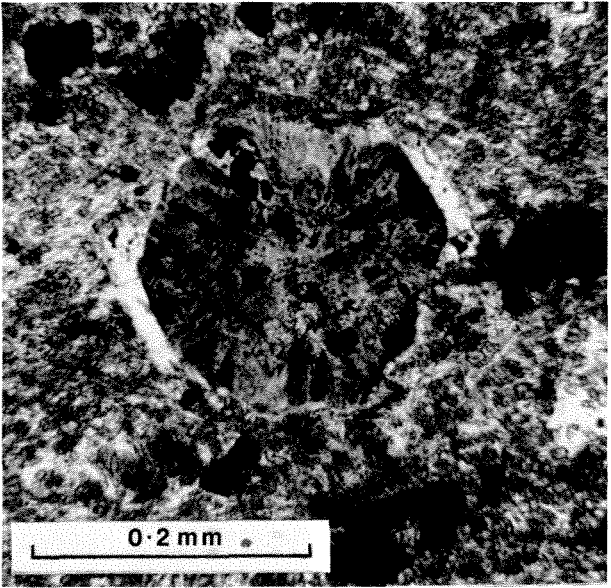
(d) K-feldspar.

However, the mechanism of the last step is not yet clearly established.

An alternative volcanic origin in the form of an ultrapotassic ultrabasic tuff, diluted by organic matter and diagenetic sulphide, is possible. There are three suggestive pieces of evidence:

- (a) Recognizable volcanic clasts include K-feldspar (orthoclase) grains and volcanic rock with trachytic texture.
- (b) The present composition of the shales, recalculated on a sulphide- and carbon-free basis, is quite similar to the composition of fresh lamproitic rocks from the Kimberley region of Western Australia. Comparison of these shales with lamproite tuffs and a fresh lamproite (analyses provided by J.D. Lewis, pers. comm.) is given in Table 5.
- (c) Scattered detrital grains in the Marra Mamba Iron Formation—now quartz, with relic sectoral twinning—may once have been leucite. (Fig. 6).

Lamproite would be a better source rock than kimberlite because of its inherent high K₂O/MgO ratio and its very low Na₂O content.



GSWA 21736

Figure 6. Photomicrograph of possible leucite crystal—now quartz—showing primary sectoral twinning. Marra Mamba Iron Formation at 74.2 m.

SUMMARY OF DEPOSITIONAL CHANGES IN THE VICINITY OF THE BOUNDARY

The lowest rocks of the core indicate that there was mixed deposition of clastic material, including clastic sand, silt, limestone, some tuffs, and organic residues, and some chemical deposition (carbonate). The environment was reducing and may have been marine as the boron content of the lower shale is quite high (Degens and others, 1957). The clastic detrital component of the lower shale decreased with time.

At 157.9 m in the core, deposition of black shale was "overprinted" by extensive chemical deposition of chert-carbonate. Shale continued to form but was grossly diluted by the chert-carbonate.

Deposition of chert-carbonate temporarily ceased (at 150.1 m) and shale formation again became dominant. Conditions were still reducing, but with very little visible clastic detrital material (and less boron) the environment may have been less obviously marine. The upper shale may have formed as an organic gel containing volcanic dust and accompanied by limited carbonate deposition.

At 141.95 m, chert-carbonate deposition was renewed and became persistent. It included iron-rich components which subsequently became phyllosilicates. At the same time, the nature of the volcanism, which contributed a tuffaceous component, may have changed from highly potassic to more conventional felsic except, possibly, for small eruptions which have left their mark by clasts or crystal grains of leucite. Carbonaceous shale deposition and chemical precipitation continued jointly for some considerable time (represented by about 50 m of core) before conditions for organisms in the "ocean" became almost impossible. As conditions deteriorated the carbonaceous shale component diminished, but did not finally disappear until 92.5 m in the core. Meanwhile the chemical deposition of "iron-formation" was accompanied by periodic outpourings of felsic tuff (now represented by stilpnomelane). The chert-carbonate and later magnetite-rich layers of the iron-formation may possibly be considered as distal-hydrothermal? expressions of the volcanism. During the deposition of the iron-formation, depositional conditions gradually became slightly less reducing and allowed the formation (after diagenesis?) of abundant magnetite.

Sulphides in all units may have formed penecontemporaneously or during early diagenesis by hydrothermal- or organic-reduction of oceanic sulphate.

DISCUSSION

The position of the Fortescue-Hamersley Group boundary

This paper presents a detailed examination of the Jeerinah Formation-Marra Mamba Iron Formation boundary at one locality. The results show that there are transitional changes at, and in the vicinity of, the boundary. There is no complete break between the two formations. The results support previous suggestions (Kriewaldt, 1964; Trendall and Blockley, 1970) that (at least) the upper Jeerinah Formation is lithologically more similar to the Hamersley Group than it is to the dominantly basaltic Fortescue Group. Although local volcanic units occur in the Jeerinah Formation (for example, the Nallanaring Volcanic Member in the northwest and the Baramine Volcanic Member in the northeast (Hickman, 1983, p.123), in most areas the formation is composed wholly of shale, chert, sandstone, and minor amounts of dolomite. The Marra Mamba Iron Formation is absent in the east where it appears to be represented by shale containing local thin intercalations of iron-formation (Hickman, 1983). The observation that the Marra Mamba Iron Formation wedges out eastwards, apparently through a change of sedimentary facies, casts considerable doubt on the Roy Hill Shale-Marra Mamba Iron Formation boundary being an appropriate dividing line between two major groups.

The accepted boundary between the two groups is artificial—MacLeod and others (1963) said that "the upper limit of the (Fortescue) Group is arbitrarily placed at the base of the Marra Mamba Iron Formation". However, the succession from the Fortescue to Hamersley Groups, seems essentially continuous, hence the comment that the Fortescue Group upper boundary is arbitrarily positioned.

Available geochronology, summarized in Blake and McNaughton (1984), indicates that the middle part of the Fortescue Group, represented by the Kylenea Basalt, is at least 2.75 Ga old and that the lower-middle part of the Hamersley Group, represented by the Dales Gorge Member of the Brockman Iron Formation, is about 2.5 Ga old. This is a substantial time-interval.

If there is a break between the two groups, this work suggests that it is not at the base of the Marra Mamba Iron Formation. It is probably lower in the succession, at the base of the Jeerinah Formation, where a widespread sandstone member marks a change from the thick volcanic formations of the Fortescue Group to the dominantly sedimentary formations of the Hamersley Group.

Economic considerations

There is no current economic significance attributed to the lower part of the Marra Mamba Iron Formation. The iron content is relatively low in this core (and elsewhere in this part of the formation), and metal values are not high enough to merit exploration interest.

However, the Roy Hill Shale has been an exploration target for many years. The shales within the member are weakly mineralized in Zn and, to a lesser extent, in Cu but no concentrated zone of mineralization has yet been found.

Exploration of the Roy Hill Shale has, in the past, been based on the assumption that it was a clastic deposit formed in quiet water in an anoxic environment (basin, lagoon, or barred shelf). The source of the base metals is unknown, but these metals were collected by sulphides as they formed diagenetically in reducing conditions.

A largely clastic origin for the shale is no longer tenable, and possible alternatives need further investigation. The sulphides may indeed have formed during early diagenesis but the primary origins of the base metals are not established. The volcanic debris suggests that an igneous or hydrothermal source is possible. On the other hand, Smith (1976) suggested that hydrothermal/metamorphic leaching of the underlying Maddina Basalt might have contributed base metals, particularly Cu, to the Roy Hill Shale.

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APPENDIX

ABBREVIATED LOG OF CORE 186

	Depth From	(m) To
Marra Mamba Iron Formation		
Laminated but non-fissile iron-formation, mainly dark-coloured, but containing relatively rare green layers; many dark layers are strongly magnetic; siderite is the main carbonate; most laminations are relatively even, but there are occasional pinch-and-swell zones; some of the greener layers have diffuse boundaries (green nodules are rare and there are trace amounts of sulphide); there are local indications of slumping and isolated scours.	54.0	78.1

Laminated iron-formation containing relatively abundant green (stilpnomelane-rich) layers; most dark layers are magnetic; dolomite is the main carbonate; certain layers are auto-brecciated or contain concretions; little sulphide.	78.1	94.2
Green-black laminated iron-formation; infrequent shaly partings.	94.2	96.5
Dark grey-green-black iron-formation containing thin layers of shale; black layers strongly magnetic; a few layers are auto-brecciated; one small zone appears cross-bedded.	96.5	100.2
Iron-formation containing thin bands of shale; as a whole is less magnetic than that above; siderite is the dominant carbonate.	100.2	116.0
Black shale containing zones of more massive iron-formation (green and black); siderite still dominant carbonate, but magnetic zones fewer and thinner.	116.0	132.0
Dark-green, mainly shaly rock; almost no magnetic bands.	132.3	136.2
Disturbed black shaly zone; carries abundant siderite; non-magnetic; fractures filled by quartz (chert) or carbonate, and sparse sulphide.	136.2	141.95
Jeerinah Formation - Roy Hill Shale Member		
Upper black shale unit		
Sulphidic, thinly laminated black shales; patches of nodular sulphide and auto-brecciated zones; sulphides occur both in thin (1-3mm) layers and disseminated as very small grains; almost no clastic detritus.	141.95	150.1
A transition zone with distorted black shales veined with quartz (chert) and carbonate.	150.1	152.9
Chert-carbonate unit		
Laminated chert-carbonate (siderite and dolomite).	152.9	156.2
Transition from chert-carbonate back to black shale; zone contains green (stilpnomelane-rich) layers.	156.2	157.9
Lower black shale		
Dark-coloured carbonate and black shale; thin layers of sulphide.	157.9	159.0
Thinly laminated sulphidic black shales, essentially carbonate- and clastic detritus-free.	159.0	188.8
Black shales becoming silty and sandy downwards; the shales are more massive because of contained carbonate (mainly dolomite); lithic grains include quartz, carbonate, and volcanic clasts.	188.8	207.5
End of hole.		

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