

GEOLOGICAL SURVEY
OF
WESTERN AUSTRALIA

REPORT 10

A CHEMICAL AND MINERALOGICAL STUDY OF
LOW-GRADE ZINC MINERALIZATION AT
THREE LOCALITIES IN THE PROTEROZOIC
BANGEMALL BASIN OF WESTERN AUSTRALIA

By
Richard Davy



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FOREWORD

This report describes the chemistry and mineralogy of rocks, in drill core, at three weakly mineralized localities in the Bangemall Basin. The purpose of the investigation was identification of the nature and origins of the mineralization and recognition of geochemical characters including indicator elements which would be of use in prospecting for this type of mineralization.

The recognition that mineralization occurs in two different sedimentary environments has been an important feature of the project.

The Geological Survey is committed to the resolution of problems related to economic geology and this report reflects this commitment.

A.F. Trendall
Director
Geological Survey

11 June 1980

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ABSTRACT

Chemical and mineralogical studies have been carried out on weakly mineralized drill cores from the Quartzite Well, and the Mount Vernon and Mount Palgrave areas of the Bangemall Basin of Western Australia.

The mineralization is mainly sphalerite with traces of covellite and other copper sulphides. Most mineralization is stratigraphically controlled. Deposition has taken place in black shales of the Kiangi Creek Formation (Glen Ross Shale Member) at Mount Vernon, in black shales of the Jillawarra Formation at Mount Palgrave, and in evaporitic siltstones of the Jillawarra Formation at Quartzite Well.

The primary mineralization was syngenetic, but sphalerite and pyrite in particular, were mobilized into veins during diagenesis. Galena, sphalerite, and pyrite also occur in a fault zone at Quartzite Well. This mineralization is believed to have been derived from the stratabound mineralization.

No material of volcanic origin was found. The most probable source of the sulphides is either connate or river water, but detrital copper sulphides, present in the stratabound zone at Quartzite Well, are believed to have been derived from a nearby topographic high of pre-Bangemall basement.

Major differences in the overall chemistry of the mineralized sequences are attributed to a varied provenance of the constituents, and also reflect differences in the environments of deposition.

The black shales at Mount Vernon and Mount Palgrave are interpreted as having been deposited in shallow marine waters. These shales have patterns of anomalous trace-element chemistry analogous to those of the Mecca Quarry Shale (U.S.A.) and the Corella Formation (Queensland).

The diversity of the chemical associations at the three localities renders it unlikely that there will be consistent indicator elements for use in prospecting. The most promising element is Cu, but Pb, Zn, Ni, Ag and Ba are all of possible use.

For this study, core samples (0.10 to 0.15 m long) of mineralized and nearby unmineralized material were examined. Mineralogical determinations of fine-grained and opaque (carbonaceous) samples were made by X-ray diffraction analysis at the Western Australian Government Chemical Laboratories. The mineralogies of other samples were determined from thin and polished sections.

The samples were analysed for selected major elements, sulphur, carbon, and twelve trace elements. In addition boron (B) and gallium (Ga) were determined on approximately 40% of the samples. The methods of analysis are summarized in Table 1, and the results of chemical and mineralogical analyses are presented.

Statistical manipulations have been used for sorting the data, and tables of mean values, standard deviations, and correlation coefficients together with cluster analysis dendrograms are on file at the Geological Survey.

A CHEMICAL AND MINERALOGICAL STUDY OF
LOW - GRADE ZINC MINERALIZATION AT
THREE LOCALITIES IN THE PROTEROZOIC
BANGEMALL BASIN OF WESTERN AUSTRALIA

INTRODUCTION

Low-grade mineralization occurs at widely scattered localities in rocks of the Bangemall Group in the Bangemall Basin of Western Australia. This paper reports a combined mineralogical and chemical study of drill core from three of these localities.

Samples were obtained from seven drill cores identified and located as follows:

<i>This paper</i>	<i>Company</i>	<i>Latitude</i>	<i>Longitude</i>
<i>Mount Vernon area</i>			
V 2	DDH 2	24°18'30"	118°11'00"
V 3	DDH 3	24°18'30"	118°09'40"
<i>Mount Palgrave area</i>			
P 13	DDH 13	23°21'45"	113°40'00"
<i>Jillawarra area</i>			
J 2	DDH JLWA 2	22°51'40"	115°57'00"
J 9	DDH JLWA 9	24°38'45"	118°28'00"
J 14	DDH JLWA 14	24°39'50"	118°20'30"
J 16	DDH JLWA 16	24°39'50"	118°20'15"

The Mount Palgrave and Mount Vernon areas were drilled by Westfield Minerals (W.A.) N.L., who donated core to the

Geological Survey on relinquishment of their claims. The Jillawarra area was drilled by AMOCO Minerals Australia Co., and samples were kindly provided by that company; J14 and J16 were from a sub-area known as the Quartzite Well prospect.

Stratabound sulphide mineralization is present at Mount Palgrave, Mount Vernon, and Quartzite Well. There is, in addition, fault-zone mineralization at Quartzite Well. None of these deposits are considered economic.

The prime purpose of this study was to arrive at an understanding of the nature and origins of the mineralization at these localities, and to determine whether any chemical constituents could be used as indicators of ore for prospecting purposes. A subordinate purpose was a comparison of the relationships of these rocks with others of a like nature to see if they reflected a universal pattern of mineralization that could be used as a basis for further prospecting. A final consideration was the usefulness of chemistry in interpreting the sedimentation conditions of the sedimentary rocks.

For this study, core samples (0.10 to 0.15 m long) of mineralized and nearby unmineralized material were examined. Mineralogical determinations of fine-grained and opaque (carbonaceous) samples were made by X-ray diffraction analysis at the Western Australian Government Chemical Laboratories. The mineralogies of other samples were determined from thin and polished sections.

The samples were analyzed for selected major elements, sulphur, carbon, and twelve trace elements. In addition boron (B) and gallium (Ga) were determined on approximately 40% of the samples. The methods of analysis are summarized in Table 1, and the results of chemical and mineralogical analyses are presented in Appendix A.

Statistical manipulations have been used for sorting the data, and tables of mean values, standard deviations, and correlation coefficients, together with cluster analysis dendrograms are on file at the Geological Survey.

TABLE 1. SUMMARY OF METHODS USED FOR CHEMICAL ANALYSIS

<i>Constituent</i>	<i>Method</i>	<i>Analyst</i>
SiO ₂	XRF	GCL
Al ₂ O ₃	XRF and AAS	GCL & GSWA
Fe ₂ O ₃	All iron as Fe ₂ O ₃ - XRF	GCL
FeO	titration with K ₂ Cr ₂ O ₇	GCL
MgO	AAS	GCL & GSWA
CaO	AAS	GCL & GSWA
Na ₂ O	AAS	GCL & GSWA
K ₂ O	AAS	GCL & GSWA
TiO ₂	XRF	GCL
P ₂ O ₅	XRF	GCL
MnO/Mn	XRF and AAS	GCL & GSWA
C	ignition at 1050°C, collection of CO ₂ on 'Ascarite'	GCL
CO ₂	HCl attack, collection of CO ₂ on 'Ascarite'	GCL
S	as BaSO ₄	GCL
Cu	AAS	GSWA
Pb	AAS	GSWA
Zn	AAS	GSWA
Ni	AAS	GSWA
Ag	AAS	GSWA
V	AAS	GCL & GSWA
Li	AAS	GSWA
Ba	XRF and AAS	GCL & GSWA
Rb	XRF and AAS	GCL & GSWA
Sr	AAS	GSWA
U	paper chromatography using "PAN"	GCL
B	spectrophotometry using curcumin	GCL
Ga	XRF	GCL

XRF - X-ray fluorescence

AAS - Atomic absorption spectroscopy

GSWA - Geological Survey of Western Australia, AAS following the general methods of Wenden (1975)

GCL - Government Chemical Laboratories.

REGIONAL SETTING

The stratigraphy of the Proterozoic Bangemall Group (about 1 000 m.y. old) is given in Brakel and Muhling (1976). An expanded description of the geology will be found in Muhling and Brakel (in prep.). The relevant stratigraphy below the Discovery Chert horizon is as follows:

Jillawarra Formation ('Prospect Shale' of some workers)

Kiangi Creek Formation - quartz arenite member
- Glen Ross Shale Member
- quartz arenite member

Mineralization at the Mount Palgrave and Quartzite Well prospects occurs in the Jillawarra Formation, at Mount Vernon in the Glen Ross Shale Member.

In the Mount Palgrave area, hole Pl3 was drilled into a syncline of Jillawarra Formation. Near-surface rocks are leached fine-grained siltstones, which display pyritic gossans and green cupriferous staining at the surface. The hole terminated in black shale and siltstone.

The Mount Vernon holes were drilled into steeply dipping beds of the Glen Ross Shale Member on the northern limb of the Mount Vernon Syncline. Surface outcrop is silicified, and, again, marked by green cupriferous staining. The holes intersected siltstone and shale of similar nature to that at Mount Palgrave and terminated within unmineralized carbonate-bearing siltstone.

A Quartzite Well, holes J14 and J16 were drilled into the Coolina Anticline. The core of the anticline is a basement inlier of metamorphosed sedimentary rocks, which are unconformably overlain by rocks of the Bangemall Group. The oldest exposed Bangemall Group rock in this area is the Jillawarra Formation. The Coolina Anticline is overturned to the north, and the northern boundary of the inlier is a reverse fault (dip approximately 60°S), which has brought south-dipping overturned quartz-chlorite-magnetite rocks against overturned rocks of the Bangemall Group. Drill hole

J14, on the northern limb of the anticline, commenced in basement rock and passed through the fault into siltstone and silicified rock of the Jillawarra Formation. Hole J16 was also drilled into overturned rocks of the Jillawarra Formation, but was collared south of the fault. The surface expression of sulphides included boxworks after pyrite.

Hole J9 was drilled through upward-facing metasedimentary basement rocks, and J2 was drilled into a dolerite sill intruded into the Bangemall Group. No evidence was found which related the mineralization to the dolerite.

PETROLOGY OF THE HOST SEDIMENTARY ROCKS

QUARTZITE WELL

Only the mineralized interval J16 was sampled. This interval (91.3 m to 121.8 m) is believed to be close to the top of the Jillawarra Formation (Muhling and Brakel, in prep.). Between 91.3 and 99.7 m, the core consists of sheared, partly to wholly recrystallized grey siltstone, containing abundant quartz veins. Silicified zones are common, and all quartz is recrystallized though many grains appear to have retained their original silt size. Bedding is emphasized by carbonaceous partings, and stylolites are abundant. Between 101.9 m and 121.8 m, most of the core is a meta - carbonate-siltstone that contains angular to sub-rounded clasts of quartz in a reconstituted clay-chlorite-siderite matrix. Siderite varies from micritic to relatively coarse (0.15 mm) and occurs in the matrix and, with quartz, in veins. Within this interval, a zone of massive pyrite containing sparse quartz (116.0 m) overlies fractured and veined black shale, which has been partly absorbed by remobilized quartz and microcrystalline silica.

The main sulphide mineral is pyrite. As well as massive pyrite, stratigraphically controlled pyrite, sphalerite and copper sulphide minerals are dispersed throughout the section.

MOUNT PALGRAVE

The hole Pl3, was drilled in the upper part of the Jillawarra Formation. The rock is an opaque, black carbonaceous siltstone containing clasts of quartz and mica, and pellets that were once clay but are now composed of re-constituted phyllosilicates. The phyllosilicates throughout the rock are mica and kaolinite; the kaolinite has replaced pre-existent chlorite, which is, however, still present where protected from alteration by quartz.

Much of the rock is quartz rich, but there are zones composed almost entirely of phyllosilicates.

Pyrite is present throughout the core except in the topmost 6 m, where the rock is weathered. Covellite and sphalerite, the main sulphides of interest, are restricted to the lower 28 m (55.2 m to 83.2 m), and, in particular, to the lowermost 10 m (74 m to 83.2 m) of the core. Both sphalerite and covellite occur within the matrix of the rock, but most sphalerite is contained in late-stage siliceous veins.

MOUNT VERNON

Four zones can be recognized in the Mount Vernon cores:

- (i) highly weathered (oxidized) near-surface rocks (shales and quartzites) (0 m to 43 m);
- (ii) partly altered shale and siltstone (43 m to 84 m*);
- (iii) fresh, black shale and siltstone (84 m* to 180 m*);
and
- (iv) grey carbonate siltstone and shale (180 m* to end of hole).

Zone (ii) consists mainly of black shale in V2; and of alternations of black shale with hematitic and dolomitic shale and siltstone in V3.

* There is a minor difference in the position of the inter-sections in the two cores.

The black shale and siltstone of zones (ii) and (iii) is similar to that of Pl3, but is generally finer grained. Black-shale layers of varying thickness are separated by thin layers (to 2 m) of slightly coarser, black siltstone. The siltstone contains more visible clastic material. Pyrite and copper minerals are present throughout the black shale, but sphalerite is almost wholly restricted to zone (iii) in the cores. The shale of zone (iii) contains, in addition to dispersed clasts of quartz and mica, flattened ovoid pellets now composed of quartz, opal, phyllosilicates and/or sulphides. Some of these pellets were once clay; the origin of the remainder is not clear. Early formed rhombic carbonate minerals have been replaced by sulphide. In V3, the main mineralized interval is heavily veined with sparry quartz and subordinate siderite, sphalerite, and/or goethite.

The underlying carbonate siltstone is coarser grained and contains abundant clasts of mica and quartz in a carbonate matrix. There are no sulphide minerals; iron is present as hematite and/or goethite.

POST-DEPOSITIONAL CHANGES

Post-depositional changes in the Bangemall Group at Quartzite Well and Mount Vernon are due to diagenesis on compaction, and involve recrystallization of clays, micro-faulting and localized veining.

Post-depositional changes are slightly more intense at Mount Palgrave, and approach the boundaries of the greenschist facies. Changes include partial resorption (pressure solution) of clasts by bituminous matrix, the development of authigenic tourmaline and pyrite, and the recrystallization of mica. In areas of deformation, incipient kink cleavage has developed and zones of massive pyrite have suffered marginal granulation.

Apart from oxidization of free carbon and sulphide minerals, near-surface weathering at Mount Vernon and Mount

Palgrave has not greatly modified the mineralogy except for the production of kaolinite. This mineral is recognized throughout P13 and in the two upper zones of V2 and V3. It has formed by weathering, at the expense of chlorite, which is only retained in these zones in the presence of carbonates or where it is enclosed by the impermeable microcrystalline silica.

Pyrite and covellite coexist with kaolinite in V2, pyrite, sphalerite and covellite with kaolinite in P13. This association of minerals leads to a conclusion that the transformation of chlorite to kaolinite is a more sensitive indicator of the onset of weathering than is oxidation of sulphide and carbon.

Near-surface samples were not collected from the Jillawarra cores. Kaolinite occurs in small proportion to depths of 100 m in J16, again apparently at the expense of chlorite. In this case, the cause may be deep weathering, or argillic alteration related to the faulting that has affected the core.

SULPHIDE MINERALOGY IN STRATABOUND ROCKS

Pyrite is the dominant sulphide, normally ranging from 5% to 25% of the rock at Mount Vernon and Mount Palgrave. In J16, most samples contain 5% pyrite, and isolated bands of massive pyrite (~70%) are present in P13 and J16. Sphalerite (<2%) and small traces of chalcopyrite, covellite, and/or chalcocite are present at all three localities. Galena was not identified in the stratabound mineralization, but has been reported at Mount Vernon and Mount Palgrave (Marshall, 1969) and at Quartzite Well (Amoco Minerals Australia Co. Annual Report for 1977).

Most sulphides are stratabound, but late-developed sulphides occur in cross-cutting veins.

There is little difference in sulphide morphology at the three localities, and for convenience a combined description is given. Common characteristics do not, however,

necessarily imply close genetic relationships. The morphological types of sulphide at each locality are listed in Tables 2, 4 and 5.

TABLE 2. MORPHOLOGICAL TYPES OF PYRITE PRESENT IN STRATABOUND MINERALIZED (META-) SEDIMENTARY ROCKS

Morphological type	Size	Quartzite Well	Palgrave	Vernon
i) Fine-grained disseminated	1-30 μm	✓	✓	✓
ii) Loose to massive aggregates	<500 μm	✓		✓
iii) Massive	1.5mm-2cm	✓	✓	
iv) Porous masses	<250 μm	✓	✓	
v) Within podlike bodies	50-250 μm		✓	✓
vi) Pseudomorphs after				
(a) Carbonate	<100 μm		✓	✓
(b) phyllosilicates	<200 μm			✓
vii) Authigenic euhedra	<5 mm	✓	✓	✓
viii) In veins	20 - 50 μm	✓	✓	✓

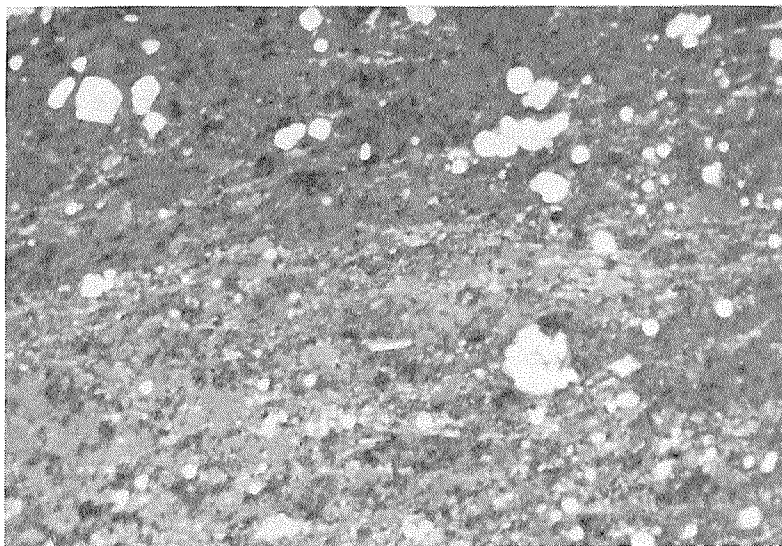


Fig. 1. Disseminated pyrite and sphalerite in mineralized black shale, Mount Vernon, V2, 42467, 86.8 m. Field of view 0.245 mm. (Polished section.)

PYRITE

(i) Fine-grained disseminated pyrite is common in thinly laminated shale (Fig.1). The size distribution is bimodal and the two most common sizes are 5 μm and 20 to 25 μm . Cubes, framboids and anhedral grains are all present either as discrete crystals or in trains up to 10 mm long and 20 μm to 50 μm thick.

(ii) Loose to massive aggregates and nodules consist of euhedral or subhedral grains, which are commonly loosely grouped together. In certain nodular forms, the cores are of coalescent framboids or euhedra with rims of radially arranged elongate grains 10 μm to 20 μm long (Fig.2). These nodules appear to be in a state of arrested accretion. Many of the loose aggregates are 30 mm long, 100 μm to 200 μm thick and are always elongate parallel to the bedding.

(iii) Massive pyrite occurs in structureless or weakly laminated layers up to 20 mm thick. Many layers at Mount Palgrave are marginally granulated (Fig.3). The laminations are emphasized by aligned inclusions of phyllosilicate matrix (Marshall, 1969). Massive pyrite shows shrinkage cracks up to 1 mm wide.

(iv) In some places porous masses of pyrite are present, either isolated or adjacent to massive pyrite (Fig.3). These masses are of irregular size and shape, show no internal trace of crystal faces or cleavage. They may possibly be source material for remobilized pyrite.

(v) Pyrite occurs within pod-like bodies particularly at Mount Vernon where there is a common association of sphalerite, quartz, opal and chlorite (Fig.4). The pyrite occurs as irregular to subhedral grains commonly in the centre of the pods. The minerals within the pods are all of diagenetic origin. The pods themselves may be flattened globular masses of uncertain origin or flattened clay pellets like those found in adjacent barren sediments at Mount Vernon (Fig.5).

TABLE 3. TRACE-ELEMENT CONTENTS OF PYRITE USING ELECTRON PROBE MICRO ANALYSIS.

Pyrite type	Locality	No. of samples	Ni (%)		Co (%)		Cu (%)		Zn (%)	
			\bar{x}	range	\bar{x}	range	\bar{x}	range	\bar{x}	range
Fine-grained massive aggregate	Quartzite Well (J16)	6	0.13	0.06-0.18	0.08	0.04-0.11	0.06	0.02-0.10	0.03	0.01-0.06
	Mount Palgrave	6	0.29	0.09-0.61	0.08	0.04-0.11	not determined		not determined	
	Mount Vernon (V2)	2	0.11	0.11	0.07	0.07	not determined		not determined	
Authigenic euhedra	Mount Palgrave	4	0.02	0.01-0.04	0.07	0.04-0.09	not determined		not determined	
Vein Pyrite	Mount Palgrave	2	0.04	0.04	0.06	0.06	not determined		not determined	
	Mount Vernon	1	not detected		0.09		not determined		not determined	

Analyst: R.J. Marston, courtesy of
CSIRO Division of Mineralogy

\bar{x} = arithmetic mean

(vi) Pseudomorphic pyrite has replaced both carbonate and phyllosilicate minerals. Pseudomorphs with rhombic outlines have probably replaced dolomite/siderite. Two forms occur: (a) the outer shape is rhombic, but the replacing pyrite is in aggregates of small euhedral and anhedral grains (Fig.6); and (b) pyrite has totally replaced carbonate (Fig. 7). Overgrowths on replaced rhombs are common, and produce conspicuously lenticular aggregates. The replacement of carbonate by pyrite is most common at Mount Vernon, where pseudomorphic pyrite of this nature is pitted, suggesting corrosion after formation.

Pseudomorphs after phyllosilicates are ovoid in shape and the lamination of the phyllosilicate is retained (Fig. 8).

(vii) Authigenic euhedra and subhedra apparently have grown in situ (Fig. 9). In contrast with other types of pyrite they are large. Most are between 1 mm and 2 mm in diameter (rarely reaching 5 mm). There are few indications of compaction around the grains though a few have developed quartz pressure fringes particularly at Mount Palgrave. These large grains contain small inclusions of sphalerite, chalcopyrite and, at Jillawarra, silicates and carbonate. Unlike the pseudomorphic forms, they show no trace of pitting or corrosion.

(viii) Vein pyrite occurs with quartz and sphalerite as irregular small, mainly isolated grains. It has crystallized at the same time as vein sphalerite and occurs both as inclusions in, and enclosing, that mineral. Electron probe analyses of pyrite show two main varieties in terms of contained nickel and cobalt (Table 3). Fine grained, massive, and aggregate pyrite contain appreciable nickel and cobalt, whereas authigenic euhedra and vein pyrite contain little nickel.

SPHALERITE

Sphalerite occurs in several forms (Table 4).

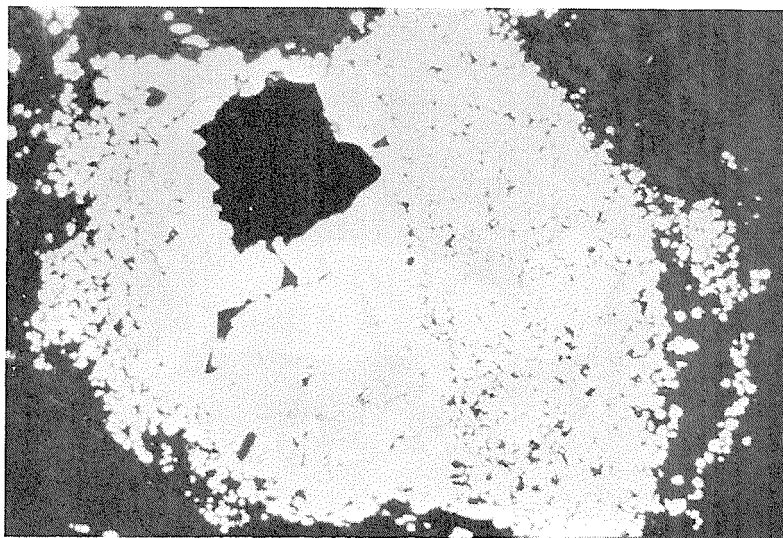


Fig. 2. Nodules of disseminated pyrite with core coalescing to massive pyrite (black mass at upper left is a hole where pyrite was plucked from the section during preparation). Mount Palgrave P13, 42683, 55.2 m. Field of view 0.62 mm. (Polished section.)

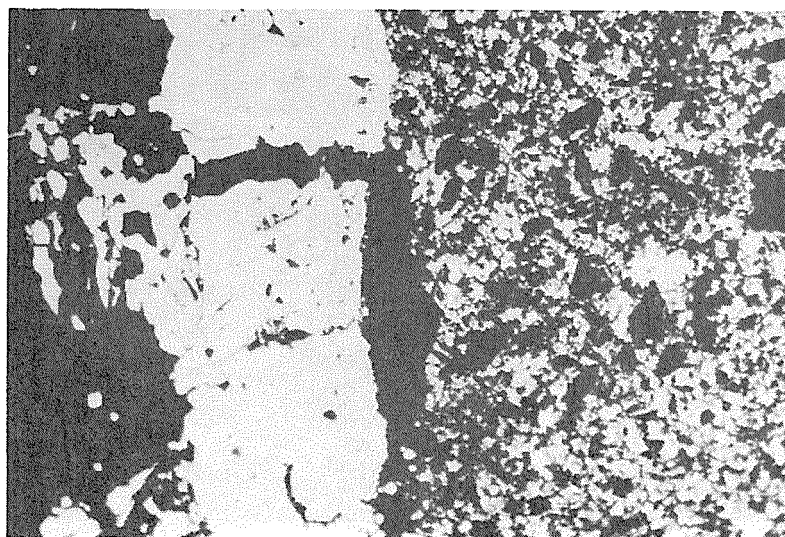


Fig. 3. Comparison of fractured vein of massive pyrite (left centre) with porous mass of pyrite (right). Late formed intergranular galena on left-hand side. Jillawarra 14 48534, 193.6 m. Field of view 0.62 mm. (Polished section.)

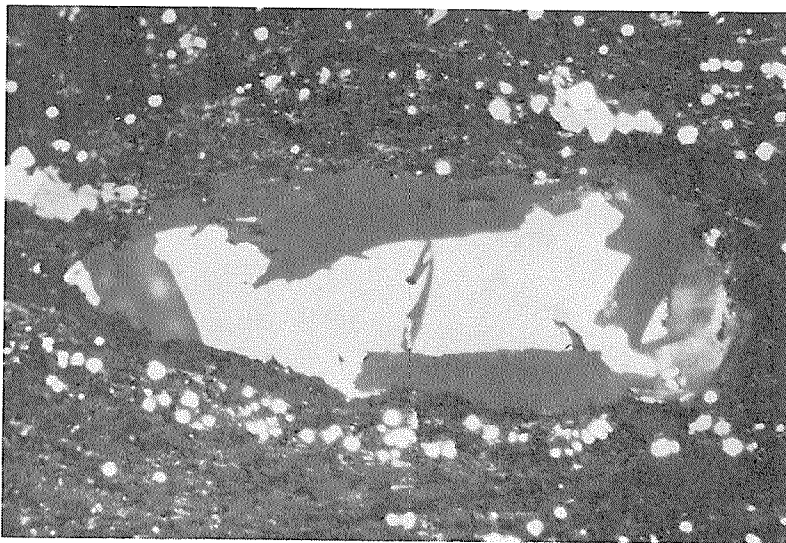


Fig. 4. Flattened pod-like body in black siltstone containing sulphides, mainly sphalerite, enclosed by quartz. Mount Vernon, V2, 42467, 86.8 m. Field of view 0.245 mm. (Polished section.)

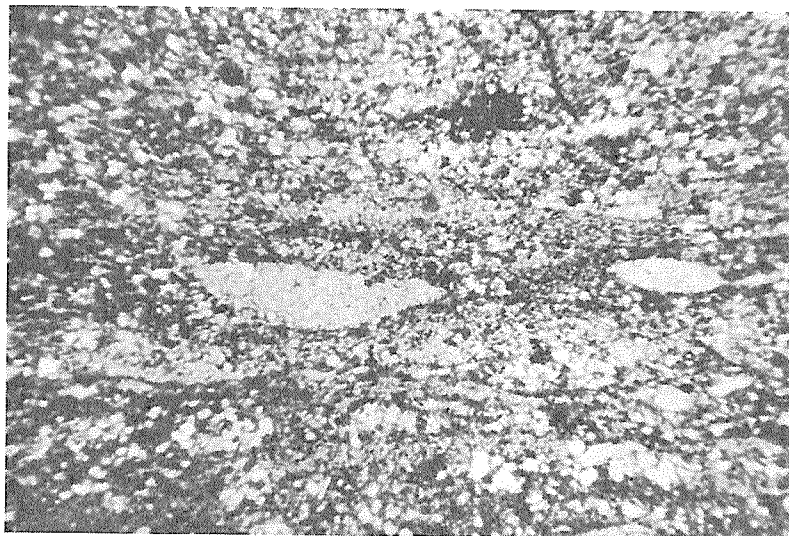


Fig. 5. Flattened clay pellets still clearly recognizable in barren siltstone. Mount Vernon V3, 42651, 61.0 m. Field of view 4 mm. (Thin section, plane polarized light.)

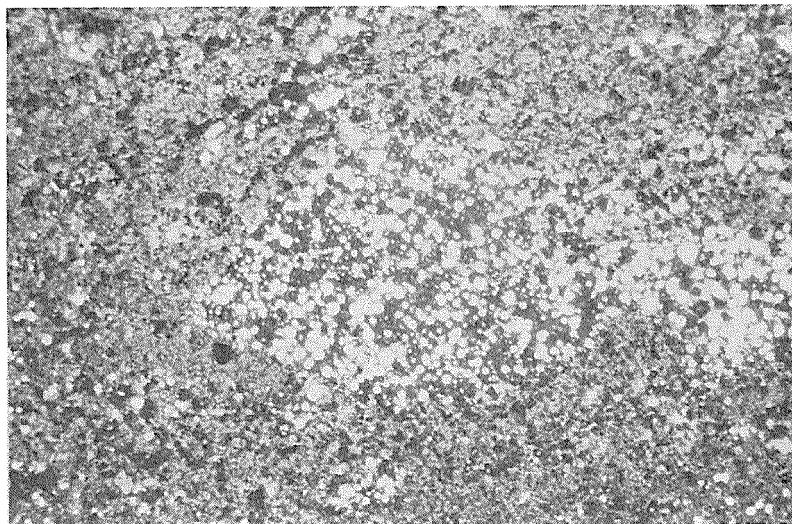


Fig. 6. Euhedra of fine-grained pyrite replacing probable dolomite. Mount Vernon V3, 42658, 109.5 m. Field of view 0.62 mm. (Polished section.)

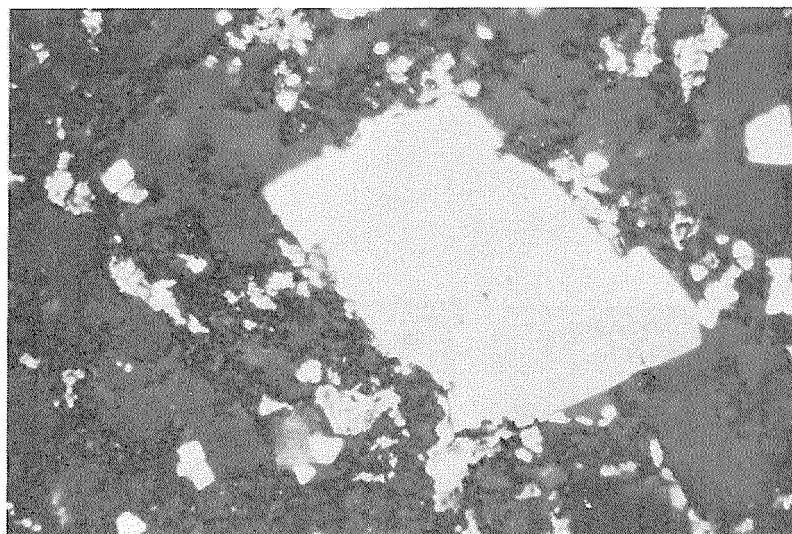


Fig. 7. Pyrite rhomb, rimmed with sphalerite, replacing probable dolomite rhomb. Mount Palgrave P13, 42686, 74.7 m. Field of view 0.245 mm. (Polished section.)

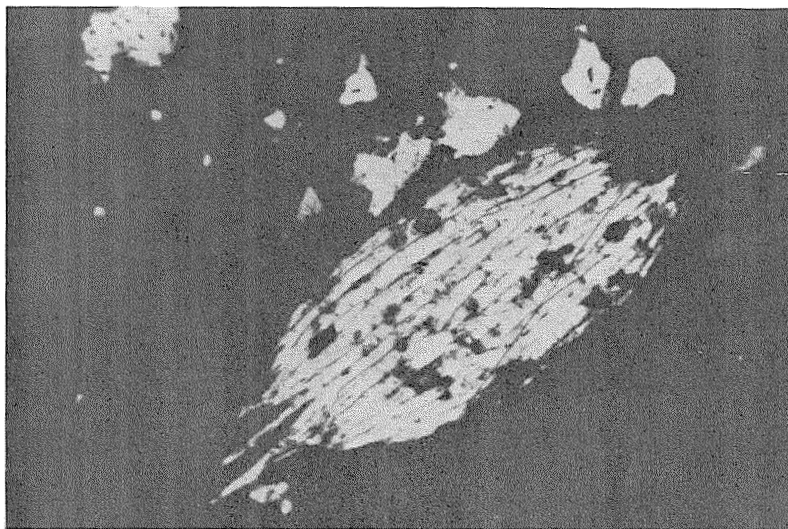


Fig. 8. Pyrite replacing phyllosilicate mineral. Mount Vernon, V2, 42472, 134.3 m. Field of view 0.245 mm. (Polished section.)

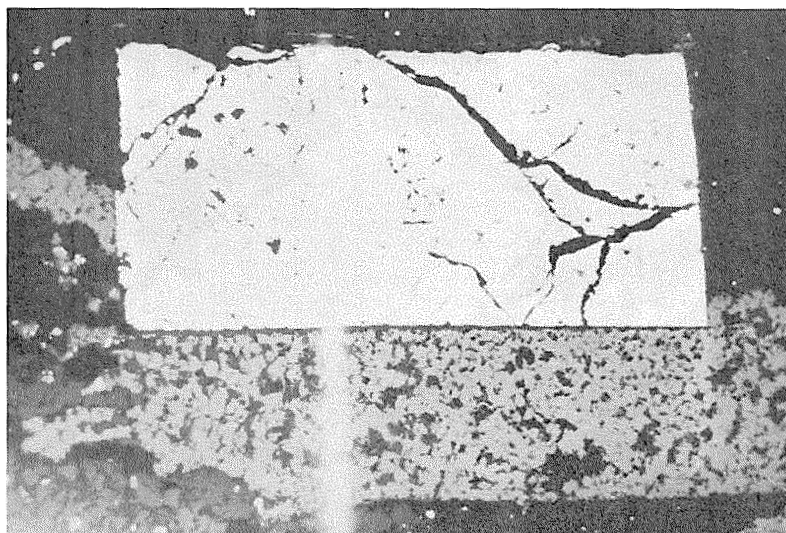


Fig. 9. Authigenic pyrite with syneresis crack. Sphalerite in the adjacent vein. Mount Palgrave P13, 42686, 74.7 m. Field of view 1.22 mm. (Polished section.)

(i) *Disseminated grains*: Small irregular grains dispersed within the siltstone and shales (Fig. 1).

(ii) *Enclosed within pods*: This type of occurrence is prominent at Mount Vernon (Fig. 4). Within the pods referred to previously (pyrite, type v), sphalerite occurs as irregular grains either alone or admixed with pyrite, quartz, opal or carbonate. Pods are up to 0.5 mm long by 0.2 mm wide.

(iii) *Within nodular masses of pyrite*: This is probably a variety of type (i) above.

(iv) *Within or marginal to authigenic pyrite*: Sphalerite here tends to occur as irregular droplets within the pyrite. The grain size is small relative to the enclosing pyrite.

(v) *In veins* (Fig. 10); Where it occurs as subrounded 'spherulitic' yellow grains up to 40 μm in diameter. Many grains have aggregated to form clusters 5 mm to 10 mm long along the sides of the veins.

TABLE 4. MORPHOLOGICAL TYPES OF SPHALERITE PRESENT IN STRATABOUND MINERALIZED (META-)SEDIMENTARY ROCKS

<i>Morphological type</i>	<i>Size</i>	<i>Quartzite Well</i>	<i>Palgrave</i>	<i>Vernon</i>
i) Disseminated	10-50 μm	✓		✓
ii) Enclosed within pods	45 μm			✓
iii) Within nodular masses of pyrite	25 μm	✓		✓
iv) Within authigenic pyrite	30 μm		✓	✓
v) In veins	40 μm	✓	✓	✓

Electron probe analyses were obtained as follows:

	<i>No. of samples</i>	\bar{x}	<i>Fe % range</i>
Mount Palgrave matrix	2	2.58	2.46-2.71
Mount Vernon matrix (V2) and pod	2	1.58	1.39-1.97
Mount Palgrave vein*	3	0.04	0.01-0.10

\bar{x} = arithmetic mean

COPPER MINERALS

No significant copper mineralization is present in these mineralized cores; however, copper sulphides are an ubiquitous but scarce accessory (Table 5).

Chalcopyrite is present within authigenic pyrite at Mount Palgrave and Mount Vernon, but at Quartzite Well, it is present only in veins enclosed by silica and as rare grains enclosed by goethite.

Covellite, which occurs as discrete grains, commonly less than 5 μ m diameter, is the most common copper sulphide. In J16, certain grains appear detrital (Fig. 11) though many have corroded surfaces, which make such identification equivocal. Some covellite grains are rimmed with chalcocite. Covellite also occurs in veins in J16 where it appears to have formed at the expense of chalcopyrite. In V2 covellite occurs within pods in a manner analogous to sphalerite and pyrite (Fig. 12).

A single occurrence of bornite was identified as a film on a pyrite grain boundary in a sphalerite-pyrite vein (P13).

LEAD MINERALS

Lead minerals were not identified in the stratabound mineralization even though trace element studies on J16 suggested their possible existence in small quantity.

* Ni and Co were determined on one grain with values of 0.04% and 0.01% respectively.

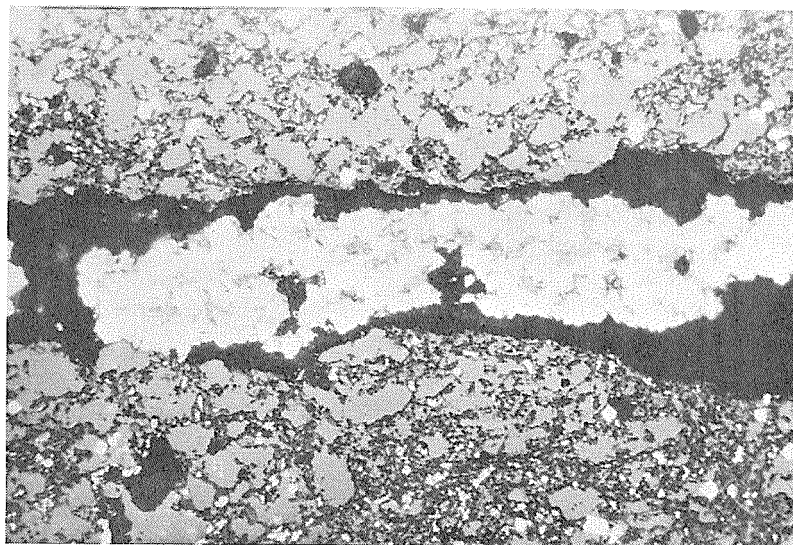


Fig. 10. Sphalerite in vein in siltstone, polished to emphasize rather spherulitic nature. Mount Palgrave Pl3, 42686, 74.7 m. Field of view 0.62 mm. (Polished section.)

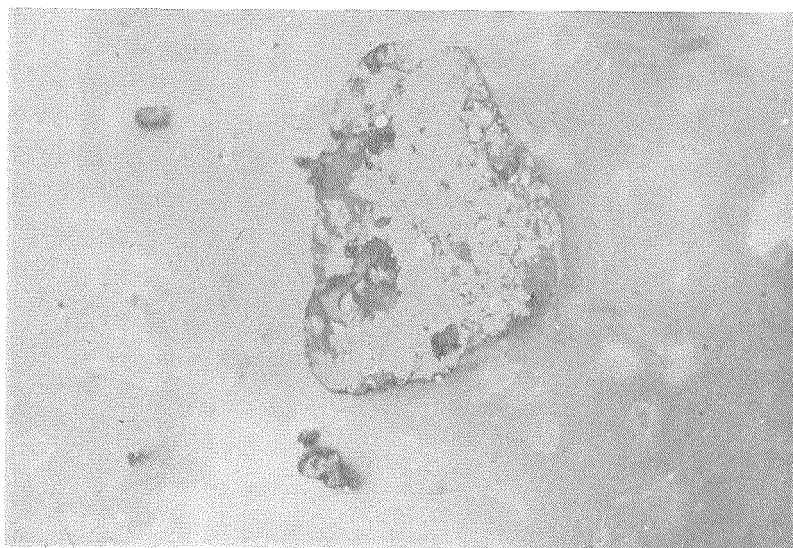


Fig. 11. Probable detrital copper sulphide in silicified siltstone. Central part is covellite, rim is probably digenite. Jillawarra J16, 48511, 116.75 m. Field of view 0.10 mm. (Polished section.)

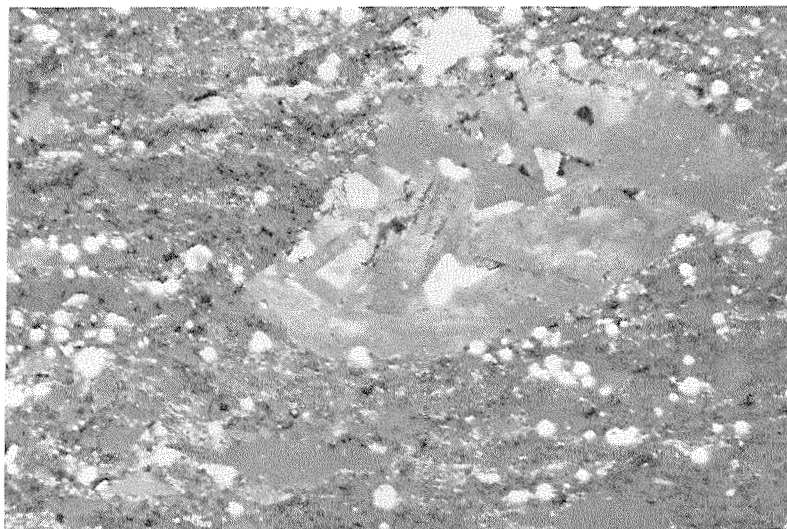


Fig. 12. Copper sulphides, mainly covellite, with minor pyrite in pod in black siltstone. Disseminated pyrite and traces of sphalerite in the matrix. Mount Vernon V2, 42467, 86.8 m. Field of view 0.245 mm. (Polished section.)



Fig. 13. Microcrystalline and sparry quartz pseudomorphing gypsum in silicified siltstone ('chert'). Jillawarra, J14, 48541, 231.1 m. Field of view 10.5 mm. (Thin section, plane polarized light.)

TABLE 5. MORPHOLOGICAL TYPES OF COPPER SULPHIDES PRESENT IN STRATABOUND MINERALIZED (META-)SEDIMENTARY ROCKS

<i>Morphological types</i>	<i>Mineral</i>	<i>Size</i>	<i>Quartzite Well</i>	<i>Palgrave</i>	<i>Vernon</i>
i) Disseminated irregular grains	Covellite	1-5 μm -(10 μm)	✓	✓	✓
ii) Irregular detrital grains	Covellite and digenite	40-60 μm	✓		
iii) Enclosed within pods	Covellite	20-25 μm			✓
iv) Within authigenic pyrite	Chalcopyrite	120 μm most 50 μm		✓	✓
v) Within goethite	Covellite Chalcopyrite	40 μm	✓		
vi) In veins	Covellite	40 μm	✓	✓	

TRACE ELEMENTS IN SULPHIDES

In the light of a review of trace elements in sulphides as indicators of ore genesis (Loftus-Hills and Solomon, 1967), the matrix pyrite, with low nickel and a low Co:Ni ratio is of sedimentary origin, whereas the authigenic grains and the vein pyrite, with very low nickel and a higher Co:Ni ratio are of diagenetic origin.

Sphalerite co-existing with pyrite contains less iron than sphalerite co-existing with both pyrite and pyrrhotite. However the iron content of the matrix sphalerite is lower than that of sphalerite occurring elsewhere in Western Australia (Marston, 1979) and is consistent with either a sedimentary or volcanogenic origin. The late-stage iron-free sphalerite is most likely to be diagenetic, or, possibly, hydrothermal in origin.

Three sulphur isotope values, (one from Pl3 and the others from Mount Vernon) in the range $\delta^{34}\text{S} = +2.5$ to $\delta^{34}\text{S} = +3.5$ are reported by Marshall (1969).

FAULT - ZONE MINERALIZATION AND CONTAINING ROCKS

Mineralization occurs in breccia near the faulted contact of the overturned pre-Bangemall rocks and the Jillawarra Formation in core J14 at Quartzite Well. The core was sampled from 100.65 m to 304 m.

The pre-Bangemall rocks consist of quartz-chlorite - iron oxide rocks, which have been extensively deformed. Relic textures suggest that the original rock may have been a ferruginous siltstone. Magnetite of metamorphic origin forms euhedra (up to 250 μm in diameter), has quartz pressure fringes, and is now partly granulated. It is partly altered to martite-hematite. Pyrite is the only sulphide.

The core intersects the major fault at 172-173 m. A second breccia zone occurs near 209 m and this zone contains the massive sulphides (pyrite, galena, sphalerite).

Other subsidiary fault zones contain sulphides, mainly pyrite. Fault induced disturbances diminish towards the bottom of the core. Vein mineralization, preponderantly sphalerite, but including some galena, occurs down to 255 m.

The present host rock for the mineralization is 'cherty' in hand specimen, and is believed to be Jillawarra Formation. In its upper part this cherty material consists of secondary silicified siltstone with relic mica, clastic K-feldspar, and prominent accessory tourmaline, zircon and altered titanium minerals. Between 227.0 m and 232.7 m the rock is a silicified evaporite which once contained clastic quartz and mica, and authigenic gypsum (Fig. 13). Gypsum is now pseudomorphed by microcrystalline or sparry quartz and, in a few places, by pyrite. Traces of barite occur in veins with quartz, pyrite, and sphalerite.

The silicified evaporite passes downwards through a sulphide-silica zone, whose textures and structures suggest it was once a gel (e.g. at 253.1 m), into stratigraphically higher (but still Jillawarra Formation) black pyritic micaceous siltstone and, near the end of the core, siderite meta-marl. No sulphides other than pyrite occur in the samples below 260 m.

SULPHIDE MINERALS IN THE FAULT ZONE, J14

Sulphide minerals in the fault zones of J14 consist mainly of pyrite, galena and sphalerite. The main zone of mineralization contains partly granulated euhedra of pyrite (up to 1 mm in diameter), either singly or in aggregate, in a matrix of sphalerite and galena (Fig.14). Sphalerite occurs in irregular masses (up to 3 mm in diameter) and single corroded grains (up to 1 mm in diameter) (Fig.15). Commonly it contains exsolved cleavage-controlled inclusions of pyrite and chalcopyrite (Fig. 16). Galena encloses and corrodes both pyrite and sphalerite in irregular poikiloblastic plates up to 10 mm long.

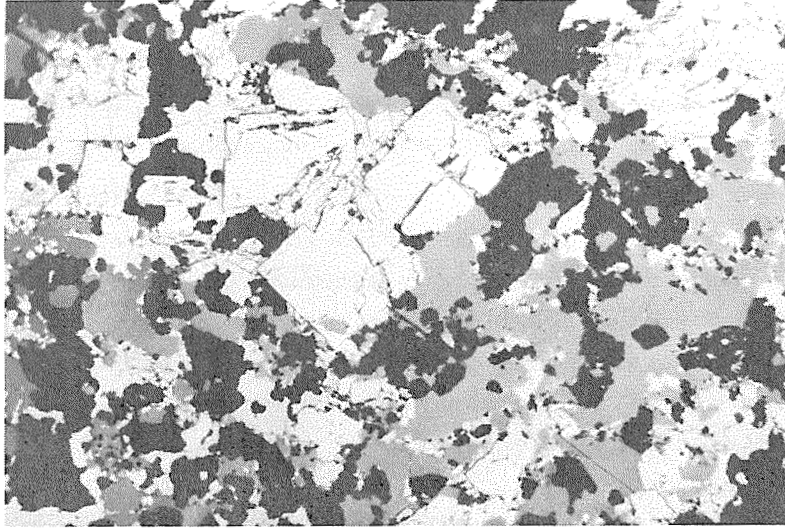


Fig. 14. Mineralization in main fault zone of J14. Photograph shows subhedral pyrite (white, bold outlines) with interstitial galena (slightly darker), sphalerite (medium grey) and quartz (black). Jillawarra J14, 48566, 208.35 m. Field of view 1.2 mm. (Polished section.)

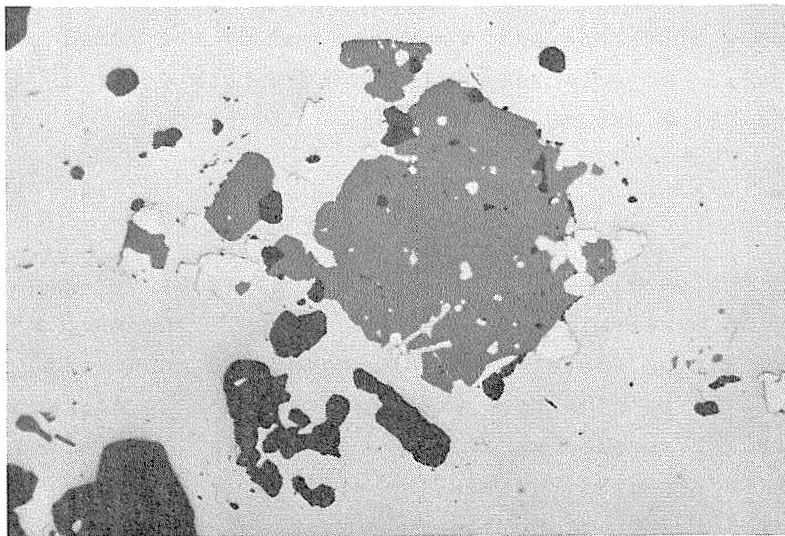


Fig. 15. Caries texture in sphalerite (medium grey) with galena (light grey) the corroding medium. White grains are pyrite, black quartz. Jillawarra J14, 48566, 208.35 m. Field of view 0.62 mm. (Polished section.)

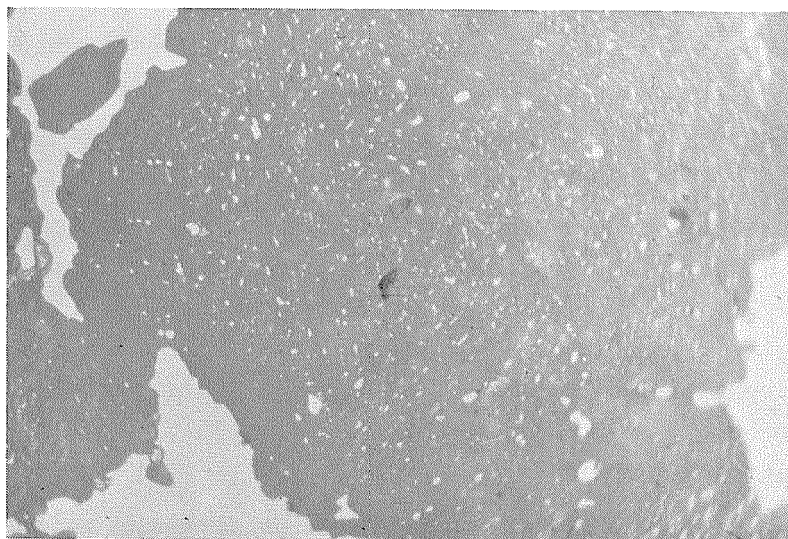


Fig. 16. Pyrite and chalcopyrite exsolution laminae in sphalerite (medium grey) indicating control of exsolution by cleavage directions. White mineral is galena. Jillawarra J14, 48566, 208.35 m. Field of view 0.10 mm. (Polished section.)

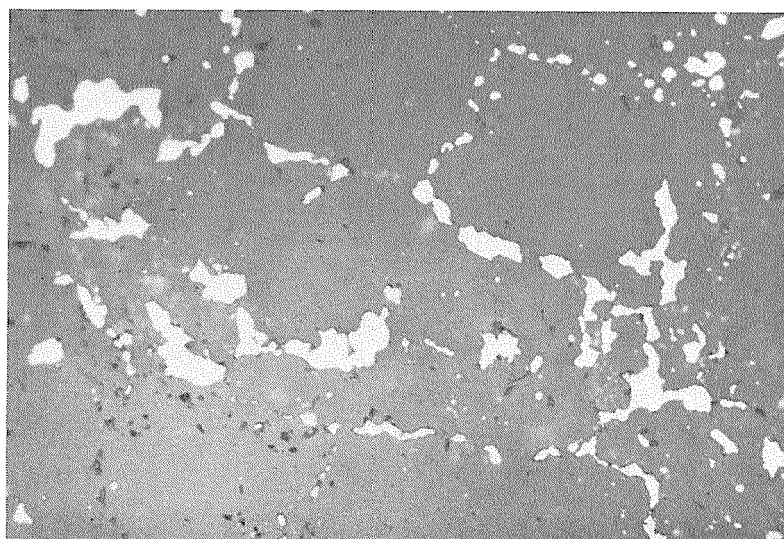


Fig. 17. Galena (white) in veinlets and intergranular fractures in secondary quartz. Jillawarra J14, 48534, 193.6 m. Field of view 0.62 mm. (Polished section.)

Sulphide rich zones at 193.6 m and 242.7 m are composed of aggregates of massive pyrite enveloped, and partly replaced by fibrous chalcedony and granular microcrystalline quartz. At 193.6 m the pyrite contains minor galena, at 242.7 m minor sphalerite.

Isolated rounded grains (<20 μm) of pale-yellow sphalerite dispersed throughout the silicified siltstone, appear primary in origin. Most sphalerite, however, occurs as irregular grains up to 150 μm in diameter in veins with microcrystalline and crystalline quartz. Away from the main breccia zones, galena occurs as small grains in veins and intergranular fractures (Fig. 17).

Electron probe analyses of grains from the main breccia ore gave results as follows:

<i>Mineral</i>	<i>No. of grains</i>		<i>Co (%)</i>	<i>Zn (%)</i>	<i>Cu (%)</i>	<i>Fe (%)</i>
Pyrite	4	\bar{x}	0.07	0.24	0.08	n.d.
		r	0.05-0.10	0.12-0.34	0.04-0.24	n.d.
Sphalerite	4	\bar{x}	n.d.	54.0	0.79	1.0
		r	n.d.	53.47-54.39	0.40-1.11	0.62-1.38

\bar{x} - arithmetic mean. r = range. n.d. = not determined.

Nickel was not detected in pyrite (<0.01%) and cadmium was not detected in sphalerite.

UNMINERALIZED ROCKS

UNMINERALIZED PRE-BANGEMALL GROUP METASEDIMENTARY ROCKS

These rocks were sampled in core J9 between 97.3 m and 149.1 m for comparison with Jillawarra Formation rocks. The pre-Bangemall rocks are partly recrystallized siltstones which are siliceous between 97.3 m and 136.25 m, and are carbonated thereafter. The carbonate siltstone contains zones of limestone and intraformational limestone breccias.

Pyrite is the only sulphide. Primary sedimentary textures such as graded bedding, truncated bedding, cross-bedding, slumping and low-angle microfaults are preserved. Dendritic aggregates of pyrite, the largest some 20 mm by 10 mm, have grown, apparently by diffusion, from bedding fractures, particularly between 97.3 m and 116.8 m.

DEPOSITIONAL CONDITIONS OF THE SEDIMENTARY ROCKS AND DISCUSSION OF THE ORIGINS OF THE STRATABOUND MINERALIZATION

GEOLOGICAL EVIDENCE OF DEPOSITIONAL CONDITIONS

Geological evidence suggests that the Glen Ross Shale Member and the Jillawarra Formation were, in general, deposited in low-energy, shallow-water, mainly marine conditions, in a near-shore environment (Brakel and Muhling, 1976). Evidence for shallow-water deposition is provided in thin section by small-scale graded bedding, cross-bedding, small scour and fill structures, the presence of recrystallized mud pellets, and intraformational breccias. Elsewhere in the Jillawarra Formation stromatolites are believed to have grown in inter-tidal or marginally subtidal conditions (K. Grey, pers. comm.). Muhling and Brakel (in prep.) believe that, in general, deposition took place on an open marine shelf, in the vicinity of wave base.

The mineralization at Quartzite Well occurs in rocks of different lithology from those at Mount Palgrave and Mount Vernon, and at Quartzite Well the depositional environment was probably evaporitic.

CHEMICAL EVIDENCE OF DEPOSITIONAL CONDITIONS

Boron-gallium-rubidium (B-Ga-Rb) diagrams have already been related to depositional conditions based on sedimentological and stratigraphic studies (Davy and others, 1978). It is now pertinent to consider the depositional conditions of the host rocks of mineralization as revealed by those diagrams (Figs 18-23).

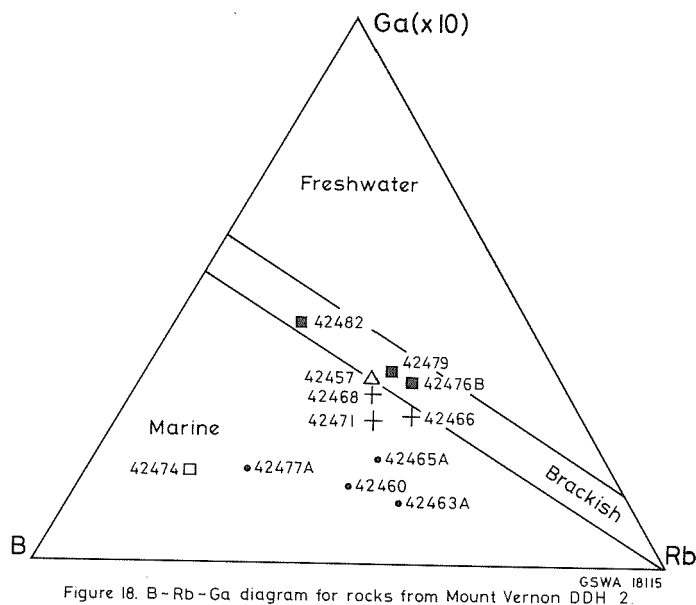


Figure 18. B-Rb-Ga diagram for rocks from Mount Vernon DDH 2.

- Unmineralized black shale
- Carbonate siltstone
- + Mineralized black shale
- Limestone
- △ Weathered shale

Boundaries of marine-brackish-freshwater field set by Degens and others 1958

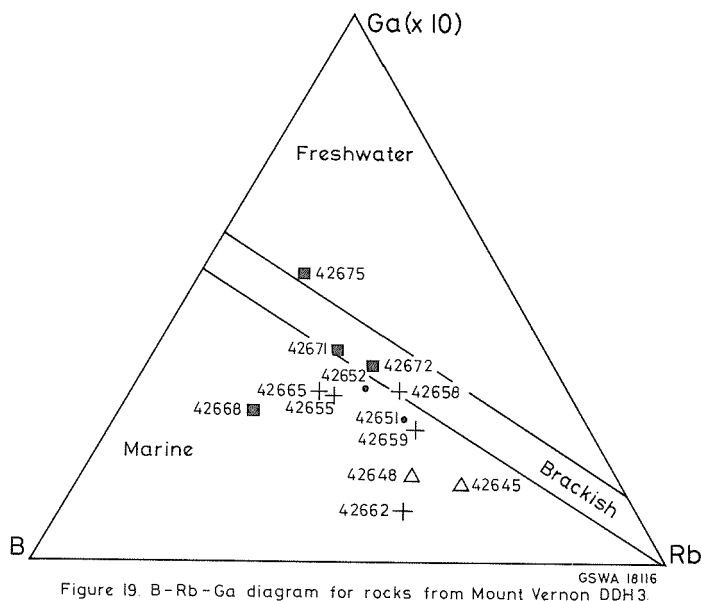


Figure 19. B-Rb-Ga diagram for rocks from Mount Vernon DDH 3.

In V2, V3 and P13 (Figs 18-20) the mineralized black shale-siltstone plots as marine, as does most of the slightly altered shale-siltstone. However the barren carbonate siltstone at Mount Vernon (which, as already noted, lacks pyrite and appears to be oxidized) plots in the brackish water area. The two very micaceous samples in P13 plot in the freshwater field.

In J16, the carbonate-rich sediments hosting mineralization appear to have formed in a brackish-to-marine environment (Fig. 21). The diagram may not indicate open marine conditions, but rather hypersaline depositional conditions. The diagram for J14 is given in Figure 22. In terms of the origins of both rocks and mineralization, this diagram is less useful because of the undoubted redistribution of metal sulphides into the fault zones - caused by metamorphism in the case of the pre-Bangemall rocks and by silicification of the sedimentary rocks enclosing the mineralization. The inferred hypersalinity of the zone containing pseudomorphed gypsum is not reflected in the diagram. The relatively unaltered sedimentary rocks (48546A-553B) plot in the brackish-to-fresh-water zones.

Deposition conditions of the unmetamorphosed pre-Bangemall rocks of J9 are shown in Figure 23.

In summary, sedimentological, chemical and mineral evidence shows that the sediments hosting the stratabound syngenetic mineralization were formed in highly reducing conditions, in shallow marine water.

NATURE OF THE MINERALIZATION

A genetic sequence is evident for pyrite and for sphalerite in the stratabound mineralization.

The sequence for pyrite is threefold: syngenetic, diagenetic and diagenetic/hydrothermal. The dispersed pyrite is believed to be syngenetic; it is stratigraphically

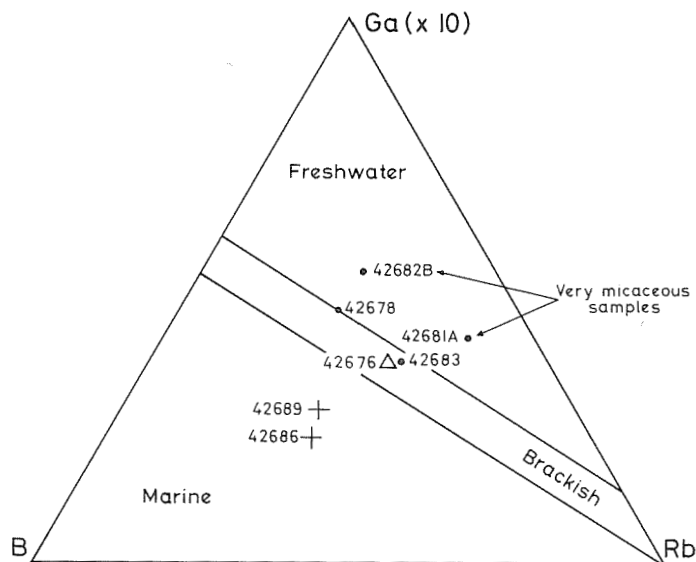


Figure 20 B-Rb-Ga diagram for rocks from Mount Palgrave DDH 13

- Unmineralized black shale/siltstone Δ Weathered shale
- + Mineralized black shale

controlled and there is no evidence for introduction of this type of pyrite. A second, diagenetic phase is shown by the pyrite pseudomorphs after carbonate and phyllosilicates. This replacement is believed to have occurred early in the life of the rocks and the replacing pyrite is a high-nickel variety, comparable to the disseminated pyrite. The syngenetic and diagenetic phases may have been, in effect, simultaneous - with growth and replacement occurring together. The third phase is the vein and authigenic pyrite, which is low in nickel. This is quite clearly later than the first two phases. Additional electron probe analyses are needed to assign a position to the other varieties of pyrite; however, they all appear to be related to the first two phases.

The sphalerite shows only two phases. The disseminated and pod-enclosed sphalerite are syngenetic or possibly very early diagenetic. The second phase is the vein

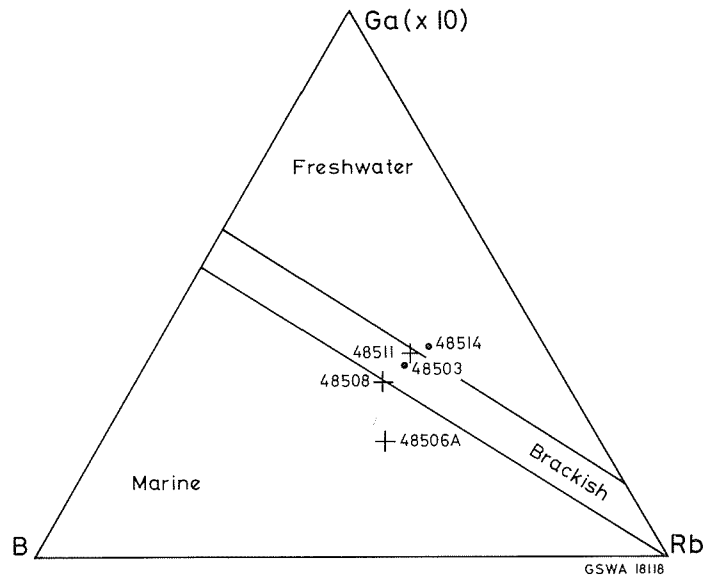


Figure 21. B-Rb-Ga diagram for rocks from core Jillawarra 16

+ Mineralized siltstone • Less mineralized siltstone

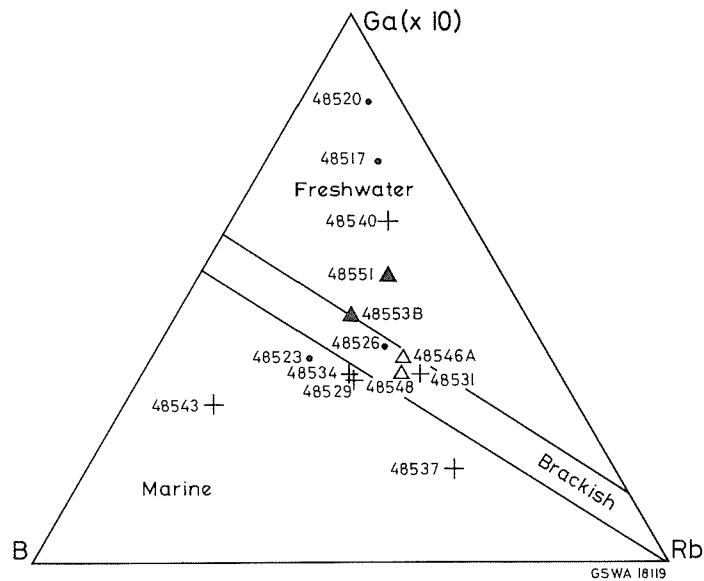
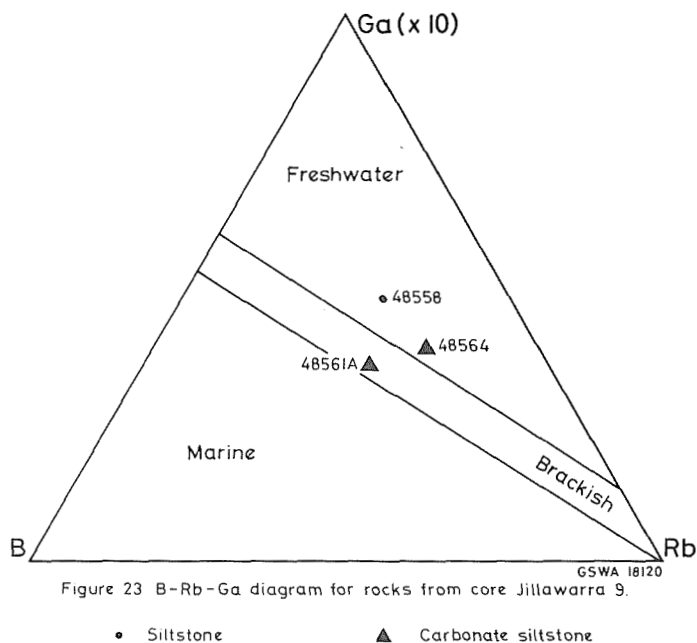


Figure 22. B-Rb-Ga diagram for rocks from core Jillawarra 14.

• Quartz-chlorite-magnetite rock ▲ Carbonated siltstone shale
+ Mineralized silicified zone △ Siltstone shale, no carbonates



sphalerite, with low iron content, of diagenetic or hydrothermal origin.

SOURCE OF THE SULPHIDES

No ultimate source of the mineralization has been identified. No products of volcanic activity were identified near any of the three localities, and, in any case, the minor-metal content and the low Co:Ni ratio of the nickel 'rich' pyrite suggest a sedimentary origin for this mineral (Loftus-Hills and Solomon, 1967). The $\delta^{34}\text{S}$ values reported by Marshall (1969) are also consistent with a sedimentary origin.

The mineralization is restricted to certain stratigraphic levels and the following sources are possible:

- (i) leaching from adjacent country rock, above, below or laterally;
- (ii) detrital input from rivers during sedimentation;

- (iii) precipitation, during sedimentation, from sea water of base-metal ions introduced to the area either by river waters or by upwelling ocean currents;
- (iv) precipitation from mineralized connate waters.

Geochemical data on pre-Bangemall rocks are only available for the two cores, J9 and J14 (in part), and do not encourage belief in leaching from older rocks. The rocks have low background values of base metals, though they are rich in iron. All cores from the Jillawarra area are, however, slightly enriched in barium compared with those from the Mount Vernon and Mount Palgrave areas. The covellite and/or chalcocite grains in J16, which are believed to be detrital, can only be derived from topographic highs of pre-Bangemall rocks at the edge of the "Bangemall Sea".

Upwelling of oceanic waters has been cited by Vine (1969) as the source of low-grade zinc mineralization in black shales of the Phosphoria Formation of Wyoming. An apparent consequence of upwelling waters is a high phosphate content. There is no evidence to support this hypothesis in the Bangemall Group.

The majority of the sulphide appears to have been precipitated in place, but it cannot be determined whether the source was sea, river, or connate waters. Mineralization from waters such as these (except sea water) must have come from the lowest Bangemall Group during compaction, or from erosion of pre-Bangemall basement rocks.

DEPOSITIONAL CONDITIONS FOR THE SULPHIDES

Stratabound mineralization

The primary mineralization formed in strongly reducing conditions. Eh/pH diagrams in Garrels and Christ (1965, p.230, 399) suggest that the assemblage chalcopyrite-pyrite-sphalerite(-galena) may have formed at an Eh of about -400 mv, with pH in the range 6-9. The presence of covellite which has replaced chalcopyrite except where this mineral

has been protected by impervious silica suggests that, since deposition, the Eh has risen slightly and the pH decreased. The difference between the Quartzite Well (J16) host rock (abundant siderite, and minor sulphide and free carbon) and the host rocks of Mount Palgrave and Mount Vernon (P13, V2, and V3) (much sulphide and free carbon, and very little carbonate) lies more in the relative availability of sulphide and carbonate ions than in the physico-chemical conditions of deposition.

Deposition has probably been caused by sulphate-reducing bacteria, known to be in existence long before Bangemall time (Chukrov and others, 1970). Formation of the metal sulphides was probably assisted at Mount Palgrave and Mount Vernon by the abundant organic materials, which would trap metal ions by adsorption.

Vein mineralization

At all localities this mineralization represents the last, low-temperature diagenetic movement of the sulphides. Sphalerite has been more mobile than pyrite, which in turn has been more mobile than the copper minerals.

The source of the vein mineralization is believed to be the stratabound sulphide. This is supported by mineralogical investigations. Thin and polished sections reveal a zone of sulphide depletion in the vicinity of the veins.

Fault-zone mineralization

This mineralization probably formed at higher temperatures and pressures than the stratabound mineralization. However, there is a total absence of diagnostic mineral assemblages to indicate temperature and pressure conditions.

The source of the breccia mineralization is considered to be the adjacent stratabound mineralization (e.g. J16 type) which contains all the base metals of the fault-zone mineralization though in greatly reduced quantity.

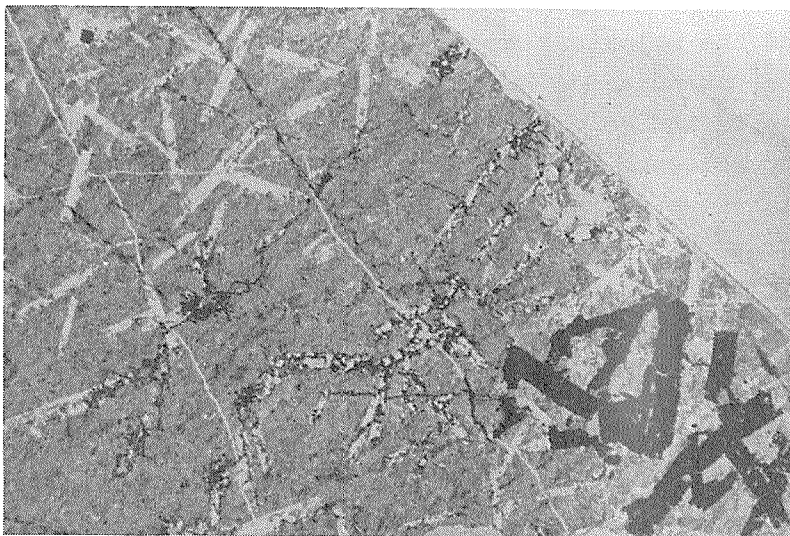


Fig. 24. Pyrite (and silica) pseudomorphs after gypsum in sili-
cified siltstone ('chert'). Jillawarra J14, 48540, 230.15 m.
Field of view 1.5 cm. (Thin section, plane polarized light.)

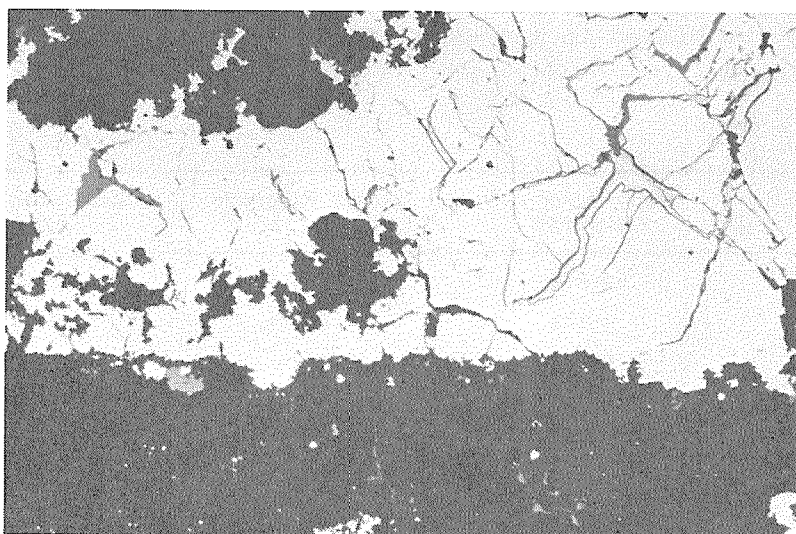


Fig. 25. Enlarged polished section of lower right hand part of
Fig. 24 showing galena (very light grey) and sphalerite (medium
grey) filling syneresis cracks in pyrite (white, itself pseudo-
morphing gypsum). Jillawarra J14, 48540, 230.15 m. Field of
view 1.2 mm.

The apparent paragenesis is complicated by the behaviour of the sulphides under strain. Pyrite displays marginal granulation without recrystallization, whereas sphalerite and galena have recrystallized after deformation. Further evidence for late stage movement of the lead and zinc is shown in the lower part of the J14 mineralized core. Gypsum is replaced by silica and pyrite, and galena and sphalerite fill the shrinkage (syneresis) cracks in the pyrite (Figs 24, 25).

OTHER CHEMICAL CONSIDERATIONS

COMPARISON OF THE CHEMISTRY OF THE MINERALIZED SEQUENCES

The rock chemistry of the three mineralized sequences is different. Though there is a scatter of values (with overlap between the sites) the mean values for almost all constituents are appreciably different in the three localities.

Differences are highlighted in the summary table (the ranges are biased in favour of the most common values) given below:

	<i>Mount Vernon(a)</i> (V2-V3)	<i>Mount Palgrave</i> (P13)	<i>Quartzite Well</i> (J16)
SiO ₂	50-80%	50-80%	50-90%
Al ₂ O ₃	4-17%	10-30%	3-11%
Fe ₂ O ₃ ^(b)	5-17%	2-8%	<1-20%
MgO	1-3%	0.6-1.3%	0.5-4%
CaO	0.4-1.4%	<0.1%	<0.1-2.5%
Na ₂ O	<0.3%	<0.2%	<0.3%
K ₂ O	2-4.5%	2.2-7%	0.8-3.5%
C	2-7%	0.5-5%	0.1-0.5% (-3.4%)
CO ₂	almost absent	almost absent	'absent' - 12%
P ₂ O ₅	0.15-0.8%	<0.1%	<0.25%
S	0.5-9%	1-4%	0.2-2.5% (-43%)

	<i>Mount Vernon(a)</i> (V2-V3)	<i>Mount Palgrave</i> (P13)	<i>Quartzite Well</i> (J16)
Cu	100-1500 ppm	50-250 ppm	5-100 ppm (-340 ppm)
Pb	<30 ppm	<50 ppm	20-700 ppm
Zn	200 ppm - 1%	30 ppm - >2%	400-5000 ppm
Ni	80-300 ppm	50-1000 ppm	<80 ppm
Mn	<100 ppm	<30 ppm	< 50-5000 ppm
V	200-1200 ppm	150-800 ppm	20-250 ppm
U	2-20 ppm	2-15 ppm	<1 (-8 ppm)
Li	20-35 ppm	25-80 ppm	20 ppm
Ba	150-300 ppm	100-250 ppm	1000-5000 ppm
Sr	10-50 ppm	<30 ppm	<30 ppm
Rb	70-250 ppm	70-370 ppm	35-150 ppm
B	80-215 ppm	75-155 ppm	30-115 ppm
Ga	7-17 ppm	8-32 ppm	3-13 ppm

(a) Excluding 3 very siliceous rocks in V3

(b) Total iron expressed as ferric oxide

Figures in brackets indicate isolated unusually high values.

* * *

Differences between Quartzite Well and the other two localities (e.g. in C, CO₂) reflect differences in the environment of deposition and in the provenance of the constituents. Differences between P13, V2, and V3 reflect mainly variations in the nature of source materials.

R-mode cluster analysis has been used to examine the relationships of the analysed constituents, in particular of the base metals. Diagrams for the mineralized sequences of V2, P13, and J16 are given in Figures 26-28. The diagram for V3 closely resembles that for V2 and is not reproduced. SiO₂ is omitted from the diagrams since in chemical analyses which sum to 100% its value represents 100 less the sum of all other constituents and it cannot be considered as an independent variable.

The patterns for V2 and P13 suggest that there are fundamentally two groups of minerals, phyllosilicates

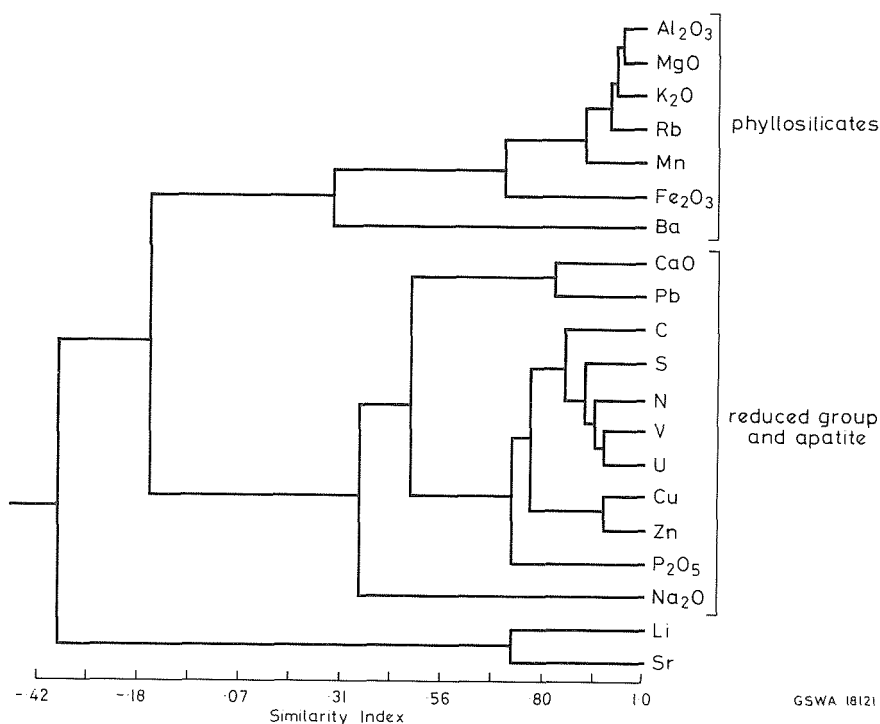


Figure 26 R-Mode Cluster Analysis for mineralized shale, Mt Vernon, V 2

represented by Al_2O_3 , MgO , K_2O , Rb , Ba and a 'reduced' group of minerals including C , S , Ni , Zn , V , Cu , P_2O_5 . Some constituents show spurious relationships because they combine low absolute values with high analytical scatter near the detection limits, and the increments of analytical determination are, in any case, too wide. In these cases, the data represent in only a very generalized way the behaviour of these constituents. Examples of such constituents include Na_2O and Pb (both cores) and CaO , P_2O_5 and Mn in Pl3. The cause of the separation of Li and Sr in V2 is not clear, in V3 Sr is related to CaO and P_2O_5 (presumably as apatite) and Li is found in the phyllosilicate grouping.

The base metals Zn , Cu , Ni are in the 'reduced' group of both V2 and Pl3. In Pl3 the relationship of C with S , Ni and Zn strongly suggests that carbonaceous material, i.e. organic remains, may have promoted deposition of the

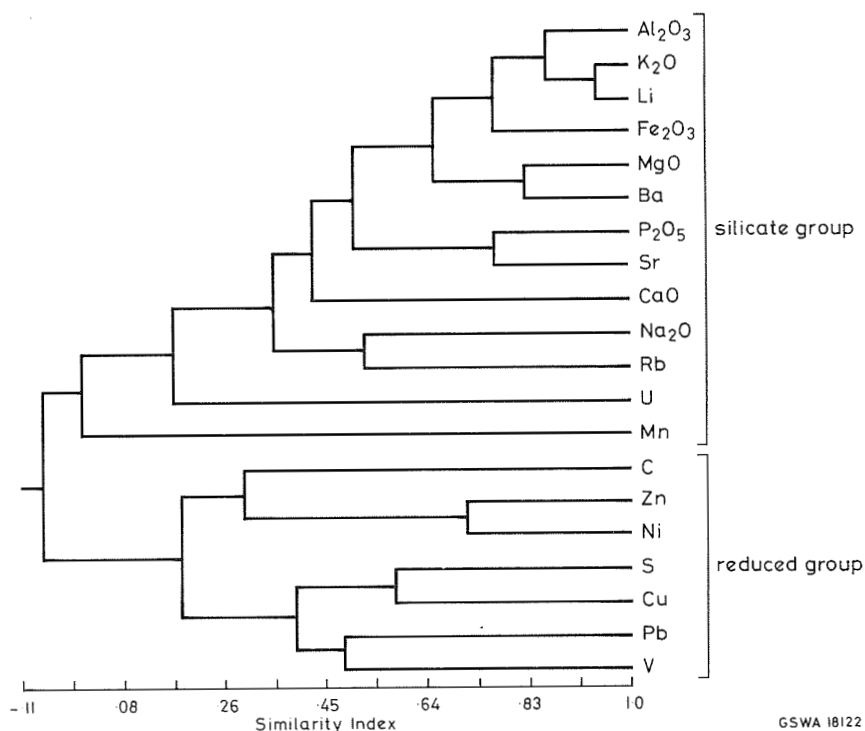


Figure 27 R-Mode Cluster Analysis for mineralized shale, Mt. Palgrave, P13.

pyrite and sphalerite. Cu is closely related to Zn in V2, but less so in P13, suggesting that there may be differences in mode of Cu deposition between the two occurrences. Pb is apparently associated with CaO in V2 (possibly as apatite), with Rb - and hence the phyllosilicate group - in P13; certainly no galena was detected in any polished section from V2, V3 or P13.

The clustering for J16 shows an excellent division in terms of mineral components. Major groups can be isolated corresponding to the minerals kaolinite-chlorite, apatite, ?hematite, siderite, (? + sphalerite), muscovite, and a sulphide group (excluding Zn). Li and U appear unrelated to any minerals because of their flat and low distribution.

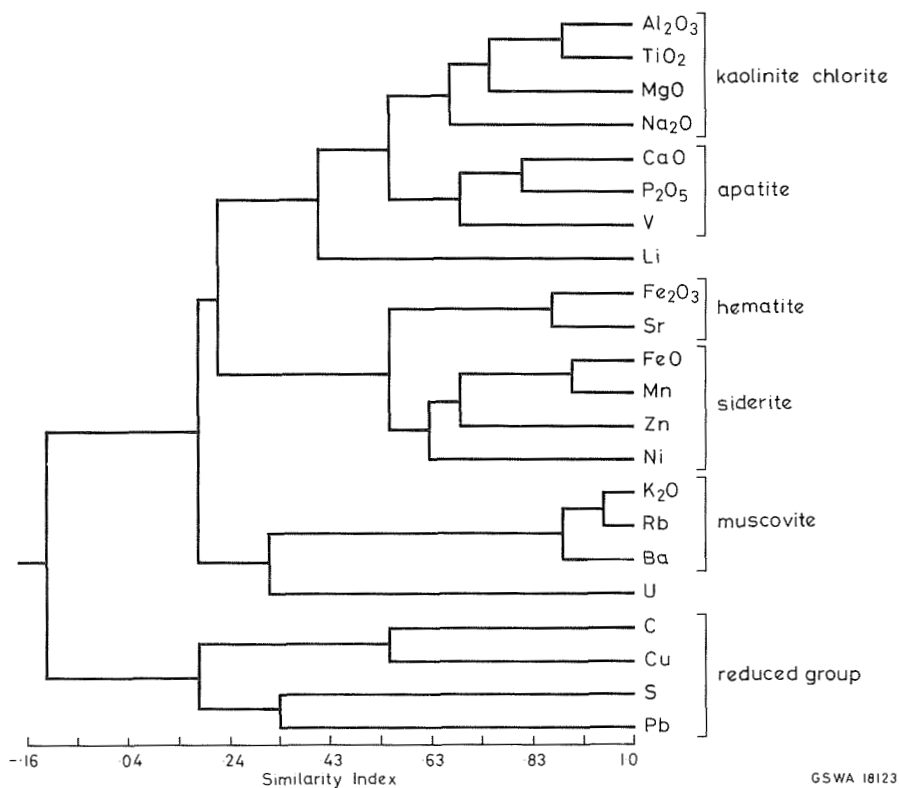


Figure 28 R-Mode Cluster Analysis for mineralized siltstone Quartzite Well, J16

The feature of the base metals in J16 is that, though Pb and Cu are related to S and C (sulphides whose precipitation may have been assisted by organic matter), Zn and Ni are found in association with FeO and Mn in the siderite group, and there does not always appear to be enough S for sphalerite formation (Appendix D, sample 48507). It is probable that Zn and Ni were originally precipitated in the carbonate lattice. During diagenesis Zn at least tended to migrate and capture all available sulphide.

COMPARISON OF THE BLACK-SHALE SEQUENCE (V2, V3, P13) WITH BLACK SHALES REPORTED BY OTHER WORKERS

There is little literature on mineralized carbonate shales-siltstones of the J16 type, and these are not discussed further.

The shales at Mount Palgrave and Mount Vernon would be classed by Pettijohn (1975) as very mature chemically because of their very low Na_2O content and a low $\text{Na}_2\text{O}:\text{K}_2\text{O}$ ratio; but the Palgrave shales with their very low Na_2O , CaO , P_2O_5 and Mn values are unusual.

Vine and Tourtelot (1970) proposed a measure of the degree of mineralization in black shales, called an 'enrichment index', to allow comparisons between black shales. A shale sample was defined as 'metal enriched' if any minor metallic element exceeded in value the value of the 90th percentile of the cumulative frequency for that element as measured in a large number of samples. The value of the 90th percentile is considered the upper limit of normality. The element enriching index is the percentage of samples for a given element which exceed in value the 90th percentile for that element (e.g. a suite of shales with 7 out of 50 samples 'metal enriched' in copper would have a copper enrichment index of 14). The overall enrichment index is formed by summing the percentage of samples for a given rock unit, or for a nominated suite of rocks, which are metal enriched with respect to a set of minor trace elements measured on a large reference number of samples.

A comparison of the Mount Palgrave and Mount Vernon shales (grouping the 'less oxidized' with the 'unoxidized' black shales at Mount Vernon) with rocks from the USA cited by Vine and Tourtelot (1970) and from Queensland cited by Duff (1976) and from Smith and Walker (1971) (adjusted so that the same elements are measured as in the present study) is given in Table 6. The overall enrichment index is higher at Mount Vernon than at Mount Palgrave. With one exception the examples of Vine and Tourtelot (1970) data cited are those sets which show the greatest similarity to the Bange-mall rocks. The rocks suites illustrated in columns 4 to 8 of Table 6 are believed to have formed either on shallow marine shelves or in embayments on a shallow marine shelf (Vine and others, 1969; Vine and Tourtelot, 1970; Duff, 1976 and Smith and Walker, 1971). The exception, the Belden Shale (Table 6 column 11) gives a pattern of metal

TABLE 6. COMPARISONS OF THE MINOR-ELEMENT-ENRICHMENT INDEX; FOLLOWING THE PATTERN OF VINE AND TOURTELOT (1970), BUT MODIFIED BY AVAILABILITY OF DATA

Element	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Cu	(a) 65	21	21	22	14	71	19	-	53	70	-	6
Pb	-	-	-	-	-	10	21	-	-	80	7	50
Zn	35	57	14	32	56	22	11	18	32	60	-	25
Ni	35	21	29	57	23	69	-	7	72	-	-	-
Mn	-	11	-	-	-	10	6	11	-	100	28	31
V	47	7	-	73	30	-	-	7	-	-	-	-
U	12	-	-	-	80	-	-	-	-	-	-	-
Li												
Ba	-	-	-	-	-	-	-	-	-	-	-	81
Sr	-	-	-	-	49	-	-	11	-	-	-	-
Rb												
B	17	20	14	-	-	-	-	11	43	-	30	-
Ga	-	-	14	-	-	-	36	39	-	-	28	-
SUM (=ENRICHMENT INDEX)	(b) 211	137	92	184	252	182	93	104	200	310	93	193

(a) Element-enrichment index for copper.

(b) Overall enrichment index for all analysed elements (sum of individual indices).

Samples are defined as metal-enriched if they exceed the 90th percentile value as computed by Vine and Tourtelot (1970)

A dash indicates no sample is metal-enriched. A space indicates not sought in the study.

BANGEMALL BLACK SHALES

- (1) Mount Vernon DDH-2 all shales (n = 17)
- (1) Mount Vernon DDH-3 all shales (n = 14)
- (3) Mount Palgrave DDH-13 black shales (n = 14)

BLACK SHALES IN THE USA, DEPOSITED IN SHALLOW STABLE MARINE CONDITIONS (MODIFIED FROM VINE AND TOURTELOT 1970)

- (4) Mecca quarry shale (n = 37)
- (5) Meade Peak Shale (n = 43)
- (6) Houy Formation (n = 51)
- (7) Cherokee Formation (n = 47)
- (8) Heath and Tyler Formations (n = 28).

SHALES FROM QUEENSLAND DEPOSITED IN A SHALLOW MARINE EMBAYMENT

- (9) Corella Formation (Duff, 1976) (n = 70)
- (10) Urquhart Shale (Smith and Walker, 1971) (n = 10)

BLACK SHALE DEPOSITED IN RAPIDLY SUBSIDING TROUGH

- (11) Belden Shale (Vine and Tourtelot, 1970) (n = 43)

FOR COMPARISON, SHALE OF JILLAWARRA 16

- (12) Jillawarra J-16

enrichment quite dissimilar to that of the Palgrave and Vernon shales. This rock is a shale deposited by rapid dumping and burial in a 'quickly' subsiding trough (Vine and Tourtelot, 1970). The conclusion to be drawn from this comparison is that the Bangemall black shales fall within that group of sedimentary rocks deposited on a shallow epicontinental marine shelf, which are universally recognized as having potential for mineralization (e.g. Park and MacDiarmid, 1970; Stanton, 1972 p.508,519).

POSSIBLE INDICATOR ELEMENTS FOR USE IN PROSPECTING

Copper staining and pyrite gossans at Mount Vernon and Mount Palgrave encouraged consideration of the areas as copper prospects (Marshall, 1969; Westfield Minerals (W.A.) N.L. Ann. Rept for 1966). However analysis of near surface rocks in V2, V3 and Pl3 suggested no anomalous concentrations of copper. Notwithstanding this, copper is retained in the near surface environment. Though it may migrate some distance laterally, it is readily precipitated by carbonate-bearing waters in near neutral solutions, and the solubility of Cu in aerated water at pH 7.0 is only 64 mg/L (ppm) (Garrels and Christ, 1965). At pH 8.0, the solubility is one-tenth of this value. Copper may therefore be an excellent indicator of mineralization.

Though the main base-metal mineral is sphalerite, zinc is not normally recommended as a geochemical exploration indicator, as it is very mobile under ambient conditions - more so than copper. Concentrations 'considerably exceeding' 1 ppm in solution are stable at pH 7.0 (Sillen and Martell, 1964; Hem, 1970) and the leached zinc can travel considerable distances. Nevertheless zinc occurs in the highly oxidized zone in core DDH 1 at Mount Vernon in concentrations up to 2200 ppm (Westfield Minerals (W.A.) N.L. Ann. Rept for 1966). The location of the zinc has not been identified; it is probably adsorbed on clay.

Lead was not found in above background values in the near surface samples examined (V2, V2, Pl3 only). Any lead mineralization which reaches the surface should be

identifiable, since lead compounds are not very soluble in neutral water though they are substantially more soluble than copper at this pH.

The identification of nickel in pyrite suggests that this element will be useful as an indicator of bodies of sulphide within black shale. However, not all pyrite masses contain base-metal sulphides. Nickel is therefore only an indirect indicator of other base metals. Even within the pyrite, the concentration of nickel varies, and it is necessary to re-examine nickel anomalies even when the anomaly:background ratio is low. High nickel values in gossans and related rocks will almost certainly represent nickelian pyrite.

Other elements identified as of potential value for prospecting are silver, which occurs with the sphalerite mineralization at Mount Vernon and Jillawarra, and possibly barium. Mineralization at Jillawarra is accompanied by high barium values (to 0.59%), but at Mount Palgrave and Mount Vernon, barium occurs only in background quantity.

CONCLUSIONS

(i) The greater part of the mineralization studied at Mount Vernon, Mount Palgrave and Quartzite Well consists of syngenetic sulphides formed initially in unconsolidated sediments, in a strongly reducing environment. The mineralization is very low grade and is sub-economic.

(ii) The host rock of the mineralization at Quartzite Well is siltstone and carbonate siltstone of moderate energy interspersed with evaporites. These were deposited in a shallow, restricted marine basin or in an enclosed lagoon.

The host rocks of mineralization at Mount Palgrave and Mount Vernon are black shale and siltstone deposited in shallow marine conditions on a continental shelf.

(iii) The main mineral of potential economic significance is sphalerite, a variety low in iron. It is restricted to black shales and siltstones at Mount Vernon and Mount Palgrave, and to siltstones at Quartzite Well. Trace amounts of copper sulphides, mainly covellite, occur over a slightly wider stratigraphic interval than the sphalerite. Lead minerals are present at Quartzite Well. Pyrite is the only other sulphide present.

Primary mineralization was syngenetic, but was modified on compaction. Later diagenetic activity has mobilized sphalerite and pyrite into veins. Covellite has developed from chalcopyrite during diagenesis, but has not been mobilized into veins.

Fault-zone mineralization (pyrite, galena and sphalerite) at Quartzite Well has been derived from the stratabound mineralization by mobilization of sulphides from the sedimentary rocks.

(iv) No material of volcanic origin has been found in the material studied. The most probable source for the sulphides is either connate or palaeo-river (spring) water, but detrital copper sulphides are present in the stratabound zone at Quartzite Well. The source of these sulphides is thought to have been a nearby pre-Bangemall basement topographic high.

(v) There are appreciable differences in the overall chemistry of the mineralized Bangemall sequences. This is attributed to a varied provenance for the constituents and, comparing the Quartzite Well area with the other two sites also reflects differences in the environment of deposition.

At Quartzite Well, zinc (and nickel) were originally co-precipitated with siderite. At Mount Vernon and Mount Palgrave they form part of a group of 'reduced' constituents including carbon, and it is considered that organic matter probably played a major part in the precipitation of base metals at these localities.

(vi) The black shales of the Mount Vernon and Mount Palgrave areas have a pattern of anomalous trace-element

chemistry closely similar to the Mecca Quarry Shale (U.S.A.) and to the Corella Formation (Queensland). These sedimentary rocks were also formed in shallow epicontinental seas. The Bangemall black shales thus form part of a lithological association, which is at least weakly mineralized at various horizons at various places in the world.

(vii) The diversity of the chemical associations at the three localities means that it is unlikely that there will be consistent indicator elements for use in prospecting. The most promising element is Cu, with Pb, Zn, Ni, Ag and Ba all of possible use.

ACKNOWLEDGEMENTS

The Geological Survey is indebted to Westfield Minerals (W.A.) N.L., and in particular to Dr A. Marshall, for the generous donation of core from Mount Palgrave and Mount Vernon, and to AMOCO Minerals of Australia Ltd for core from the Jillawarra area.

APPENDIX
CHEMISTRY AND MINERALOGY OF THE CORES

NOTES : MAJOR CONSTITUENTS IN PERCENTAGES
MINOR ELEMENTS IN PARTS PER MILLION
MINERALS IN PERCENTAGES (ESTIMATED FROM THIN
SECTION AND BY X-RAY DIFFRACTION). T = Trace

Values below detection limit for chemical constituents have, except for silver, been arbitrarily ascribed to half the detection value.

A space in the chemical composition indicates that the constituent in question was not determined, in the mineralogy it indicates that the mineral was not found.

The iron in pyrite has been calculated based on the sulphur value.

The Fe_2O_3 figure for Mount Vernon and Mount Palgrave cores is the total iron expressed as the oxide.

Covellite appears in many mineralized samples in trace proportions. It was only identified in polished section.

A. CHEMISTRY AND MINERALOGY OF CORE V 2

Formation name	GLEN ROSS SHALE MEMBER; KIANGI CREEK FORMATION								
G.S.W.A. No.	42455	42456	42457	42458	42459	42460	42461	42462	42463A
Rock type	(1)	(2)	(3)	(3)	(4)	(5)	(5)	(5)	(5)
Depth (m)	0.3	6.4	14.3	33.2	42.7	42.9	49.3	58.8	59.4
SiO ₂	50.0	71.2	86.5	78.8	88.1	84.7	73.4	61.6	56.4
Al ₂ O ₃	22.3	7.6	3.4	5.1	2.3	3.6	4.7	4.9	5.7
Fe ₂ O ₃	3.0	13.6	0.72	5.0	0.57	0.7	0.70	3.6	3.6
Fe in pyrite						1.9	2.0	8.0	9.3
MgO	0.50	0.65	0.36	0.36	0.05	0.05	0.41	0.25	0.41
CaO	0.84	0.29	0.14	0.17	1.2	0.15	0.08	0.1	0.13
Na ₂ O	0.61	0.005	0.005	0.005	0.005	0.04	0.01	0.005	0.005
K ₂ O	4.1	1.8	1.4	1.3	0.05	0.2	1.1	1.0	1.4
TiO ₂									
C	0.08	0.03	0.07	0.09	0.08	4.4	9.3	6.1	4.1
CO ₂									
P ₂ O ₅	0.20	0.15	0.26	0.27	1.31	0.29	0.52	0.25	0.12
S	5.1	0.77	0.30	0.60	0.40	2.2	2.3	9.2	10.6
Cu	20	50	15	460	110	390	675	130	145
Pb	5	20	20	15	5	30	65	15	20
Zn	115	60	25	140	140	10	70	60	50
Ni	60	15	5	70	30	60	60	235	230
Mn	30	70	20	25	35	5	5	10	10
V	1140	600	125	650	90	170	930	470	600
U	0.5	0.5	3	10	10	9	14	11	10
Li	15	10	10	5	15	2.5	15	2.5	5
Ba	840	390	250	280	30	120	240	160	140
Sr	600	170	55	100	5	20	40	25	10
Rb	20	70	75	60	5	15	65	55	90
B			60			15			65
Ga			7			0.5			2
Ag	2	2	2	6	<2	3	5	2	2
Quartz	25	60	75	75	90	85	65	50	45
Mica	T	15	15	15	T		15	15	20
Chlorite									
Kaolinite	10	5	5	5					
Dolomite									
Siderite									
K-feldspar									
Carbon						4	10	5	4
Pyrite						6	5	15	15
Hematite	5	15	5	5					
Sphalerite									
Tourmaline									
Leucoxene									
Rutile			T						
Sphene									
Alunite	60	5		5	5				
Fe-oxy sulphate								15	15
Opal					5				
Unidentified						5	5		

ROCK TYPE (1) Quartz-alunite rock. (2) Hematite shale. (3) Shale.
(4) Impure quartzite. (5) Black shale.

A. CHEMISTRY AND MINERALOGY OF CORE V-2

Formation name	GLEN ROSS SHALE MEMBER; KIANGI CREEK FORMATION								
G.S.W.A. No.	42463B	42464	42465A	42465B	42466	42467	42468	42469	42470
Rock type	(6)	(5)	(5)	(5)	(6)	(5)	(5)	(7)	(7)
Depth (m)	59.4	66.4	70.0	70.0	83.1	86.8	89.6	93.9	109.7
SiO ₂	68.3	79.4	56.5	67.3	82.9	55.8	53.5	54.5	56.9
Al ₂ O ₃	4.5	4.2	8.0	8.5	3.2	9.6	9.9	12.6	16.8
Fe ₂ O ₃	1.4	0.90	2.2	0.60	1.5	2.9	6.4	10.7	3.7
Fe in pyrite	5.0	2.4	5.6	2.7	1.9	4.0	7.6	4.5	1.9
MgO	0.30	0.41	0.65	0.59	0.28	1.2	1.5	2.2	2.3
CaO	0.15	0.34	0.27	0.81	0.54	1.4	1.4	0.67	1.0
Na ₂ O	0.01	0.01	0.05	0.26	0.02	0.005	0.07	0.005	0.005
K ₂ O	0.6	0.8	1.6	0.9	0.8	2.2	2.1	3.2	4.5
TiO ₂					0.10				
C	2.7	5.1	7.5	6.8	3.5	7.1	6.1	6.5	4.7
CO ₂					0.11				
P ₂ O ₅	1.39	0.71	0.36	1.17	0.65	0.59	0.66	0.29	0.40
S	5.7	2.8	6.4	3.1	2.1	5.3	8.9	5.9	2.2
Cu	160	100	295	250	520	1425	390	825	240
Pb	15	5	20	10	5	20	20	20	20
Zn	60	195	160	410	3725	14500	3150	13500	1275
Ni	130	145	280	115	110	400	280	270	100
Mn	10	5	10	10	15	55	75	90	95
V	830	530	860	1000	570	1340	1170	1000	750
U	10	16	16	24	7	20	15	11	6
Li	5	5	20	40	95	35	35	35	25
Ba	110	130	170	170	190	140	130	170	260
Sr	15	35	45	180	250	45	45	45	50
Rb	35	50	120	55	35	150	150	200	240
B			95		20		120		
Ga			5		2		12		
Ag	<2	<2	2	2	3	16	5	9	2
Quartz	70	75	45	55	85	40	30	35	35
Mica	10	10	25	15		25	30	30	40
Chlorite					3	20	15	18	15
Kaolinite			5	10					
Dolomite									
Siderite									
K-feldspar					4				
Carbon	3	5	7	7	4	5	6	6	5
Pyrite	10	10	9	6	3	10	18	10	5
Hematite									
Sphalerite		T			1	T	1	1	
Tourmaline									
Leucoxene									
Rutile									
Sphene									
Alunite									
Fe-oxysulphate	7		10						
Opal				3					
Unidentified									

ROCK TYPE (6) Veined black shale
(7) Silty black shale

A. CHEMISTRY AND MINERALOGY OF CORE V 2

Formation name	GLEN		ROSS	SHALE MEMBER		?QUARTZ ARENITE MEMBER		KIANGI CREEK FORMATION	
G.S.W.A. No.	42471	42472	42473	42474	42475	42476A	42476B	42477A	42477B
Rock type	(8)	(8)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
Depth (m)	134.1	134.3	154.2	171.9	185.6	185.9	185.9	193.8	193.8
SiO ₂	57.1	53.2	58.8	10.8	63.9	43.4	64.2	31.5	60.0
Al ₂ O ₃	16.3	17.2	16.8	1.9	13.8	11.7	12.2	9.1	14.0
Fe ₂ O ₃	4.7	4.6	5.9	11.3	5.7	17.7	10.8	40.3	15.6
Fe in pyrite	2.3	2.3	1.5	0.20	0.40	0.2	0.1	0.1	0.1
MgO	2.7	2.7	2.7	15.1	2.1	4.5	2.7	1.7	2.5
CaO	0.60	1.2	0.95	20.0	0.48	7.0	1.0	0.92	0.49
Na ₂ O	0.05	0.08	0.11	0.005	0.07	0.005	0.05	0.02	0.05
K ₂ O	4.3	4.3	4.4	0.4	4.3	2.9	2.9	2.2	2.9
TiO ₂							0.45		
C	3.1	3.2	2.3	0.05	2.2	1.3	1.3	0.5	0.6
CO ₂				39.4		10.2	2.5	7.9	2.1
P ₂ O ₅	0.16	0.41	0.14	0.26	0.13	0.22	0.14	0.18	0.04
S	2.6	3.3	1.7	0.23	0.42	0.28	0.16	0.12	0.15
Cu	115	2025	35	5	5	15	70	10	45
Pb	5	40	20	10	5	170	20	1400	100
Zn	475	14500	335	70	115	240	285	305	170
Ni	120	150	55	2.5	30	10	30	30	40
Mn	105	105	220	3600	210	1325	1375	6000	2500
V	630	650	230	60	120	90	70	30	40
U	4	7	0.5	0.5	0.5	1	0.5	3	0.5
Li	30	35	35	5	40	25	35	15	45
Ba	270	280	320	30	300	210	230	160	250
Sr	30	30	20	55	20	30	15	15	10
Rb	230	245	245	5	290	85	165	45	50
B	190			20			95	100	
Ga	15			0.5			13	3	
Ag	2	22	2	2	<2	2	<2	2	<2
Quartz	35	30	30		35	20	50	20	40
Mica	40	40	40		40	30	20	25	30
Chlorite	15	20	20		20	15	15	10	15
Kaolinite									
Dolomite			T	95		20	6		
Siderite						2		20	5
K-feldspar						2	3	2	3
Carbon	3	3	3	1	2	1	1	2	1
Pyrite	7	6	5	1					
Hematite			2	3	T		5	20	5
Sphalerite	T	1							
Tourmaline	T								
Leucocoxene							T		
Rutile									
Sphene									
Alunite									
Fe-oxysulphate									
Opal									
Unidentified									

ROCK TYPE (8) Dark grey silty shale. (9) Dolomite. (10) Shale with siltstone.
 (11) Dolomitic shale. (12) Dolomitic siltstone.
 (13) Sideritic shale. (14) Sideritic siltstone.

A. CHEMISTRY AND MINERALOGY OF CORE V 2

Formation name	?QUARTZ-ARENITE	MEMBER;	KIANGI	CREEK	FORMATION
G.S.W.A. No.	42478	42479	42480	42481	42482
Rock type	(15)	(13)	(16)	(13)	(15)
Depth (m)	200.7	213.3	220.7	233.2	238.9
SiO ₂	56.2	50.5	36.1	56.4	57.1
Al ₂ O ₃	14.7	12.1	7.5	15.3	12.7
Fe ₂ O ₃	9.4	8.1	3.7	7.2	12.3
Fe in pyrite					
MgO	5.0	5.8	10.6	4.8	5.6
CaO	3.4	6.3	18.5	3.2	3.4
Na ₂ O	0.08	0.20	0.18	0.31	0.19
K ₂ O	3.1	2.6	2.4	4.2	2.8
TiO ₂					
C	0.2	0.05	0.05	0.05	0.05
CO ₂	4.2	9.9	22.1	4.5	4.3
P ₂ O ₅	0.09	0.11	0.17	0.06	0.05
S	0.09	0.08	0.08	0.05	0.05
Cu	30	20	20	15	25
Pb	5	15	20	20	20
Zn	70	70	40	65	65
Ni	55	35	25	40	40
Mn	2000	3025	5000	1150	1500
V	50	40	30	60	50
U	0.5	0.5	0.5	0.5	0.5
Li	35	40	25	65	55
Ba	250	220	170	290	240
Sr	20	40	60	35	35
Rb	175	110	55	165	50
B		75			90
Ga		10			11
Ag	<2	2	<2	<2	2
Quartz	35	30	10	10	30
Mica	30	15	10	40	10
Chlorite	20	25	10	10	40
Kaolinite					
Dolomite	10		70		20
Siderite		30		40	
K-feldspar	3				
Carbon					
Pyrite					
Hematite	2	T	T	T	T
Sphalerite					
Tourmaline		T			T
Leucocoxene					T
Rutile		T		T	
Sphene				T	
Alunite					
Fe-oxysulphate					
Opal					
Unidentified					

ROCK TYPE (15) Dolomitic siltstone and shale.
(16) Quartzose dolomite.

B. CHEMISTRY AND MINERALOGY OF CORE V 3

Formation name	GLEN ROSS SHALE MEMBER; KIANGI CREEK FORMATION								
G.S.W.A. No.	42645	42646	42647	42648	42649	42650	42651	42652	42653
Rock type	(1)	(2)	(2)	(2)	(2)	(3)	(4)	(5)	(6)
Depth (m)	6.1	15.5	24.1	30.2	43.2	43.4	61.0	69.5	71.7
SiO ₂	85.0	96.5	94.2	95.3	91.8	71.0	73.6	62.6	69.1
Al ₂ O ₃	6.2	0.85	0.85	1.1	0.4	11.2	7.5	8.0	6.1
Fe ₂ O ₃	3.9	0.4	1.1	1.3	4.7	8.6	6.3	21.7	8.6
Fe in pyrite									
MgO	0.66	0.05	0.17	0.12	0.10	1.6	2.1	0.58	2.5
CaO	0.15	0.08	0.66	0.03	0.10	0.64	1.7	0.48	3.8
Na ₂ O	0.05	0.08	0.01	0.005	0.005	0.005	0.20	0.04	0.03
K ₂ O	1.7	0.3	0.4	0.4	0.3	3.6	2.4	1.9	2.1
TiO ₂							0.31		
C	0.05	0.1	0.3	0.05	0.1	0.12	0.11	1.6	0.6
CO ₂	0.21						2.3		4.4
P ₂ O ₅	0.05	0.01	0.005	0.01	0.01	0.21	0.18	0.30	0.26
S	0.07	0.08	0.02	0.04	0.04	0.04	0.05	0.03	0.05
Cu	40	15	10	15	20	40	30	60	65
Pb	20	5	5	5	5	5	5	55	45
Zn	40	15	30	15	55	65	30	30	35
Ni	35	10	10	10	15	85	25	20	30
Mn	425	15	800	225	2650	950	2350	150	1975
V	60	10	10	10	20	70	50	90	50
U	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Li	15	5	5	5	10	40	30	40	25
Ba	210	90	50	100	40	280	260	170	150
Sr	20	5	5	10	25	25	25	25	45
Rb	170	15	10	15	15	120	105	105	50
B	70			10			65	90	
Ga	4			0.5			6	9	
Ag	<2	<2	<2	<2	<2	2	<2	2	3
Quartz	75	98	95	98	95	50	55	55	60
Mica	15		T	T	1	30	15	15	
Chlorite							15		15
Kaolinite	5				1	10		15	
Dolomite			2				10		10
Calcite									
K-feldspar	2	1		T	1	5	3	3	
Carbon								2	
Pyrite									
Hematite	3	1	2	1	2	5	2	10	15
Sphalerite									
Tourmaline	T	T	T		T	T			
Leucocene									
Rutile						T			
Sphene	T								
Zircon	T		T		T	T			
Jarosite							T		
Monazite	T								
Staurolite									

ROCK TYPE (1) Silty sandstone, (2) Quartzite, (3) Siltstone.
 (4) Dolomitic siltstone.
 (5) Hematitic silty shale.
 (6) Quartz-dolomite-chlorite-hematite rock.

B. CHEMISTRY AND MINERALOGY OF CORE V 3

Formation name	GLEN ROSS SHALE MEMBER, KIANGI CREEK FORMATION								
G.S.W.A. No.	42654	42655	42656	42657	42658	42659	42660	42661	42662
Rock type	(7)	(8)	(9)	(10)	(9)	(9)	(9)	(11)	(9)
Depth (m)	84.3	84.5	93.3	94.2	109.5	110.4	127.6	128.0	136.3
SiO ₂	67.2	65.9	67.1	81.1	65.7	77.5	90.0	81.3	91.8
Al ₂ O ₃	11.8	9.1	8.3	4.2	8.9	7.2	1.9	2.4	1.7
Fe ₂ O ₃	9.0	14.0	3.2	4.3	1.4	1.3	0.1	1.0	0.1
Fe in pyrite		0.2	4.6	0.5	5.3	2.4	0.6	4.0	0.4
MgO	1.7	1.3	1.2	0.25	1.1	0.83	0.17	0.10	0.12
CaO	0.59	0.21	0.64	0.22	0.38	0.38	0.56	0.97	0.62
Na ₂ O	0.04	0.005	0.04	0.05	0.04	0.08	0.05	0.05	0.31
K ₂ O	4.1	3.3	3.0	2.1	3.5	2.8	0.6	0.8	0.6
TiO ₂					0.37				
C	0.6	3.2	3.2	1.7	3.5	3.4	5.3	4.1	3.2
CO ₂			0.20		0.12				
P ₂ O ₅	0.37	0.19	0.42	0.09	0.26	0.23	0.31	0.54	0.37
S	0.06	0.18	5.3	0.52	6.1	2.9	0.63	4.8	0.45
Cu	25	75	120	290	90	115	45	100	50
Pb	25	30	25	25	20	15	25	25	50
Zn	950	1150	200	1750	1850	3550	540	2300	1275
Ni	60	70	180	75	95	100	80	205	85
Mn	110	60	65	15	35	55	5	5	15
V	120	270	440	200	210	340	210	400	190
U	0.5	2	2	5	2	5	8	15	10
Li	35	30	25	75	35	35	5	20	5
Ba	250	210	210	170	200	180	80	110	70
Sr	20	10	20	15	20	20	15	25	15
Rb	190	115	145	70	175	140	35	40	30
B		135			110	80			20
Ga		11			13	7			0.5
Ag	3	2	4	3	4	4	< 2	3	2
Quartz	55	50	50	85	45	60	85	75	85
Mica	25	25	20		25	20	5	5	5
Chlorite	10	5	5	5	5	5			
Kaolinite									
Dolomite			1		2				T
Calcite									
K-feldspar	3	3	5	4	5	5		1	T
Carbon	1	2	5	2	6	3	5	4	3
Pyrite			10	1	11	7	5	14	7
Hematite	6	15		2					
Sphalerite				1				1	
Tourmaline	T	T							
Leucocoxene									
Rutile	T								
Sphene									
Zircon		T							
Jarosite									
Monazite									
Staurolite									
Unidentified			5						

ROCK TYPE. (7) Shale. (8) Black silty shale. (9) Black shale.
 (10) Black quartz-chlorite-opaques rock.
 (11) Veined black shale.

B. CHEMISTRY AND MINERALOGY OF CORE V 3

Formation name	GLEN ROSS		SHALE	MEMBER		?QUARTZ ARENITE MEMBER			
				KIANGI	CREEK	FORMATION			
G.S.W.A. No.	42663	42664	42665	42666	42667	42668	42669	42670	42671
Rock type	(9)	(9)	(12)	(12)	(3)	(13)	(14)	(15)	(4)
Depth (m)	136.7	153.8	163.1	173.6	177.4	190.6	194.2	196.6	215.6
SiO ₂	72.3	64.6	60.0	64.2	65.5	31.5	48.6	67.0	61.7
Al ₂ O ₃	3.2	8.0	14.5	14.7	13.2	6.7	9.3	13.8	10.9
Fe ₂ O ₃	0.2	4.2	7.0	8.0	9.4	6.2	6.8	8.2	7.6
Fe in pyrite	7.2	3.1	1.7	0.3	0.1			0.1	0.1
MgO	0.33	1.7	2.5	2.9	2.3	10.6	7.5	3.5	5.8
CaO	1.0	1.3	0.64	0.41	0.15	18.3	9.7	0.14	3.0
Na ₂ O	0.30	0.27	0.24	0.31	0.07	0.06	0.07	0.08	0.14
K ₂ O	1.2	2.5	4.5	3.9	3.5	2.1	4.0	3.1	3.3
TiO ₂									
C	3.9	5.9	2.5	1.2	0.75	0.05	0.05	0.1	0.1
CO ₂			0.98			25.1	14.0	0.44	4.8
P ₂ O ₅	0.67	0.79	0.29	0.12	0.06	0.22	0.13	0.05	0.08
S	8.2	3.9	2.2	0.37	0.12	0.03	0.05	0.14	0.14
Cu	145	625	500	30	35	25	10	10	30
Pb	30	35	35	15	10	5	5	5	5
Zn	700	8000	5000	775	455	145	40	55	55
Ni	275	220	185	170	75	50	30	40	30
Mn	15	65	430	300	455	2650	1475	195	575
V	350	1170	480	90	70	50	60	60	40
U	10	10	6	0.5	0.5	0.5	0.5	0.5	0.5
Li	5	45	35	40	40	20	35	65	65
Ba	150	150	280	280	260	150	220	280	310
Sr	25	25	15	10	10	50	40	10	30
Rb	55	135	165	190	190	30	45	130	75
B			215			75			85
Ga			17			4			10
Ag	3	8	6	<2	2	3	2	2	<2
Quartz	60	40	30	45	40	15	15	35	45
Mica	10	25	40	25	25	35	50	) 65	) 45
Chlorite		15	15	25	25		5))
Kaolinite									
Dolomite	T	1	3			50	30	1	10
Calcite									
K-feldspar	T	2	2						
Carbon	5	7	3	1	T				
Pyrite	20	7	7	1				T	
Hematite				3	10	T	T	T	T
Sphalerite		1	T						
Tourmaline							T	T	T
Leucoxene									
Rutile				T			T	T	T
Sphene									
Zircon									T
Jarosite									
Monazite									
Staurolite									T
Unidentified	5	2							

ROCK TYPE (12) Black shaly siltstone. (14) Dolomitic silty shale.
 (13) Argillaceous dolomite. (15) Argillaceous siltstone.

B. CHEMISTRY AND MINERALOGY OF CORE V 3

Formation name	?QUARTZ ARENITE MEMBER, KIANGI CREEK FORMATION			
G.S.W.A. No.	42672	42673	42674	42675
Rock type	(16)	(17)	(18)	(4)
Depth (m)	215.9	245.5	263.2	277.1
SiO ₂	60.1	59.7	60.2	59.5
Al ₂ O ₃	6.4	11.3	2.4	8.4
Fe ₂ O ₃	5.0	6.3	2.6	9.3
Fe in pyrite	0.1	0.1		
MgO	5.3	5.6	4.6	7.0
CaO	7.2	2.5	13.0	5.3
Na ₂ O	0.18	0.08	0.07	0.07
K ₂ O	2.8	2.1	1.2	1.8
TiO ₂	0.28			
C	0.05	0.1	0.5	0.05
CO ₂	10.8	3.9	16.7	7.8
P ₂ O ₅	0.09	0.07	0.11	0.09
S	0.12	0.12	0.03	0.01
Cu	5	25	10	10
Pb	10	5	65	5
Zn	30	65	25	55
Ni	20	35	10	30
Mn	1000	500	575	500
V	30	60	10	50
U	5	0.5	0.5	0.5
Li	35	60	10	40
Ba	410	210	160	220
Sr	70	20	55	20
Rb	50	85	30	35
B	40			65
Ga	5			11
Ag	<2	2	2	2
Quartz	55	40	55	30
Mica	10	) 50	) 10	) 55
Chlorite	10)))
Kaolinite				
Dolomite	20	10		15
Calcite			35	
K-feldspar	5		T	
Carbon			1	
Pyrite				
Hematite	T	T	T	T
Sphalerite				
Tourmaline				
Leucosene		T		
Rutile				T
Sphene				
Zircon		T		
Jarosite				
Monazite				
Staurolite				
Unidentified				
ROCK TYPE	(16) Dolomitic siltstone breccia (17) Siltstone with dolomite layers (18) Calcarenite			

C. CHEMISTRY AND MINERALOGY OF CORE P 13

Formation name	JILLAWARRA FORMATION								
G.S.W.A. No.	42676	42677A	42677B	42678	42679	42680	42681A	42681B	42682A
Rock type	(1)	(1)	(2)	(3)	(4)	(5)	(3)	(6)	(6)
Depth (m)	3.1	6.3	6.3	9.8	16.2	32.0	35.7	35.7	45.7
SiO ₂	74.7	73.5	51.6	63.3	65.9	80.4	46.9	51.6	58.5
Al ₂ O ₃	13.0	9.5	6.2	10.7	9.6	11.7	31.4	28.0	24.2
Fe ₂ O ₃	2.3	1.4	23.2	1.7	1.01	0.6	2.9	3.3	2.2
Fe as pyrite	0.05	0.2	0.9	4.4	2.8	0.8	1.0	0.2	3.5
MgO	1.3	0.91	0.66	0.91	0.75	0.33	1.8	1.3	1.1
CaO	0.04	0.04	0.09	0.08	0.09	0.04	0.53	0.05	0.09
Na ₂ O	0.08	0.18	0.40	0.08	0.11	0.07	0.15	0.09	0.11
K ₂ O	4.1	4.3	2.8	3.0	3.4	2.2	7.4	5.9	6.5
TiO ₂	0.68								
C	0.44	1.1	0.35	3.8	1.4	1.8	0.45	1.4	0.15
CO ₂	0.13								
P ₂ O ₅	0.08	0.07	0.06	0.06	0.13	0.03	0.10	0.09	0.06
S	0.09	0.18	0.01	5.0	3.2	0.9	1.1	0.22	4.0
Cu	25	40	245	525	170	65	50	20	85
Pb	50	55	10	25	25	25	15	20	40
Zn	15	20	20	15	25	25	35	35	35
Ni	15	5	85	95	45	55	115	20	235
Mn	15	15	10	20	5	10	30	20	15
V	330	270	300	300	310	270	200	150	860
U	3	3	10	7	10	5	10	13	4
Li	55	50	20	30	35	20	80	80	60
Ba	190	190	170	130	180	80	260	230	230
Sr	50	55	60	30	75	10	25	15	30
Rb	215	210	25	70	175	105	375	65	370
B	145			80			80		
Ga	21			13			32		
Ag	2	2	3	3	2	<2	2	2	3
Quartz	50	50	50	45	45	60	10	10	20
Mica	45	45	30	30	35	25	70	70	60
Kaolinite				10	15	11	18	17	12
K-feldspar	4								
Carbon	1	1		5	1	2	1		
Pyrite				10	5	2	1	3	8
Hematite		4	15						
Sphalerite									
Covellite									
Tourmaline									T
Zircon									T
Rutile	T	T							
Alunite			5						

ROCK TYPE (1) Shale. (4) Silty shale.
(2) Hematitic siltstone. (5) Black siltstone.
(3) Black shale. (6) Grey shale.

C. CHEMISTRY AND MINERALOGY OF CORE P 13

Formation name	JILLAWARRA FORMATION							
G.S.W.A. NO.	42682B	42683	42684	42685	42686	42687	42688	42689
Rock type	(3)	(3)	(7)	(7)	(7)	(8)	(9)	(5)
Depth (m)	45.7	55.2	67.4	69.4	74.7	78.0	80.4	83.2
SiO ₂	65.9	68.6	74.4	76.9	73.4	70.0	74.2	73.2
Al ₂ O ₃	19.1	10.9	13.4	13.0	9.8	13.6	12.7	10.7
Fe ₂ O ₃	1.7	1.6	0.7	0.6	0.4	0.7	0.4	0.6
Fe as pyrite	2.0	2.8	1.1	1.2	1.9	1.2	2.0	1.8
MgO	0.69	0.66	0.70	0.66	0.62	0.99	0.73	0.31
CaO	0.08	0.01	0.03	0.07	0.01	0.09	0.005	0.07
Na ₂ O	0.08	0.06	0.10	0.10	0.08	0.12	0.12	0.12
K ₂ O	3.7	3.1	2.6	2.5	2.2	2.7	3.0	1.8
TiO ₂		0.49						
C	2.4	3.8	1.4	0.85	2.1	6.1	2.8	4.8
CO ₂		0.23						
P ₂ O ₅	0.05	0.08	0.03	0.03	0.02	0.05	0.04	0.03
S	2.3	3.2	1.3	1.4	3.3	1.4	2.2	2.5
Cu	90	260	35	75	15	100	90	110
Pb	20	55	25	10	20	40	25	30
Zn	45	225	45	80	21300	210	95	7100
Ni	145	1020	35	65	495	135	115	1370
Mn	10	20	20	15	20	10	15	15
V	770	260	170	130	210	370	340	570
U	5	6	4	2	4	6	5	15
Li	35	30	30	25	25	25	30	20
Ba	140	150	180	160	100	240	180	120
Sr	10	15	10	10	5	25	20	15
Rb	90	140	140	130	115	145	155	90
B	75	80			155			115
Ga	19	13			8			8
Ag	<2	2	<2	2	3	<2	<2	<2
Quartz	30	50	50	55	50	40	50	55
Mica	35	35	30	30	25	25	30	25
Kaolinite	30	4	15	11	15	25	15	10
K-feldspar								
Carbon	2	5	2	1	2	6	3	5
Pyrite	3	6	2	2	3	4	2	4
Hematite								
Sphalerite					5			1
Covellite								
Tourmaline			1	1	T			T
Zircon					T			
Rutile								
Alunite								

ROCK TYPE (7) Shaly siltstone. (8) Black silty shale. (9) Black and grey shale.

D. CHEMISTRY AND MINERALOGY OF CORE J 16

JILLAWARRA FORMATION									
Formation name									
G.S.W.A. No.	48501	48502	48503	48504	48505	48506A	48506B	48507	48508
Rock type	(1)	(1)	(1)	(1)	(1)	(2)	(3)	(4)	(5)
Depth (m)	91.3	94.2	96.2	96.85	97.9	99.65	99.70	101.9	110.2
SiO ₂	80.8	84.4	85.2	91.5	93.2	48.4	87.3	58.9	77.0
Al ₂ O ₃	10.2	8.1	7.7	5.5	3.1	10.6	3.9	8.1	10.4
Fe ₂ O ₃	0.5	0.1	0.4	0.05	0.05	22.0	1.5	1.8	0.3
FeO	0.1	0.1	0.2	0.1	0.1	0.4	0.4	16.3	1.3
MgO	1.1	0.9	0.5	0.5	0.3	0.6	0.4	1.4	2.3
CaO	0.07	0.08	0.09	0.09	0.09	0.48	0.14	0.05	1.4
Na ₂ O	0.18	0.16	0.10	0.05	0.04	0.75	0.04	0.15	0.26
K ₂ O	3.2	2.5	2.1	1.4	0.8	2.1	0.8	1.8	3.2
TiO ₂	0.48	0.30	0.34	0.20	0.16	0.23	0.12	0.32	0.53
C	0.25	0.42	0.19	0.13	0.13	0.18	0.10	0.05	0.19
CO ₂								11.7	0.95
P ₂ O ₅	0.09	0.05	0.08	0.05	0.04	0.27	0.07	0.11	0.16
S	0.22	0.71	0.78	0.18	0.70	2.5	2.4	0.26	0.23
Cu	15	10	20	5	10	10	20	20	45
Pb	1150	290	300	670	40	385	210	35	25
Zn	60	65	55	325	135	625	2150	5000	875
Ni	15	15	15	10	15	50	75	85	40
Mn	15	5	25	15	20	35	25	2900	800
V	80	30	30	20	30	40	10	40	90
U	0.5	0.5	0.5	0.5	0.5	0.5	0.5	8	3
Li	15	20	20	20	15	20	10	10	20
Ba	2900	2800	1250	2250	1500	1500	800	3900	5500
Sr	5	5	5	5	2.5	50	15	20	5
Rb	125	85	85	50	35	65	35	90	155
B			50			50			115
Ga			7			3			13
Ag	<2	<2	<2	<2	<2	<2	4	<2	<2
Fe in pyrite	0.2	0.6	0.7	0.2	0.6	2.2	2.2	0.2	0.2
Quartz	65	70	75	80	85	40	75	40	60
K-feldspar								T	4
Plagioclase									
Mica	30	25	20	18	14	20	15	15	15
Kaolinite	5	3	3			10			
Chlorite				T			15	15	
Calcite									
Dolomite									
Siderite								30	4
Pyrite	T	2	2	1	1	5	5	T	1
Carbon	T	T	T	T	T		T		T
Tourmaline	T	T	T	T	T		T	T	T
Zircon	T		T	T	T			T	
Leucoxene	T		T						T
Epidote		T		T					
Rutile			T						
Goethite/hematite						25	5	1	
Sphalerite				T	T		T	T	T

ROCK TYPE (1) Sheared recrystallized siltstone. (2) Hematite-veined chert.
(3) Recrystallized cherty siltstone. (4) Sideritic siltstone.
(5) Recrystallized siltstone.

D. CHEMISTRY AND MINERALOGY OF CORE J 16

JILLAWARRA FORMATION							
G.S.W.A. No.	48509	48510	48511	48512	48513	48514	48515
Rock type	(4)	(6)	(7)	(8)	(9)	(10)	(11)
Depth (m)	112.5	116.0	116.75	117.1	119.3	120.0	121.8
SiO ₂	61.0	17.5	76.7	76.2	52.2	56.3	77.7
Al ₂ O ₃	10.4	1.0	5.3	10.8	8.3	7.0	4.8
Fe ₂ O ₃	1.1	0.05	1.6	0.5	3.0	1.8	1.1
FeO	12.0	1.0	5.6	0.7	16.4	14.5	6.6
MgO	2.0	0.1	0.7	1.0	3.6	3.5	4.3
CaO	2.4	0.05	1.6	0.50	1.6	1.1	2.3
Na ₂ O	0.21	0.04	0.04	0.19	0.21	0.16	0.31
K ₂ O	2.6	0.2	1.6	3.8	2.6	2.5	0.1
TiO ₂	0.46	0.05	0.21	0.45	0.48	0.47	0.35
C	0.13	0.13	1.6	3.4	0.47	0.04	0.06
CO ₂	8.1		3.7	0.42	12.5	11.5	1.0
P ₂ O ₅	0.17	0.06	0.23	0.12	0.20	0.15	0.23
S	0.16	43.4	1.1	0.94	0.54	0.16	0.36
Cu	15	75	340	65	110	20	20
Pb	20	320	450	75	45	55	5
Zn	3500	45	2250	200	1225	360	600
Ni	50	65	75	60	60	40	70
Mn	1900	10	1000	25	5000	5000	600
V	100	10	190	250	100	80	110
U	0.5	0.5	1	0.5	0.5	5	0.5
Li	20	2.5	25	10	15	10	20
Ba	4300	150	1000	1550	2450	2600	125
Sr	10	2.5	25	5	35	10	5
Rb	135	10	55	145	100	115	2.5
B			30			50	
Ga			5			10	
Ag	<2	4	3	<2	3	<2	4
Fe in pyrite	0.1	35.4	0.7	0.8	0.3	0.1	0.3
Quartz	40	20	65	60	40	45	75
K-feldspar							
Plagioclase							
Mica	15	T	20	30	25	25	
Kaolinite							
Chlorite	20			3	5	5	20
Calcite							
Dolomite							
Siderite	25		10	1	30	25	3
Pyrite		80	2	2			2
Carbon	T	T	2	4	T		
Tourmaline	T						
Zircon							
Leucoxene							T
Epidote							
Rutile							
Goethite/hematite			2			T	
Sphalerite	T		T				

ROCK TYPE (6) Quartz-pyrite rock. (7) Carbonate chert shale.
 (8) Black silty shale. (9) Sideritic silt-chert rock.
 (10) Sideritic silty shale. (11) Chert-chlorite rock veined with siderite.

E. CHEMISTRY AND MINERALOGY OF CORE J 14

Formation name	PRE-BANGEMALL					BASEMENT			
G.S.W.A. No.	48516	48517	48518	48519	48520	48521	48522	48523	48524
Rock type	(1)	(2)	(2)	(3)	(2)	(4)	(5)	(5)	(5)
Depth (m)	100.65	103.5	109.4	116.7	126.6	135.9	145.1	154.6	165.05
SiO ₂	52.2	64.0	78.4	42.9	34.5	39.8	55.4	48.9	51.5
Al ₂ O ₃	8.3	5.1	3.4	6.3	4.2	2.8	15.6	12.5	12.1
Fe ₂ O ₃	3.6	15.1	7.8	21.3	40.5	40.6	6.8	14.5	16.9
FeO	9.2	7.8	5.0	14.4	14.1	9.9	5.9	8.9	7.0
Fe in pyrite	0.2	1.0	0.3	1.7	0.8	1.0	0.8	1.2	0.05
MgO	13.1	4.1	3.7	5.1	4.4	2.5	0.7	5.6	0.4
CaO	0.16	0.11	0.10	0.15	0.10	0.28	0.03	0.03	0.03
Na ₂ O	0.3	0.2	0.05	0.4	0.6	0.05	0.3	0.4	0.3
K ₂ O	2.1	0.21	0.02	0.95	0.32	0.20	4.2	2.6	3.6
TiO ₂	0.63	0.12	0.08	0.35	0.20	0.12	0.65	0.56	0.54
C	0.02	0.005	0.005	0.005	0.06	0.02	0.005	0.08	0.08
CO ₂									
P ₂ O ₅	0.07	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.14
S	0.24	1.2	0.33	1.9	0.86	1.2	0.90	1.4	0.01
Cu	5	10	5	15	10	5	10	10	15
Pb	30	45	5	5	40	5	85	45	55
Zn	60	40	50	70	70	55	45	60	65
Ni	50	25	20	40	30	35	65	50	45
Mn	1000	560	440	840	550	450	450	440	250
V	80	30	30	60	60	40	110	70	90
U	1	0.5	0.5	1	0.5	0.5	0.5	1	2
Li	20	10	10	15	10	5	15	30	20
Ba	2000	100	100	700	250	200	3250	2400	1300
Sr	5	5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Rb	90	10	2.5	35	10	5	230	175	195
B		5			5			120	
Ga		4			8			17	
Ag	3	<2	<2	2	2	<2	2	2	<2
Quartz	30	55	70	25	30	30	35	35	35
K-feldspar									
Plagioclase									
Mica	25	2		15	5	2	40	40	40
Chlorite	40	20	20	25	20	15	10	10	15
Dolomite									
Siderite			T						
Pyrite	T	2	1	4	1	3	2	2	
Carbon									
Magnetite	2	20	10	30	35	25	13	13	10
Hematite	3		T	1	10	25			
Tourmaline	T						1	T	
Zircon	T	T	T	T			T	T	
Epidote									
Barite							T	(T	
Apatite							T	(T	
Rutile/sphene							T	T	
Monazite							T	T	
Sphalerite									

ROCK TYPE (1) Chlorite muscovite schist.
(2) Quartz-magnetite-chlorite rock.
(3) Magnetite-quartz-chlorite-mica 'schist'.
(4) Quartz-opaques-chlorite cataclasite
(5) Cataclastically deformed metasiltstone.

E. CHEMISTRY AND MINERALOGY OF CORE J 14

Formation name	PRE-BANGEMALL BASEMENT →					← JILLAWARRA FORMATION			
G.S.W.A. No.	48525	48526	48527	48528	48529	48530A	48530B	48531	48532
Rock type	(6)	(7)	(8)	(9)	(10)	(11)	(11)	(12)	(13)
Depth (m)	165.5	165.9	170.25	172.6	172.9	174.0	174.0	174.6	184.3
SiO ₂	23.4	45.2	71.9	78.3	92.2	91.8	85.3	92.0	89.9
Al ₂ O ₃	2.6	6.3	9.2	7.4	3.3	0.3	6.1	2.5	3.8
Fe ₂ O ₃	58.2	31.1	0.4	1.4	0.5	0.2	0.4	0.1	0.3
FeO	7.6	7.1	6.5	2.4	0.1	0.1	0.3	0.2	0.2
Fe in pyrite	1.5	1.7	1.0	0.05	0.3	1.5	0.3	0.7	0.2
MgO	2.0	3.8	6.3	2.0	0.3	0.3	0.8	0.5	0.4
CaO	0.04	0.04	0.03	0.04	0.02	0.03	0.02	0.04	0.04
Na ₂ O	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
K ₂ O	0.2	1.1	1.1	2.3	0.4	0.7	2.8	1.0	1.4
TiO ₂	0.12	0.24	0.38	0.44	0.14	0.10	0.20	0.17	0.17
C	0.005	0.02	0.03	0.03	0.08	0.11	0.30	0.08	0.36
CO ₂									
P ₂ O ₅	0.09	0.09	0.09	0.19	0.03	0.04	0.06	0.04	0.07
S	1.7	2.0	1.2	0.04	0.34	1.7	0.38	0.81	0.26
Cu	10	10	75	5	15	30	25	10	5
Pb	30	5	60	10	800	750	820	210	160
Zn	115	500	195	150	135	30	50	560	270
Ni	40	110	45	50	25	40	40	45	35
Mn	210	320	725	180	85	100	85	80	75
V	40	60	50	70	10	40	40	30	70
U	2	1	2	1	0.5	1	0.5	0.5	0.5
Li	10	15	30	20	20	40	20	35	10
Ba	550	1450	8000	5200	1600	600	2200	1100	2200
Sr	40	70	2.5	2.5	2.5	2.5	2.5	5	10
Rb	15	65	40	145	20	30	100	40	50
B		45			20			20	
Ga		7			2			3	
Ag	<2	<2	3	<2	3	4	3	2	<2
Quartz	15	30	55	60	95	85	85	85	85
K-feldspar						2	2		
Plagioclase									
Mica	2	20	10	20	) T	10	10	12	13
Chlorite	15	15	30	20)				
Dolomite									
Siderite									
Pyrite	3	4			T	1	1	2	T
Carbon						1	1	T	1
Magnetite	20	15))					
Hematite	45	15	) 2	) T	5	1	1	T	1
Tourmaline	T	T			T			T	
Zircon	T	T						T	
Epidote	T				T				
Barite	T	1	1					T	T
Apatite									
Rutile/sphene			1	1					T
Monazite									
Sphalerite								1	T
Jarosite					T?				

ROCK TYPE (6) Hematite-magnetite-quartz-chlorite rock. (7) Quartz-iron oxide-talc-chlorite-(mica)-schist. (8) Quartz-chlorite-mica breccia. (9) Reconstituted quartz chlorite-mica-rock. (10) Quartz-chert breccia. (11) Chert-quartz-mica breccia. (12) Chert-quartz breccia. (13) Quartz veined, banded cherty (meta) siltstone.

E. CHEMISTRY AND MINERALOGY OF CORE J 14.

JILLAWARRA FORMATION									
Formation name									
G.S.W.A. No.	48533	48534	48535	48566	48536	48537	48538	48539	48540
Rock type	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(20)	(20)
Depth (m)	188.1	193.6	203.5	208.35	213.2	223.2	227.0	228.1	230.15
SiO ₂	92.1	41.1	93.3	19.5	89.7	83.9	93.0	91.0	92.5
Al ₂ O ₃	3.7	0.2	2.1	0.11	4.9	2.6	2.3	2.5	0.09
Fe ₂ O ₃	0.1	0.05	0.3	0.05	0.1	0.1	0.3	0.1	1.6
FeO	0.1	0.7	0.1	0.6	0.2	0.2	0.4	0.1	0.1
Fe in pyrite	0.2	24.4	0.6	21.6	0.3	5.0	0.05	1.7	0.1
MgO	0.4	0.5	0.1	0.2	0.4	0.2	0.2	0.3	0.05
CaO	0.05	0.03	0.04	0.005	0.04	0.03	0.02	0.03	0.005
Na ₂ O	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
K ₂ O	1.5	0.05	1.0	0.05	1.4	1.1	0.7	0.7	0.05
TiO ₂	0.18	0.03	0.10	0.02	0.24	0.12	0.09	0.09	0.05
C	0.38	0.09	0.30	0.17	0.34	0.42	0.22	0.26	0.16
CO ₂								0.08	0.04
P ₂ O ₅	0.10	0.04	0.05	0.06	0.10	0.07	0.01	0.01	0.005
S	0.24	30.0	0.73	24.6	0.30	5.8	0.69	2.1	1.4
Cu	10	55	10	1325	10	15	30	20	175
Pb	190	20000	170	12.6%	150	750	1000	650	3000
Zn	95	70	210	2.6%	335	300	4500	3500	8900
Ni	40	60	40	20	30	40	70	35	50
Mn	85	105	90	100	75	75	90	55	40
V	60	10	90	10	90	50	60	60	40
U	0.5	0.5	2	0.5	2	1	1	1	0.5
Li	5	2.5	2.5	2.5	5	5	2.5	2.5	2.5
Ba	1700	100	900	50	2400	450	800	600	600
Sr	5	2.5	2.5	2.5	5	2.5	2.5	2.5	2.5
Rb	50	5	30	2.5	65	35	25	25	20
B		5				15			10
Ga		0.5				1			5
Ag	2	4	2	5	2	2	2	3	11
Quartz	85	40	73	35	80	80	90	90	85
K-feldspar					5				
Plagioclase									
Mica	11	1	5		15	10	5	6	5
Chlorite									
Dolomite									
Siderite			T			T		T	T
Pyrite	2	60	20	45	1	10	2	2	5
Carbon	1		2			1	1	1	1
Magnetite									
Hematite	T								2
Tourmaline	T	T			T	T	T	T	T
Zircon					T				
Epidote									
Barite	1				T	T			
Apatite	T								T
Rutile/sphene					T				T
Monazite									
Sphalerite				5		T	2	1	2
Galena				15					

ROCK TYPE (14) Quartz veined, black banded cherty metasiltstone. (15) Pyrite quartz chert
 (16) Pyrite quartz chert siltstone breccia. (17) Quartz-sulphide rock. (rock
 (18) Siliceous cherty siltstone. (19) Siliceous siltstone veined by quartz.
 (20) Silicified evaporite siltstone.

E. CHEMISTRY AND MINERALOGY OF CORE J 14

JILLAWARRA FORMATION									
Formation name									
G.S.W.A. No.	48541	48542	48543	48544	48545	48546A	48546B	48547	48548
Rock type	(21)	(22)	(23)	(24)	(25)	(25)	(25)	(26)	(27)
Depth (m)	231.1	232.7	242.7	253.1	260.3	266.4	266.4	267.35	268.0
SiO ₂	77.1	83.6	49.3	94.5	70.2	68.4	69.0	69.6	69.7
Al ₂ O ₃	1.1	1.6	0.5	0.3	12.1	12.7	12.1	11.5	12.5
Fe ₂ O ₃	0.7	0.1	0.2	0.4	0.7	1.3	1.7	1.0	0.9
FeO	0.3	0.3	0.4	1.0	0.4	2.8	2.3	2.7	1.7
Fe in pyrite	9.0	5.5	22.6	0.7	0.3	0.1	0.2	0.05	1.7
MgO	0.1	0.3	0.1	0.1	2.4	3.4	3.0	3.4	2.4
CaO	0.04	0.05	0.04	0.04	1.1	1.3	1.2	2.4	1.4
Na ₂ O	0.05	0.05	0.05	0.05	0.75	0.88	0.80	0.56	0.85
K ₂ O	0.2	0.6	0.05	0.05	5.1	4.2	4.3	3.2	3.8
TiO ₂	0.03	0.08	0.01	0.01	0.75	0.42	0.48	0.45	0.60
C	0.23	0.38	0.20	0.17	0.07	0.11	1.4	0.45	1.6
CO ₂				0.35	0.07	0.33	0.13	2.4	0.15
P ₂ O ₅	0.03	0.01	0.03	0.01	0.23	0.16	0.23	0.33	0.41
S	10.4	6.4	26.0	0.99	0.39	0.13	0.23	0.08	2.0
Cu	40	50	55	20	10	15	35	5	40
Pb	1100	6200	600	50	40	5	75	20	65
Zn	2900	625	1100	1100	75	60	50	95	245
Ni	20	35	60	10	35	45	45	20	50
Mn	15	15	10	65	20	100	50	520	30
V	30	50	10	50	170	100	100	90	140
U	3	3	3	2	8	1	0.5	0.5	0.5
Li	2.5	5	2.5	2.5	15	15	15	15	10
Ba	150	200	50	100	4700	4200	4000	3900	1100
Sr	2.5	2.5	2.5	2.5	15	5	5	20	10
Rb	10	15	2.5	2.5	240	210	205	165	165
B			10			120			100
Ga			0.5			19			14
Ag	9	13	13	<2	2	2	2	2	3
Quartz	70	75	50	95	45	55	55	60	45
K-feldspar					T	2	2		3
Plagioclase									
Mica	4	5		1	50	25	25	25	35
Chlorite					4	15	15	10	10
Dolomite						2		4	T
Siderite				2					
Pyrite	25	20	50	2	1		1		5
Carbon	1	1					2	1	2
Magnetite									
Hematite									
Tourmaline					T			T	
Zircon		T			T	T			
Epidote									
Barite					T				
Apatite									
Rutile/sphene					T				
Monazite						T			
Sphalerite	1	T	T	1					

ROCK TYPE (21) Silicified siltstone breccia, (22) Veined and brecciated siliceous cherty siltstone. (23) Chert-pyrite rock, (24) Nodular conglomeratic chert. (25) Quartz-mica schist (meta shale). (26) Black silty shale veined with dolomite. (27) Black shale.

E. CHEMISTRY AND MINERALOGY
OF CORE J 2

Formation name	NOT APPLICABLE		
G.S.W.A. No.	48554	48555A	48555B
Rock type	(1)	(2)	(1)
Depth (m)	128.4	139.75	139.75
SiO ₂	49.6	56.7	52.3
Al ₂ O ₃	14.0	2.2	11.9
Fe ₂ O ₃	2.1	0.05	3.2
FeO	10.7	1.4	14.4
Fe in pyrite	0.05	0.05	0.4
MgO	9.4	0.4	5.6
CaO	2.1	20.0	3.4
Na ₂ O	3.9	0.05	4.2
K ₂ O	0.9	0.05	0.6
TiO ₂	1.5	0.03	2.2
C	0.05	0.05	0.05
CO ₂	0.45	18.1	2.4
P ₂ O ₅	0.19	0.23	0.31
S	0.02	0.20	0.48
Cu	90	5	50
Pb	5	5	25
Zn	120	30	125
Ni	65	10	15
Mn	1750	1650	1575
V	300	20	350
U	0.5	0.5	0.5
Li	40	2.5	15
Ba	4500	1100	2400
Sr	95	100	35
Rb	35	5	35
B			5
Ga			19
Ag	2	2	<2
Quartz	20	50	20
K-feldspar			
Plagioclase	30		30
Mica	5	5	5
Chlorite	45		35
Calcite		45	6
Dolomite			
Siderite			
Pyrite			
Tourmaline			
Zircon			
Rutile			
Carbon			
Altered sphene			4

ROCK TYPE (1) Altered dolerite.
(2) Quartz-calcite vein.

F. CHEMISTRY AND MINERALOGY OF CORE J 9.

Formation name	PRE-BANGEMALL				BASEMENT				
G.S.W.A. No.	48556	48557	48558	48559	48560	48561A	48561B	48563	48564
Rock type	(1)	(2)	(1)	(1)	(1)	(3)	(4)	(5)	(4)
Depth (m)	97.3	107.05	116.84	126.7	136.25	144.25	144.25	145.55	147.3
SiO ₂	60.5	61.4	63.5	64.9	68.9	19.0	49.9	30.5	60.4
Al ₂ O ₃	8.6	10.9	12.8	12.3	8.0	2.4	14.2	6.2	14.6
Fe ₂ O ₃	1.6	0.8	2.2	1.1	1.1	0.05	0.8	0.4	1.3
FeO	6.7	4.1	4.5	6.2	7.4	1.6	3.7	1.8	3.4
Fe in pyrite	1.7	0.7	0.4	0.4	0.3	0.1	0.1	0.1	0.1
MgO	6.1	5.3	5.6	5.5	4.8	1.1	3.9	2.4	3.9
CaO	1.0	2.7	1.2	1.1	1.0	37.0	10.5	27.0	6.6
Na ₂ O	1.4	1.6	1.7	2.6	1.2	0.30	1.7	0.83	1.7
K ₂ O	1.9	2.9	2.8	1.7	0.9	0.4	2.7	1.2	3.0
TiO ₂	0.56	0.56	0.60	0.57	0.42	0.08	0.46	0.20	0.59
C	0.05	0.05	0.05	0.05	0.12	0.05	0.05	0.05	0.05
CO ₂	0.27	3.2	0.44	0.14	0.06	35.4	10.5	26.9	5.0
P ₂ O ₅	0.08	0.10	0.08	0.09	0.06	0.44	0.16	0.35	0.13
S	1.9	0.77	0.51	0.50	0.31	0.14	0.08	0.07	0.09
Cu	100	65	55	35	50	35	25	10	25
Pb	30	30	10	45	5	10	5	25	5
Zn	70	75	130	65	70	80	40	15	40
Ni	55	20	15	15	10	5	10	5	20
Mn	280	1175	365	310	380	3375	1425	1800	445
V	90	90	80	100	60	10	100	60	90
U	0.5	0.5	0.5	0.5	0.5	0.5	1	0.5	0.5
Li	30	20	25	20	25	5	20	5	25
Ba	2100	4000	3400	2200	1500	2250	4500	3250	5000
Sr	5	15	5	5	5	430	155	330	60
Rb	90	150	135	80	50	20	130	40	200
B			85			15			85
Ga			20			2			18
Ag	<2	<2	<2	2	<2	6	<2	4	2
Quartz	50	50	45	50	60	15	40	25	35
K-feldspar	1	T	1	1	T				T
Plagioclase	4	5	4	4	2			T	
Mica	20	25	25	15	10	5	25	12	30
Chlorite	20	15	25	20	15		10	3	25
Calcite						80	25	60	10
Dolomite	2	5	T	T					
Siderite									
Pyrite	3	T							
Tourmaline	1	T	T	T	T			T	T
Zircon	T			T					T
Rutile				T					
Carbon								T	
Altered sphene									

ROCK TYPE (1) Siltstone. (2) Dolomitic siltstone. (3) Limestone.
 (4) Calcareous siltstone. (5) Limestone siltstone breccia.

F (continued)

Formation name	PRE-PANGEMALL BASEMENT
G.S.W.A. No.	48565
Rock type	(4)
Depth (m)	149.1
SiO ₂	51.4
Al ₂ O ₃	15.6
Fe ₂ O ₃	0.8
FeO	2.8
Fe in pyrite	0.1
MgO	3.5
CaO	12.0
Na ₂ O	1.8
K ₂ O	2.8
TiO ₂	0.45
C	0.05
CO ₂	9.7
P ₂ O ₅	0.19
S	0.12
Cu	15
Pb	5
Zn	35
Ni	2.5
Mn	650
V	90
U	0.5
Li	20
Ba	5500
Sr	140
Rb	140
B	
Ga	
Ag	<2
Quartz	50
K-feldspar	
Plagioclase	
Mica	25
Chlorite	
Calcite	25
Dolomite	
Siderite	
Pyrite	
Tourmaline	
Zircon	
Rutile	
Carbon	T
Altered sphene	

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