1:250 000 Metallogenic Map Series
Explanatory Notes and
Mineral Deposit Data Sheets

CALVERT HILLS SE 53-8
1:250 000 METALLOGENIC MAP SERIES

EXPLANATORY NOTES
AND
MINERAL DEPOSIT DATA SHEETS

CALVERT HILLS SE53-8

M. AHMAD
A. S. WYGRALAK

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MAP
1: 250 000 Metallogenic map of Calvert Hills (SE 53-8) in pocket
ABSTRACT
In the Calvert Hills area basement sequence of the Early Proterozoic Murphy Inlier is flanked to the northwest by the Middle Proterozoic McArthur Basin sequence and to the southwest by the Middle Proterozoic Lawn Hill Platform and the overlying South Nicholson Basin successions.

Murphy Metamorphics (greenschist facies quartz-albite-muscovite-biotite schist and gneiss), Cliffdale Volcanics (calc-alkaline ignimbrite, rhyolite and tuff), and Nicholson Granite Complex (adamellite, granodiorite, granite and alkali granite) constitute the Murphy Inlier sequence. The Tawallah Group, oldest group of the McArthur Basin, unconformably overlies the Murphy Inlier sequence and consists essentially of a succession of sediments and volcanics. The basal arenites (Westmoreland Conglomerate) of the Tawallah Group, are of fluvial origin and were derived from the northeast. The other sedimentary formations of this group were deposited in a shallow marine to lacustrine environment and were probably derived from the south. The volcanic rocks in the Tawallah Group are dominantly subaerial and consist of basalt, trachyandesite, trachyte and latite. An upwards — fractionating trend and geochemical variations support a co-magmatic origin for these volcanic rocks. The overlying McArthur Group is represented by the Masterton Sandstone and the Karns Dolomite. The Lawn Hill Platform sequence starts with basal fluvial arenites (Wire Creek Sandstone) followed by a prolonged period of acid and basic, dominantly subaerial volcanism, represented by the Peters Creek Volcanics. The later are followed by shallow marine sequence of the Fickling Group and the overlying South Nicholson Group.

The Nicholson Granite Complex and Cliffdale Volcanics contain several uneconomic cassiterite bearing quartz-muscovite greisens as irregular pods and as tabular veins with both interstitial and vug-filled cassiterite and minor wolframite. Uranium mineralisation is present as veinlets in volcanics and matrix-fill in the Westmoreland Conglomerate, and is localised adjacent to and along the contact of the Westmoreland Conglomerate with relatively reduced volcanic rocks. Uranium was probably leached from the Westmoreland Conglomerate and deposited along the oxidised-reduced interface. A majority of uranium occurrences are auriferous and carry free gold. Heavy mineral suite from stream draining the upper part of the Westmoreland Conglomerate also contains gold along with cassiterite and wolframite. This suite is also found in the matrix of some conglomerate beds in the Westmoreland Conglomerate. Vein type hydrothermal copper mineralisation is found as fracture filling in the Murphy Inlier sequence and Seigal Volcanics. In the Redbank area there are several copper-bearing breccia pipes and vein filled copper occurrences. Although stratiform base-metals concentrations are observed in several places in the McDermott and Wollogorang formations, no economic grades are found. A number of uneconomic residual manganese occurrences are located in the Karns Dolomite. Scattered microdiamonds are found in the stream sediments from the southwestern part of the area.

INTRODUCTION
CALVERT HILLS* area bounded by latitudes 17°S and 18°S and longitudes 136°30'E and 138°E, is centered 1250 km SE of Darwin (Figure 1).

The main access to the area is by a graded road connecting Borrooloola and Burketown. This road crosses the north-eastern part of the sheet area, passing through Wollogorang Homestead. Another graded road branches of the Tableland Highway near Anthony Lagoon and runs north-east through Benmara and Calvert Hills homestead cutting the sheet area from south-west to north-east. Both roads are accessible during most of the year.

Three permanently occupied homesteads exist in the area: Benmara, Calvert Hills and Wollogorang. Redbank mining camp is currently placed on care and maintenance. A small group of Aborigines recently established a camp near the Dry Creek waterhole. All above mentioned locations have landing grounds suitable for light aircraft. There are also other Aboriginal groups intermittently occupying some permanent water holes.

The climate is semi-arid, with a warm dry season from April to September and a hot wet season from October to March. Available statistical data on the mean annual rainfall for the last several years shows an increase of rainfall toward the northeast, from 472 mm near Benmara through 811 mm in Calvert Hills to 915 mm near the Wollogorang Homestead. Most of the rainfall falls between December and March.

The first systematic geological work in the area was carried out in 1939-1940 when several traverses along the Queensland border and in the Wollogorang district were made (Jensen, 1941). The first geological map (1:250 000) of CALVERT HILLS was compiled by Roberts and others in 1963. Sweet and others (1981) published a 1:100 000 scale geological map of SEIGAL covering the southeastern corner of CALVERT HILLS. Numerous mapping programmes have also been undertaken by various exploration companies operating in the area.

These notes and the accompanying metallogenic map are based on the field work carried out by the Northern Territory Geological Survey during 1982-85 and they also incorporate some data from the open file company reports.

PHYSIOGRAPHY
The physiography of the Calvert Hills area has been described by Christian and others (1954), Roberts and others (1963) and Aldrick and Wilson (in prep). The major physiographic divisions of Aldrick and Wilson are shown in Figure 2. Table 1 gives a brief description of these major divisions.

TECTONIC SETTING
CALVERT HILLS is located within three major Proterozoic geotectonic units which together form a part of the Northern Australian Craton (Plumb, 1979).

The oldest of them — the Murphy Inlier (Figure 3) — consists of the Early Proterozoic igneous and low-grade metamorphic rocks which constitute the eastern

* Names of 1:250 000 scale map sheets are in block capitals, e.g. CALVERT HILLS. Names of 1:100 000 scale map sheet are in smaller block capitals, e.g. SEIGAL.
edge of the Early Proterozoic North Australian Orogenic Province (GSA, 1971).

The Murphy Inlier is unconformably overlain by the Middle Proterozoic McArthur Basin to the north and by the Middle Proterozoic Lawn Hill Platform and the South Nicholson Basin to the south. The McArthur Basin, the Lawn Hill Platform and the South Nicholson Basin are a part of the North Australian Platform Cover and comprise flat-lying to gently folded Middle Proterozoic unmetamorphosed sedimentary and subordinate volcanic rocks.

Cambrian, Cretaceous and Cainozoic sediments deposited in shallow basins or as terrestrial accumulates mask the Proterozoic rocks in most of the central and eastern portions of the sheet area.

**STRATIGRAPHY**

**PROTEROZOIC STRATIGRAPHY** (Table 2)

**THE MURPHY INLIER SEQUENCE**
The east northeast-trending Murphy Inlier of Early Proterozoic ‘basement’ rocks formed an intrabasinal high which separated the McArthur Basin from the Lawn Hill Platform and South Nicholson Basin throughout the Middle Proterozoic. It consists of the Murphy Metamorphics, the Nicholson Granite Complex and the Cliffdale Volcanics.

**MURPHY METAMORPHICS** (Elm)
The Murphy Metamorphics are essentially a sequence of shale, siltstone, greywacke and volcanics deposited
Table 1  Description of generalised physiographic divisions after Aldrick and Wilson (in prep).

<table>
<thead>
<tr>
<th>FEATURE</th>
<th>RELIEF</th>
<th>SOILS</th>
<th>VEGETATION</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) — Lateritic Plain</td>
<td>Gently undulating plateau with intact mature laterite.</td>
<td>Ferruginous lithosols, shallow lateritic podsol and earthy sands.</td>
<td>Low open woodland of <em>E. dichromophloia</em> and <em>E. leucophloia</em> over <em>Plectachne</em> sp. (<em>Spinifex</em>) Sandy areas have <em>E. setosa</em>.</td>
<td>Erosionally stable areas. Correlates to Cainozoic sediments.</td>
</tr>
<tr>
<td>(B) — Dissected Country</td>
<td>Escarpments, low hills and pediplains.</td>
<td>Grey and brown clays, lithosols and shallow earthy sands.</td>
<td>Mid-high open woodland of <em>E. leucophloia</em>, <em>E. pruinosa</em>, <em>E. dichromophloia</em> &amp; <em>E. ferruginea</em>. Stands of <em>Acacia sherleyi</em> occur on cliffs and slopes.</td>
<td>Laterite or sandstone cap rock incised, exposing relatively soft underlying materials. High rate of erosion. Correlates with Mesozoic rocks.</td>
</tr>
<tr>
<td>(C) — Sandstone Ridges</td>
<td>Plateaux, strike ridges and intervening valleys.</td>
<td>Lithosols &amp; shallow siliceous sands.</td>
<td>Mid-high open woodland of <em>E. miniata</em>, <em>E. dichromophloia</em> with <em>E. teredonta</em> and <em>E. ferruginea</em>.</td>
<td>Low rates of erosion due to resistant nature of rocks. Correlates to Palaeozoic and Precambrian rocks, particularly Bukalara Sandstone and Tawallah Group rocks.</td>
</tr>
<tr>
<td>(D) — Coastal Plain</td>
<td>Low lying gently undulating country. Erosional and some depositional plains.</td>
<td>Red earths, earthy sands and lithosols. Some clays and alluvial soils along drainage lines.</td>
<td>Very variable mid-high open woodland of mixed eucalypts. <em>E. dichromophloia</em> and <em>E. leucophloia</em> common in the south, with <em>E. terminalis</em>, <em>E. testicula</em> and some <em>E. microtheca</em> in the north.</td>
<td>Low relief, gentle erosional slopes and large competent streams characteristic. Correlates to Cainozoic sediments in the north and the Precambrian Nicholson Granite in the south.</td>
</tr>
<tr>
<td>(E) — Barkly Tableland</td>
<td>Broad flat plains.</td>
<td>Grey and brown clays with some sandy areas.</td>
<td>Grassland with <em>Eulalia fulva</em>, <em>Chrysopogon fallax</em>, <em>Isilema vaginiflorum</em> and some <em>Astragalus squarrosa</em>.</td>
<td>Low permeability increases runoff and erosion. Correlates to Cainozoic sediments.</td>
</tr>
</tbody>
</table>
in geosynclinal conditions and metamorphosed to
greenschist facies quartz-albite-muscovite-biotite schist
and gneiss. The rocks are isoclinal folded along east-
west axes, dip vertically or steeply due north and are
unconformably overlain by the Cliffdale Volcanics;
both are intruded by the Nicholson Granite Complex.

The Murphy Metamorphics are poorly exposed
and rarely form topographic highs. Two informal units
are identified in the Collins Creek/Nicholson River
area:

Elm_1 represents a sequence of predominantly silty
metapelite and shale consisting of quartz, muscovite,
biotite and albite with accessory zircon, tourmaline,
leucogne and opaques.

Elm_2 comprises immature meta-arenites consisting
of angular quartz, lithic fragments, muscovite,
biotite and albite with accessory tourmaline, zircon and
opaques. The original rocks may have been quartz- and
lithic greywackes.

The Murphy Metamorphics lithologically resemble
the Yaringa Metamorphics in the Mt Isa Block and
the Burrell Creek Formation in the Pine Creek
Geosyncline. Their upper age limit of 1883±83 Ma is
constrained by the older phases of the Nicholson
Granite Complex and is in agreement with an earlier
suggestion by Plumb and Derrick (1975) that the
Murphy Metamorphics are at least 1900 Ma and
possibly 2100 Ma old.

**NICHOLSON GRANITE COMPLEX (Pgn)**
The Nicholson Granite Complex was defined by Sweet
and Slater (1975) and includes the Norris and Nichol-
songranites of Roberts and others (1963). Although
Gardner (1978) mapped and described eight lith-
ological units within the complex, it is possible to
simplify these into two broad petrological and age-
related groups (Gardner, 1978, Ahmad, 1987b). The
earlier mapping of 'Nicholson' and 'Norris' granites is
not substantiated as the younger 'Norris Granite'
includes both groups.

Group A (Pgn_a) generally forms low undulating
hills in SEIGAL and rubble-covered flats in NICHOLSON
RIVER. It includes units 1, 2 and 4 and comprises
inequigranular, coarse- to medium-grained hornblende
Figure 3  Tectonic setting.

and/or biotite-bearing granite, adamellite and granodiorite, emplaced into the mesozone. Mafic xenoliths rich in hornblende, biotite and plagioclase are common. Large K-feldspar phenocrysts, often up to 70 mm long, are common (Plate 1). They are frequently euhedral, perthitic and carry inclusions of groundmass minerals, suggesting a metasomatic origin resulting from late stage K-rich fluid (Gardner, 1978). The groundmass includes quartz, plagioclase, perthite, hornblende and biotite with accessory sphene, apatite, zircon and monazite. The crystallisation sequence appears to be K-feldspar followed by plagioclase joined by quartz. This excludes the K-feldspar phenocrysts which formed later.

Group B (Egnb) generally forms undulating hills and is well exposed in SEIGAL area. In Nicholson River it forms conical hills in the surrounding flat country occupied by Egnb. It includes units 5, 6, 7 and 8 and comprises equigranular biotite and/or muscovite-bearing adamellite, granite and alkali granite emplaced into the epizone (Plate 2). Hornblende is rare, mafic xenoliths and K-feldspar phenocrysts are usually absent. Myrmekitic quartz-K-feldspar intergrowths are common suggesting simultaneous crystallisation. Zircon, apatite and fluorite are common accessory minerals, sphene is rare.

**Geochemistry and age**

Geochemically the Egnb stocks are more fractionated. They have higher SiO₂, Al₂O₃, Rb, K and lower Sr, Ca, and Mg values (Table 3). The FeO₉/FeO ratios are also notably higher. Initial Sr⁹⁰/Sr⁹⁸ ratios for the ‘Nicholson Granite’ are 0.7178±0.0038 (Gardner, 1978). Regrouping of the analyses given by Gardner (1978) suggests poorly defined initial Sr³⁹/Sr³⁸ ratios for Egnb to be 0.7132±0.0059 and for Egnb, 0.715±0.0058 (Fanning, 1986).

The Nicholson Granite Complex is characterised by high K₂O, low CaO, FeO/Fe₂O₃ values and generally has a high concentration of trace elements. In most respects they are comparable to the Kalkadoon and Ewen Batholiths in the Mount Isa Block for which a mantle origin has been proposed (Wyborn and Page, 1983).


Nicholson and Norris granites were dated by McDougall and others (1965), AMDEL (1973, 1975) and Fanning and Webb (1988a,b). Although a total of 37 Rb-Sr analyses are available, the precise dates of the various phases are uncertain. McDougall and others (1965) gave an average age for the Nicholson Granite of 1815 Ma, and for the Norris Granite an age of 1790 Ma, but the spread in the measured age was greater than the experimental error and it was concluded that these granite were experimentally indistinguishable. AMDEL (1973) determined two distinct rock isochrons by combining analyses from unit 1 and 6, and from unit 2 and 5. The isochron obtained from units 1 and 6 gave
Table 2: Summary of Proterozoic stratigraphic units.

<table>
<thead>
<tr>
<th>McARTHUR BASIN</th>
<th>MURPHY INLIER</th>
<th>LAWN HILL PLATFORM AND SOUTH NICHOLSON BASIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mc ARTHUR GROUP (Pm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Karns Dolomite (EmK) 130 m+</td>
<td></td>
<td>SOUTH NICHOLSON GROUP (Es) 300 m +</td>
</tr>
<tr>
<td>Alternating dolomite, siltstone and sandstone</td>
<td></td>
<td>Sandstone, silstone and shale</td>
</tr>
<tr>
<td>Masterton Sandstone (Ems) 150 m+</td>
<td></td>
<td>FICKLING GROUP (Ef)</td>
</tr>
<tr>
<td>Sandstone, minor conglomerate</td>
<td></td>
<td>Doomadgee Formation (Etl) 400 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sandstone, dolomite, siltstone and shale</td>
</tr>
<tr>
<td>TAWALLAH GROUP (Pt)</td>
<td></td>
<td>Mount Les Stilson (Etd) 90 m</td>
</tr>
<tr>
<td>Packsaddle Microgranite (Egr)</td>
<td></td>
<td>Dolomitic siltstone and shale</td>
</tr>
<tr>
<td>Porphyritic microgranite</td>
<td></td>
<td>Walford Dolomite (Etw) 400 m</td>
</tr>
<tr>
<td>Hobblechain Rhyolite (Eth) 60+</td>
<td></td>
<td>Dolomite, silicified dolomite, shale, sandstone</td>
</tr>
<tr>
<td>Porphyritic rhyolite</td>
<td></td>
<td>Fish River Formation (Efl) 250 m</td>
</tr>
<tr>
<td>Gold Creek Volcanics (Etg) 180 m</td>
<td></td>
<td>Sandstone</td>
</tr>
<tr>
<td>Trachyte, latite, tuff and sandstone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wollogorang Formation (Eto) 180 m</td>
<td></td>
<td></td>
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<tr>
<td>Dolomite, siltstone and sandstone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Settlement Creek Volcanics (Ete) 150 m</td>
<td></td>
<td>Peters Creek Volcanics (Etp) 600 m</td>
</tr>
<tr>
<td>Quartz latite and trachyte</td>
<td></td>
<td>Alternating sequence of basalt, rhyolite and some rhyodacite; some intermediate volcanics; minor tuff, shale, sandstone, silstone and dolomite</td>
</tr>
<tr>
<td>Aquarium Formation (Etg) 160 m</td>
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<tr>
<td>Glaucolithic sandstone</td>
<td></td>
<td>Wire Creek Sandstone (Etil) 50 m</td>
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<tr>
<td>Sly Creek Sandstone (Etl) 320 m</td>
<td></td>
<td>Sandstone and Conglomerite</td>
</tr>
<tr>
<td>Sandstone</td>
<td></td>
<td></td>
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<tr>
<td>McDermott Formation (Etd) 200 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dolomite, siltstone and sandstone</td>
<td></td>
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<tr>
<td>Seigal Volcanics (Ets) 1500 m</td>
<td></td>
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<tr>
<td>Basalt and tuff; minor sandstone</td>
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<td></td>
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<tr>
<td>Westmoreland Conglomerate (Etw) 1900 m</td>
<td></td>
<td></td>
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<tr>
<td>Sandstone and Conglomerite</td>
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<tr>
<td>NICHOLSON GRANITE COMPLEX (Egn)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Egn, Biotite ± muscovite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>granite and adamellite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Egn, Hornblende biotite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>adamellite and granodiorite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLIFFDALE VOLCANICS (Ecc) 4000 m +</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ecc, Billicumidi Rhyolite Member</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alkali rhyolite lava</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ecc, Rhyolitic and alkali</td>
<td></td>
<td></td>
</tr>
<tr>
<td>rhyolitic ignimbrite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MURPHY METAMORPHICS (Elm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quartz-feldspar-mica schist</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

an age of 1843±83 Ma and the one from units 2 and 5 an age of 1773±24 Ma. A regrouping of various available analyses gave an age for Egn of 1781±117 Ma and for Egn of 1719±22 Ma (Fanning, 1986), which statistically are not different. Plumb and others (in press) consider a minimum age for Egn to be 1840 Ma (K-Ar biotite, Phase 1; McDougall and others; 1965) or 1820±103 Ma (Rb-Sr, total rock, Phase 2; AMDEL, 1973); and for Egn, to be about 1730 (Rb-Sr total rock-muscovite Phase 8; McDougall and others; 1965; Rb-Sr total rock Phase 5 and 8; AMDEL, 1975). 1621 ± 28 Ma from Rb-rich greisen at Crystal Hill (Ahmad, 1986) suggests even younger igneous activity.

CLIFFDALE VOLCANICS (Ecc)
The Cliffdale Volcanics sequence is over 4000 m thick and has been divided into five members and several sub-members (Mitchell, 1976; Sweet and others, 1981). It is possible to simplify this subdivision by placing the rocks of about the same age and similar petrological features into two groups (Ecc and Ecc).
The lower sequence (Ec, thickness about 2000 m) generally forms steep rugged hills and is well exposed south of the Westmoreland Conglomerate belt. It includes the lower four members of Sweet and others (1981), namely, Ec1, Ec2, Ec3, and Ec4. The lithology is dominated by coarse, poorly sorted ignimbrites of dacitic and rhyolitic composition. Minor flow-banded rhyolite also occurs in places. The ignimbrites range in colour from pink to dark bluish grey. The light coloured varieties are rich in quartz phenocrysts while in the dark coloured varieties feldspar is abundant and quartz is insignificant or absent. The groundmass consists of glass strands and intergrowths of quartz and feldspar.

Minor constituents include biotite, actinolite, sphene and magnetite. Hornblende and augite are noted in the dark coloured varieties. Some dark grey coloured andesitic intrusives (Ec, of Sweet and others, 1981) are also included in the lower sequence.

The upper sequence (Ec, thickness about 2000 m) includes the Billiumidji Rhyolite Member and consists essentially of flow-banded alkali rhyolite and minor tuff. The rhyolite is red to pale pink, porphyritic and is generally flow-banded with both regular and convolute banding. Some massive flows contain vugs sometimes filled with quartz, epidote, calcite or clay.

The nature of the contact between Ec and Ec is debatable. Sweet and others (1981) described it as conformable, while Darby (1985) considers it to be locally unconformable. Darby (1986) also states that at


Plate 2 Equigranular variety of the Nicholson Granite Complex (Egn). RA 015380.

the grid reference RA 851462 (on WESTMORELAND) a stock of Egn intrudes Ec but is truncated by Ec. Mitchell (1976) described angular fragments of rhyolite and quartz near the base of Ec as flow breccia but they may well be part of a local unconformity.

**Geochemistry and age**

Geochemically Ec, is more fractionated with higher SiO2, Al2O3, Rb and K and lower Sr, Ca, and Mg. Initial Sr87Sr86 ratios are well constrained at 0.7078±0.0017 (AMDEL, 1973) but these are based on an isochron which include four samples from the upper part of Ec, close to the contact with a Egn phase and four samples from Ec. The isochron age from these eight samples is placed at 1770±20 Ma. The age of the lower sequence is thus uncertain.

**DYKES**

The Murphy Inlier sequence is intruded by both acid and basic dykes. The acid dykes are confined to the Murphy Inlier but the basic dykes extend into the younger McArthur Basin’s sequence and may be considerably younger and probably constitute feeders for the Seigal Volcanics (Sweet and others, 1981). Acid dykes occur in two main sets, one trending west to west-northwest, and the other north to northwest. They range in length from 20 m to 10 km and vary in width from 0.5 to 400 m. Chemical analyses
**Table 3** Chemical and mineralogical composition of the granite types in the Nicholson Granite Complex.

<table>
<thead>
<tr>
<th></th>
<th>Group A (14 samples)</th>
<th>Group B (9 samples)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Range</td>
</tr>
<tr>
<td>*<em>Major elements</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO₂</td>
<td>66.4</td>
<td>50.8-74.7</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>14.8</td>
<td>12.2-16.1</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>1.0</td>
<td>0.4-1.7</td>
</tr>
<tr>
<td>FeO</td>
<td>3.6</td>
<td>1.2-6.4</td>
</tr>
<tr>
<td>CaO</td>
<td>2.5</td>
<td>0.8-5.0</td>
</tr>
<tr>
<td>MgO</td>
<td>2.2</td>
<td>0.1-6.7</td>
</tr>
<tr>
<td>Na₂O</td>
<td>2.6</td>
<td>1.8-3.2</td>
</tr>
<tr>
<td>K₂O</td>
<td>5.1</td>
<td>4.5-6.0</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.5</td>
<td>0.2-0.7</td>
</tr>
<tr>
<td>Al/Na+K+Ca</td>
<td>1.1</td>
<td>0.9-1.2</td>
</tr>
<tr>
<td>Fe₂O₃/FeO</td>
<td>0.3</td>
<td>0.1-0.7</td>
</tr>
<tr>
<td>Na₂O/K₂O</td>
<td>0.51</td>
<td>0.3-0.7</td>
</tr>
<tr>
<td><strong>Trace elements</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rb</td>
<td>233</td>
<td>170-300</td>
</tr>
<tr>
<td>Sr</td>
<td>282</td>
<td>40-500</td>
</tr>
<tr>
<td>Y</td>
<td>36</td>
<td>20-80</td>
</tr>
<tr>
<td>Nb</td>
<td>15.5</td>
<td>5-35</td>
</tr>
<tr>
<td>Ba</td>
<td>982</td>
<td>240-1800</td>
</tr>
<tr>
<td>Ba/Rb</td>
<td>4.7</td>
<td>0.4-7.6</td>
</tr>
<tr>
<td>Initial ⁸⁷Sr/⁸⁶Sr**</td>
<td>0.7132</td>
<td>0.7122-0.7174</td>
</tr>
</tbody>
</table>

**Mineralogy**

- granodiorite, monzonite and quartz monzonite, some adamellite
- hornblende + biotite + spherne
- hornblende-bearing xenoliths common
- fluorite rare
- greisenisation rare

- mostly adamellite and alkali feldspar granite
- biotite + muscovite, rare hornblende and sphen
- hornblende-bearing, xenoliths rare
- fluorite common
- greisenisation common


** Calculated by regrouping of the analyses given in Gardner (1978).

show that they are of dacitic, rhyodacitic and rhyolitic composition (Sweet and others, 1981). Dykes associated with Egm and Ecc, include feldspar and quartz porphyry whereas those with Egn and Ecb generally are quartz-poor or quartz-free porphyry, aplite or microgranite.

Basic dykes mainly consist of theleitic dolerite, 3 to 30 m thick and extend over several km along strike. One of the dykes extends virtually continuously over a strike length of over 40 km in the SEIGAL sheet.

**RELATIONSHIP BETWEEN Egm and Ecc**

The relationship between Egm and Egn is clearly intrusive as is shown by truncated contacts and attendant thermal metamorphic effects. However, the relationships between the individual stock of Egm and Egn is not clear. Egm plutons intrude the Ecc sequence at several places but the contacts between Egm and Ecc are poorly exposed and are interpreted as being intrusive (Sweet and others, 1981). There are strong geochemical similarities between Egm and Ecc, suggesting a co-magmatic relationship and the same appears to be the case between Egn and Ecc (Ahmad, 1987b).

**McARThUR BASIN SEQUENCE**

**TAWALLAH GROUP**

The Tawallah Group is the oldest group of the McArthur Basin sequence. It overlies the igneous and metamorphic complexes of the Murphy Inlier with an angular unconformity and is conformably overlain by the Masterton Sandstone of the McArthur Group. The Masterton Sandstone was previously included into the Masterton Formation of the Tawallah Group (Roberts and others, 1963) but Jackson and others (1987) considered it to be the basal formation of the McArthur Group. The other members of the Masterton Formation — namely the Gold Creek Volcanics, Hobblechain Rhyolite and Pack saddie Microgranite — have been given a formation status but remain part of the Tawallah Group (Jackson and others, 1987). The Tawallah Group has a maximum composite thickness
of 4500 m and consists of alternating intervals of detrital sediments, volcanics and carbonates. The age of the Tawallah Group is constrained by the age of the Cliffdale Volcanics (1730±20 Ma), Rb-Sr isochron, (AMDELA, 1973) and the age of the middle McArthur Group (1690 Ma, U-Pb zircon dating, Page, 1981).

**Westmoreland Conglomerate (Ptw)**
The Westmoreland Conglomerate, the oldest formation of the Middle Proterozoic McArthur Basin, is exposed in an east-northeast trending belt, 140 km long and up to 20 km wide, along the northern margin of the Murphy Inlier (Plate 3). It unconformably overlies the Early Proterozoic Murphy Metamorphics in the west, the Nicholson Granite Complex in the central area and the Cliffdale Volcanics in the east. Because of its association with the uranium mineralisation, the Westmoreland Conglomerate was studied in greater detail (Ahmad and others, 1984; Wygralak and others, 1988) and the following description relies heavily on the results obtained in these studies.

**Stratigraphy and lithology**
The Westmoreland Conglomerate is up to 1800 m thick. Sweet and others (1981) divided the formation into four informal units (1-4) east of the Calvert Fault, and into three units (1 and 4) separated by a thick sandstone sequence containing conglomeratic units, west of the fault. Carter and others (1961) nominated the type section for the Westmoreland Conglomerate at a locality about 2 km southeast of Buck Hill in WESTMORELAND.

On the basis of the present study, the Westmoreland Conglomerate is divided into five sedimentary units each representing a major fining-upward cycle of sedimentation (Wygralak and others, 1988).

Stratigraphic sections through the Westmoreland Conglomerate showing these major cycles, are given in Figure 4 and some salient features are summarised in Table 4.

**Structure**
The strike of the Westmoreland Conglomerate is generally parallel to the Murphy Inlier and measured dips are 5 — 10° toward the northwest, except in the vicinity of some faults and in the zone of flexuring known as the Tin Hole Hinge Line (Roberts and others, 1963). The strata dip steeply to the north at the hinge line but rapidly resume a gentle northwesterly dip within about 100 m north of this structure.

One major outcrop of the Westmoreland Conglomerate here named the Seigal Outlier, and situated south of the hinge line, between Fish River and Tin Hole Creek, has a thickness of less than 100 m. At this locality the Westmoreland Conglomerate unconformably overlies the Nicholson Granite Complex and is conformably overlain by the Seigal Volcanics. About 2 km to the north of the Tin Hole Hinge Line the Westmoreland Conglomerate is about 1200 m thick.

Roberts (unpublished manuscript) postulated, that the Murphy Inlier was the main source for the sediments of the Westmoreland Conglomerate. Roberts and others (1963) also suggested that the significant differences in thickness may have been caused by down-flexuring and faulting of the basin north of the hinge line at the time of the deposition of the Westmoreland Conglomerate.
Table 4  Summarised description of the five units of the Westmoreland Conglomerate.

<table>
<thead>
<tr>
<th>UNIT</th>
<th>THICKNESS</th>
<th>LI ThOLOGY</th>
<th>SEDIMENTARY STRUCTURES</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0-20</td>
<td>lithic greywacke, quartzwacke and quartz arenite: medium-grained, well sorted, rounded grains of quartz, acid volcanics, muscovite and chert; sericitic and hematitic matrix. Locally red, calcareous siltstone on the top</td>
<td>medium-to large-scale planar cross-bedding, some ripple-marks</td>
</tr>
<tr>
<td></td>
<td>20-130</td>
<td>sublitharenite and lithic greywacke: coarse-grained with scattered pebbles, moderately sorted, subrounded grains of quartz, acid volcanics and chert; sericitic and hematitic matrix</td>
<td>medium-scale trough cross-bedding</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>cobble conglomerate and conglomeratic sandstone: mostly matrix-supported clasts of quartz, sandstone and acid volcanics up to 20 cm in size; interbeds of poorly sorted, medium-grained, subangular to subrounded greywacke and lithic arenite; near the top a 0.5-2.0 m thick clast-supported conglomerate (“metre conglomerate”), maximum clast size 0.5 m</td>
<td>medium-scale trough cross-bedding</td>
</tr>
<tr>
<td>3</td>
<td>0-180</td>
<td>lithic greywacke and quartzwacke: medium to coarse-grained, well sorted, subangular to rounded grains of quartz, acid volcanics and chert; sericitic matrix;</td>
<td>mega-scale planar cross-bedding</td>
</tr>
<tr>
<td></td>
<td>0-100</td>
<td>lithic arenite: very coarse-grained to granular, poorly sorted, subangular to well-rounded grains of quartz, acid volcanics, chert and sandstone; sericitic matrix with some hematite</td>
<td>medium-to large-scale trough cross-bedding</td>
</tr>
<tr>
<td></td>
<td>0-550</td>
<td>lithic greywacke: coarse-grained to granular, poorly sorted, subangular to subrounded grains of quartz, acid volcanics, muscovite, chert and locally feldspar; sericitic and often ferruginous matrix; thin pebble interbeds; lenses of matrix-supported conglomerate near the top</td>
<td>small-to medium-scale trough cross-bedding</td>
</tr>
<tr>
<td></td>
<td>0-130</td>
<td>boulder and cobble conglomerate: matrix supported, extremely poorly sorted, angular to well-rounded clasts of silicified sandstone, acid volcanics and quartz, up to 0.5 m in size; matrix of coarse, angular sandstone, often hematitic</td>
<td>inverse grading</td>
</tr>
<tr>
<td>2b</td>
<td>0-40</td>
<td>lithic arenite: medium-grained, well sorted, well rounded grains of quartz, acid volcanics and feldspar; sericitic matrix</td>
<td>small-scale planar cross-bedding</td>
</tr>
<tr>
<td></td>
<td>100-740</td>
<td>lithic greywacke: medium-grained to granular, moderately sorted, subangular to subrounded grains of quartz, acid volcanics, muscovite and locally feldspar; pebble beds in upper part</td>
<td>small-to medium-scale trough cross-bedding</td>
</tr>
<tr>
<td></td>
<td>15-300</td>
<td>boulder to cobble conglomerate: mostly matrix-supported, poorly sorted, angular to well-rounded clasts of silicified sandstone and acid volcanics; matrix of coarse sandstone and sericite; locally contains lenses of feldspathic greywacke</td>
<td>inverse grading, occasional small-scale trough cross-bedding in matrix</td>
</tr>
<tr>
<td>2a</td>
<td>100-500</td>
<td>lithic greywacke, sublitharenite, minor greywacke: medium to very coarse-grained, moderately sorted, angular to rounded grains of quartz, acid volcanics, muscovite and chert; scattered 1-2 cm pebbles of quartz, silicified sandstone and black chert; sericitic matrix</td>
<td>rip-up siltstone clasts near the top, small-scale trough cross-bedding</td>
</tr>
<tr>
<td></td>
<td>0-80</td>
<td>pebble and cobble conglomerate: matrix- or clast-supported, moderately sorted, well-rounded clasts of quartz, sandstone, siltstone, acid volcanics and chert, up to 20 cm in size; matrix of clayey sandstone; interbeds of sublitharenite and lithic greywacke; common silicification</td>
<td>small-scale trough cross-bedding in matrix</td>
</tr>
<tr>
<td>1</td>
<td>60-180</td>
<td>quartz arenite, minor sublitharenite and lithic greywacke: fine- to medium-grained, well to moderately sorted, subrounded to rounded grains of quartz; small amount of sericitic matrix; commonly silicified</td>
<td>small-to medium scale low-angle planar cross-bedding, rare small-scale trough cross-bedding, lamination</td>
</tr>
</tbody>
</table>

Cont/...
| 50-150 | sublitharomite, lithic greywacke, quartzwacke and minor quartz arenite; fine- to coarse-grained, poorly sorted, angular to subrounded grains of quartz, acid volcanics and chert; sericitic, often ferruginous matrix; granular and pebbly interbeds | medium-scale trough and planar cross-bedding |
| 0-30 | micaceous siltstone | wave ripple marks, laminaiton |
| 0-30 | talus breccia: angular clasts of acid volcanics, tuff, chert and sandstone up to 1 m in size |  |

Table 4 (continued)

This interpretation is no longer valid in view of the same, southwestern palaeocurrent directions on both sides of the hinge line (Ahmad and others, 1984; Wygrala and others, 1988) which probably represents a thrust fault along which the Westmoreland Conglomerate moved several kilometres southward (Sweet and others, 1981).

The lithology of clasts, the grain size and the overall fabric of the rocks suggest that the lower units (1, 2a, 2b and possibly 3) were either not deposited on the Seigal Outlier or were deposited and subsequently eroded.

**Lithofacies**

**Massive, matrix-supported gravel (Gms)**

This lithofacies consists of extremely poorly sorted, matrix-supported boulder conglomerate, deposited by debris flows. It comprises some 12% (by volume) of the Westmoreland Conglomerate. Contact with the underlying units is abrupt and non-erosive. The fabric is random, without internal bedding or imbrication. Maximum clast size reaches 0.6 m. Sequences commonly have inverse grading, larger clasts become concentrated near the top.

Rounding of the clasts varies widely. The larger clasts are usually well-rounded whereas the smaller ones are often angular. The clasts comprise white or pink, often silicified sandstone; grey, gravelly sandstone; vein quartz, green or red volcanic fragments and minor chert. The matrix consists of a mixture of clay minerals and sand-size sediment. This lithofacies is most abundant in the eastern part of the outcrop area of the Westmoreland Conglomerate. The most spectacular outcrop, the El Hussen Cliff (Plate 4), located some 2.5 km southwest of the Rocky Creek section, consists of up to 80 m of matrix-supported conglomerate.

**Massive or crudely bedded gravel (Gm)**

This lithofacies is represented by clast-supported conglomerate (Plate 5) with stratification formed by variation in the size and sorting of the framework clasts. This lithofacies comprises some 4% of the total volume of the Westmoreland Conglomerate.

The conglomerate sequences, usually a few to several metres thick, contain poorly sorted but commonly well rounded clasts of white sandstone, pink silicified sandstone, quartz, volcanics, siltstone and chert.

Occasional clasts are up to 0.5 m in size, but commonly do not exceed 1-5 cm. Imbrication is observed in places. The proportion of clasts varies within the sequences from clast-supported conglomerate at the bottom to conglomeratic sandstone toward the top.

The matrix consists of clay and sand-size grains, and is often red coloured due to the presence of iron oxides.

**Stratified gravel (Gt) and sand (St) with trough cross-beds**

These are the most common lithofacies, together constituting 62% of the Westmoreland Conglomerate sediments. They are characterized by abundant trough cross-bedding. The cross-bedded sets vary from large (1-3 m) to mega (more than 3 m) scale.

The lithofacies Gt and St are difficult to separate since the grain size changes gradually from medium-grained sandstone to very coarse, granular or pebbly sandstone (Plates 6 and 7).

The sediment is often immature, consists of angular grains of quartz, minor volcanic fragments and opaque clays. It is often red to brown coloured due to a high content of iron oxides. Sorting is poor. Clasts of quartz, pink, silicified sandstone and volcanic fragments, usually 1-3 cm across, are common.

**Stratified gravel (Gp) and sand (Sp) with planar cross-beds**

Some 11% of the Westmoreland Conglomerate is represented by these lithofacies. The coarser lithofacies Gp occurs only sporadically. The much commoner lithofacies Sp is characterised by lateral continuity, lack of channelling and large to mega scale planar cross-bedding.

The sediment consists of well sorted, medium to coarse sandstone, in some cases silicified and containing mica. The matrix content is minor or absent. Some beds are ripple-marked. Laminae are occasionally enriched in iron oxides.

**Horizontally laminated sand (Sh)**

This lithofacies contains fine to medium, and occasionally coarse sandstone, which sometimes is silicified. The sandstone is composed of quartz and various amounts of white, clayey matrix. It comprises almost 10% of the Westmoreland Conglomerate.

The framework is well sorted and usually rounded or subrounded. In places the sandstone includes scattered pebbles of white quartz and sandstone, commonly 1-2 cm in size.

* The terminology of lithofacies was adopted from Miall (1978)
Plate 4  Westmoreland Conglomerate — massive conglomerate of the lithofacies Gms in the El Hussen cliff. RA 038593.

Figure 4  Stratigraphic sections of the Westmoreland Conglomerate.
Horizontal lamination, often marked by bands rich in iron oxides, is characteristic for this lithofacies. Low angle (less than 10°) planar cross bedding occurs in places.

Ripple-marked sand (Sr)
This lithofacies, which comprises less than 1% of the Westmoreland Conglomerate, is made up of a mature, fine- to medium-grained, well sorted arenite composed mostly of quartz and with little matrix. Various types of small current and wave ripple-marks are common.

Other lithofacies
Early sedimentation of the Westmoreland Conglomerate was controlled by local palaeotopography. Around palaeohills talus deposits developed, represented by poorly sorted, angular boulder conglomerate and breccia, consisting of angular clasts of acid volcanics.

In other places red, micaceous, laminated and ripple-marked silts were deposited in lakes which filled palaeodepressions. Similar siltstones were developed locally on the very top of the Westmoreland Conglomerate sequence.

Interpretation of lithofacies
The several lithofacies of the Westmoreland Conglomerate reflect the results of depositional processes which acted in various parts of an alluvial fan and braided river system.

Lithofacies Gms is interpreted as a debris flow deposit. Its development requires certain conditions: lack of vegetation cover, a source providing debris and material for a muddy matrix, infrequent periods of heavy rainfall, and steep slopes.

Lithofacies Gm represents sheet flood, stream channel and sieve deposits. Many of these deposits have a tabular form and extend over a few tens of kilometres. These are interpreted as sheet flood deposits. This is by far the most common mode. In some cases the deposits are lenticular and must have been deposited in stream channels.

In places, such deposits are produced by the reworking of gravelly sands and are considered to be sieve deposits. They have a very large aerial extent.

As discussed earlier, lithofacies Gt and St occur in close association. They reflect deposition by channel fill or dunes. In most cases the troughs start in sediment of pebble to granule size and fine upward to very coarse or medium-grained sand. The upward fining is considered to be due to decreasing stream velocities.

Lithofacies Gp may be more common than identified, as it is difficult to distinguish between large, low-angle planar cross beds and bedding, especially in coarse-grained sediments. The grain size ranges from 2

Plate 6 Lithofacies Gt in the Westmoreland Conglomerate. RA 078598.
to 4 mm and material is best described as stratified grit. It presumably contains reworked finer material from the debris flows. Deposition probably occurred as tongue-shaped bars or deltaic growths from older bar remnants.

Lithofacies Sp and Sr define the top of the sequence in many areas, with Sr commonly occurring in the uppermost beds of unit Etw₄. These two lithofacies also define the completion of major cycles. They are considered to be deposited as linguoid bars Sp and ripples Sr from low-energy streams.

Lithofacies Sh is seen only in the bottom 100 m of the Westmoreland Conglomerate. It was deposited by planar bed flow.

**Vertical profile models**

Six vertical profile models, based on order of predominance of various lithofacies, were erected by Miall (1977). Even though the Westmoreland Conglomerate studies were on a much broader scale than many detailed sedimentological analyses, the vertical profile models can still be applied to the formation and they enable the description of a viable lithofacies sequence.

In the Etw₁ sequence the lithofacies in order of abundance are St-Sp-Sh. To the east, in Queensland, lithofacies Gm (?) is recorded at the base of the sequence, but the development is only local (Sweet and Slater, 1975). The lithofacies sequence for unit Etw₁ is similar to the Platte type (S_H) assemblage, deposited by sandy braided rivers. The overall grain size decreases upward and an essentially uniform sequence can be traced throughout the strike length, except in areas of slightly higher basement (Sweet and Slater, 1975).

Unit Etw₁ is locally absent in the vicinity of the Calvert Fault, where units Etw₂a and Etw₂b rest directly on the basement. It is not clear if the absence is due to erosion or whether unit Etw₁ was not deposited at all. The predominance of lithofacies Gm toward the base of these units in the eastern part indicates deposition by high energy proximal rivers.

In unit Etw₂a, the sequence at the bottom comprises lithofacies Gm-St, overlain predominantly by St. The sedimentation probably started as proximal to distal gravelly rivers (Scott type G₁ and Donjek type G₁₁₁) and finished as sandy braided rivers (South Saskatchewan type S_H).

The basal part of unit Etw₂b is dominated by lithofacies Gms and Gm (Trollheim type G₁). These are interpreted to have been deposited in the proximal fan by debris flows and high-energy rivers. This sequence is not traceable to the east and is probably absent in the area east of Rocky Creek. It is best developed in the Dry Creek area and continues as a tabular body for a distance of about 75 km. It is possible that this sequence was never deposited in the east, which would suggest a series of uplifts in that part.

The lithofacies in the upper part of unit Etw₂b in order of abundance are: St-Sh-Gp-Gt. Toward the very top lithofacies Sp is dominant. This suggests a South Saskatchewan type (S_H) deposition followed by Platte type (S_H).

In unit Etw₃, the lower part is dominated by lithofacies Gms, representing a Trollheim type (G₁) deposition by debris flows. This lithofacies thins westward and lenses out completely west of Rocky Creek.

It is overlain by a sequence dominated by lithofacies Gt and St, with Gt more abundant in the east. A proximal river environment of Scott (G₁) or Donjek (G₁₁₁) type is suggested for this sequence. Toward the top of the sequence lithofacies Sp dominates locally, indicating that the deposition of this unit ended in a Platte type (S_H) sandy braided river environment.

In unit Etw₄, the lower part of the sequence is dominated by lithofacies Gt, Gp and Gm, suggesting Donjek type (G₁₁₁) deposition by distal gravelly rivers. This environment changed up the sequence into South Saskatchewan type (S_H), dominated by facies St. The top few beds are dominated by facies Sp and Sr suggesting Platte type (S_H) deposition.

The overall profiles of the Westmoreland Conglomerate thus suggests the following sequence:

<table>
<thead>
<tr>
<th>Unit</th>
<th>Lithofacies sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Etw₁</td>
<td>G₁₁ — S_H</td>
</tr>
<tr>
<td>Etw₂a</td>
<td>G₁₁ — S_H</td>
</tr>
<tr>
<td>Etw₂b</td>
<td>G₁ — S_H — S_H₁₁₁</td>
</tr>
<tr>
<td>Etw₃</td>
<td>G₁ — G₁₁ — G₁₁₁ — S_H</td>
</tr>
<tr>
<td>Etw₄</td>
<td>G₁₁₁ — S_H</td>
</tr>
</tbody>
</table>
In general, the average grain size within each unit decreases upward. Taking the whole sequence, the average grain size increases up to unit Etw₂ and then quickly decreases. Such a pattern suggests that periodic tectonic rejuvenation of the area (uplift of the source or subsidence of the basin) reached its maximum during the sedimentation of unit Etw₂, rapidly decreasing thereafter.

**Direction of palaeotransport**

A total of some 1250 measurements of cross bedding were taken at 164 places. Most of the measurements were made on medium scale (1.0-0.25 m) trough cross bedded sets, as close as possible to the axial part of the troughs. The field data were corrected for tilt using a stereographic net. Tilt corrections were neglected if the dip of the bedding was less than 5°.

The Westmoreland Conglomerate shows strongly undirectional, southwesterly direction of palaeotransport (Figure 5). There is no appreciable difference in the general direction of palaeotransport between particular units of the Westmoreland Conglomerate. However, directions in units 1, 2a and 2b in the area around the Calvert Fault, and some measurements in the vicinity of the headwaters of Collins Creek at the western end of the Westmoreland Conglomerate belt, show considerable local variation. These variations probably indicate a local influx of sediments from the Murphy Inlier in addition to the main northeasterly source.

There is no change in the direction of palaeotransport in the Seigal Outlier, where the Westmoreland Conglomerate is less than 100 m thick, suggesting that although this part of the basement was elevated during sedimentation, it did not act as an additional source of material.

**Petrography**

**Lithology of clasts**

Except for the basal conglomerate and talus breccia of unit 1, where the clast content strongly depends on the composition of local basement, the clast content of all five units of the Westmoreland Conglomerate is uniform. The most frequent components of the framework are well rounded clasts of white vein quartz. Other clasts in order of decreasing abundance are fine to coarse often silicified sandstone, acid volcanics and tuffs derived from Clifdale Volcanics, metasediments derived from Murphy Metamorphics and, less frequently, chert and siltstone.

Some clasts in younger units consist of material derived from the older units. The best example are clasts of pink silicified sandstone of unit 1 appearing in the conglomerates of unit 2b and 3. Clasts of the Nicholson Granite Complex are noticeably absent.

**Mineral composition of sandstone fraction**

Quartz is the dominant mineral and occurs as monocrystalline and polycrystalline varieties. Monocrystalline quartz is present in three forms: clear xenomorphic, cloudy xenomorphic, and clear idiomorphic. The clear, xenomorphic variety is almost free of fluid inclusions and sometimes contains microlites of muscovite, zircon and green tourmaline. This type of quartz is very common and is interpreted as plutonic in origin. Cloudy xenomorphic quartz comprises grains with abundant fluid inclusions and is probably of hydrothermal origin. The clear idiomorphic, inclusion-free quartz with uniform extinction and common corrosion embayments, is interpreted as volcanic in origin.

Polycrystalline quartz is less abundant and occurs in two varieties. The first consists of aggregates of uniform-sized grains with mostly straight contacts and mosaic-like extinction, interpreted as metamorphic quartz formed under intense but non-shearing stress.

The second variety, which consists of stretched and elongated grains with undulose extinction and sutured grain boundaries, probably formed by shearing or straining during metamorphism.

Chert, a minor component of the sediment framework, is readily recognizable because of its fine, microcrystalline fabric. Some chert contains minor amounts of clay. The source of the chert is not known but it could be of volcanic origin.

Lithic fragments include volcaniclastic fragments of acid lava, tuff, ignimbrite, open-framework angular quartz sandstone, quartz-muscovite gneiss and fine siltstone.

Feldspar is uncommon and consists mostly of altered orthoclase and minor small grains of relatively fresh perthitic microcline. Muscovite and less commonly biotite are rare, muscovite may be, both, detrital and authigenic. Opaque minerals include hematite, finely disseminated in the matrix; minor cassiterite is present in unit 4. Zircon and tourmaline are rare but widespread constituents of the sediment framework. In some samples zircon, tourmaline and other heavy minerals are concentrated in thin bands as a result of winnowing processes.

The matrix is generally fine-grained, clayey and turbid; sericite, chlorite and opaque minerals are common but a detailed composition has not been determined.

**Quartz cement**

Diagenetic quartz is a common feature of the Westmoreland Conglomerate and constitutes up to 25% by volume (commonly 5% — 9%) of the rock. Silification has taken place selectively. A good example is the strongly silicified sandstone sequence of unit 1 interbedded with non-silicified sediments. Some silica overgrowths of this unit show undulose extinction indicating stress conditions after silification. Many of the quartz grains have two silica rims separated by bands of iron oxides, reflecting two stages of silification.

**Texture and maturity**

Sediments of the Westmoreland Conglomerate display a wide variety in sorting and rounding, and commonly contain a mixture of well rounded and angular grains, indicating a multiple source for the rocks. Rounded grains have probably been recycled.

Most of the sediments contain more than 5% matrix and are texturally immature. Sorting ranges from very poor in debris flow conglomerates and some greywackes, to very good in some quartz sandstones and quartz wackes. In a few samples (especially in unit 4) sediments with a high matrix content are well sorted and rounded. This textural inversion indicates mixed products of two energy levels and is a result of recycling of older sediments, incorporated into the final deposit.
Provenance and palaeogeography

Palaeotransport directions indicate a predominantly northeastern source for the sediments. Clast lithologies suggest that the composition of the source area was similar to the presently exposed rocks of the Murphy Inlier.

This evidence indicates that the Westmoreland Conglomerate was probably derived from a northerly extension of the Mt Isa Orogen which formed highlands northeast of the McArthur Basin. Repetitive uplifts, probably along fault-bounded escarpments, produced alluvial and braided stream deposits which now constitute the Westmoreland Conglomerate.

Apart from geophysical evidence there is little data on the basement topography and structure of the area north of the Westmoreland Conglomerate belt. A series of gravity lows trends eastward and roughly follows latitude 17°30'S as is depicted on a preliminary version of the gravimetric map of CALVERT HILLS and WESTMORELAND published by the Bureau of Mineral Resources. Geophysical modelling of a pronounced gravity low in the centre of CALVERT HILLS indicates a basement-high of granitic composition (T. Findhammer, Northern Territory Geological Survey, pers. comm. 1985). Seismic soundings at the eastern end of the gravity low, near Westmoreland Station (Collins, 1983), also indicate the existence of a belt of granitic high. It is thus conceivable that the Westmoreland Conglomerate was deposited in a west-southwest trending trough about 25 km wide, flanked to the south by the Murphy Inlier and to the north by granitic uplands.

A depositional model (Figure 6) is proposed in which the Murphy Inlier formed a topographical high and may have supplied only a small part of the detritus which probably was incorporated into the southwesterly flowing rivers. Each cycle of sedimentation was probably initiated by a separate tectonic pulse. The sequences of units 1 to 3 were the result of increasingly strong episodes of uplift, whereas the uplift responsible for deposition of unit 4 appears to have been more restrained.

Seigal Volcanics (Pts)
The Seigal Volcanics have been recently defined by Sweet and others (1981) and represent the lower part of the Peters Creek Volcanics as mapped by Roberts and others (1963). The major exposures of the Seigal Volcanics form a northeast trending, up to 10km wide belt to the north of the China Wall, between longitude 137°40' and 138°00'. In the east they are poorly exposed but in the centre and west they form rugged and discontinuous strike ridges and are well exposed. A small exposure occurs south of the China Wall between longitudes 137°30' and 137°40' (i.e. the Seigal Outlier).

The Seigal Volcanics conformably overlie the Westmoreland Conglomerate. A thin (1-2 m) reddish brown siltstone bed is exposed at the base in the EL Hussen area and is also seen in a number of drill holes in the NE Westmoreland area where similar interbeds also occur in the top few metres of the Westmoreland Conglomerate.

In the northeastern part of SEIGAL, the upper contact with the McDermott Formation appears to be conformable, but west of the Calvert Fault the Seigal Volcanics are overlain by the Sly Creek Sandstone suggesting that in this area the McDermott Formation either lenses out or was eroded before the deposition of the Sly Creek Sandstone (Sweet and Slatter, 1975).
The Seigal Volcanics are probably not thicker than 1600 m and consist predominantly of basic lavas, though minor tuff interbeds are also present. Numerous thin interbeds of siltstone and fine sandstone are also present and one sandstone interbed, the Carolina Sandstone Member, is up to 20 m thick. The outcrops of the Seigal Volcanics that lie between grid reference QA 797319 and QA 795333 on SEIGAL have been nominated as the type section (Sweet and Slatter, 1975). In the northeast the Carolina Sandstone Member is about 800 m above the base; in the type section it is about 200 m above and in the Seigal Outlier only 50 m above the base.

The lavas occur as flows, generally less than 20 m thick, and are well exposed (Plate 8). Although largely decomposed, they exhibit a massive appearance and spheroidal weathering. The tops of the flows are finer grained than the centres and contain abundant vesicles filled with quartz, chalcedony, hematite and celadonite. Below the Carolina Sandstone Member the Seigal Volcanics are generally more massive and are dominated by basaltic flows but above it the volcanics consist of amygdaloidal basalt, tuffaceous siltstone, micaceous siltstone and agglomerate (Roberts and others, 1963).

**Petrography and geochemistry**

Darby (1986) examined five thin sections prepared from the freshest looking hand specimens and found most to be strongly altered. The volcanics have ophitic to subophitic texture consisting of laths of plagioclase (An$\text{O}$-$\text{An}_{70}$) partly included in augite. Several pyroxene grains suspected of being orthopyroxene or pigeonite were subsequently analysed by Scanning Electron Microscope (SEM) and shown to be augite. The groundmass in all samples is altered and consists of varying proportions of chlorite, sericite, opaques, plagioclase and rarely quartz and alkali feldspar.

**Plate 8** Lava flows in the Seigal Volcanics. RA 050624.
Aggregates of antigorite, probably after olivine, were also noted. Based on the modal composition, Darby (1986) classified the Seigal Volcanics as basalt or trachybasalt of tholeiitic or olivine tholeiitic affinity if indeed the antigorite aggregates represent replacement of olivine.

Geochemical analyses are summarised in Table 5 and are treated in detail by Darby (1986) who concluded that the Seigal Volcanics have tholeiitic affinities, were derived from mantle and extruded in ‘within plate’ setting. The clinopyroxenes have moderately high $\text{Cr}_2\text{O}_3$ values (0.12 to 0.68%) and are considered to be indicative of tholeites of distensive areas (Darby, 1986).

Intrusives and eruptive centres
Dolerite dykes intruding the Murphy Inlier sequence are considered to be feeder of the Seigal Volcanics. Similar dykes intrude the Westmoreland Conglomerate in the proximity of the Redtree and the NE Westmoreland uranium deposits.

A plug of rhyolitic breccia (Plate 9) near the Cobar 2 uranium prospect and rhyolite dykes running in a northeast direction between the Doctors and Debbil Debbil creeks may be feeders of later Settlement or Gold Creek Volcanics (Sweet and others, 1981).

**Carolina Sandstone Member (Pt5)***
The Carolina Sandstone Member is up to 20 m thick and extends from the northeastern margin of Seigal to the headwaters of the Fish River. It is a flabby to massive, fine-grained, dark red weathering grey sandstone with some siltstone interbeds. Cross-bedding is common and some ripple marks and mud cracks are present. To the southwest the member bifurcates into two thin sandstone beds separated by about 30 m of volcanics. The western outcrops are conglomeratic and contain clasts of up to 25 cm across of pink, fine to medium quartz sandstone, quartz, pebble conglomerate, and quartz-cemented sandstone breccia (Sweet and others, 1981).

**Discussion**
The Seigal Volcanics, below the Carolina Sandstone Member appear to have been deposited predominantly under subaerial conditions. The Carolina Sandstone Member is probably a marine deposit. The presence of tuff, tuffaceous siltstone, micaceous siltstone and agglomerate in the upper part of the Seigal Volcanics suggests an increasingly subaqueous environment.

**McDermott Formation (Pt5)**
Although the name McDermott Formation has been used informally by several authors, (eg. Roberts and others, 1963, Sweet and others, 1981), it was formally defined only recently, by Jackson and others (1987). The McDermott Formation conformably overlies the Seigal Volcanics in the northeastern part of Seigal. To the southwest it lenses out and the Seigal Volcanics are overlain by the Sly Creek Sandstone, possibly with a minor angular unconformity. Regionally the McDermott Formation is considered a time-equivalent of the lower part of the Sly Creek Sandstone (Jackson and others, 1987). In CALVERT HILLS it crops out in three main areas viz., Branch Creek in the east, Little Calvert River in the central part, and along headwaters of the Robinson River in the west.

Jackson and others (1987) nominated the thickest known section (400 m, base not exposed) in the Horse Creek area south of the Calvert Hills homestead as the stratotype, and designated as a reference section for the lower part of the McDermott Formation a section exposed in the Branch Creek area (Figure 7). They have divided the McDermott Formation into four informal units (not shown on the map).

The McDermott Formation is characterised by alternating beds of arenite and dolostone. Numerous sections studied indicate that although the style of sedimentation is similar everywhere, the formation is characterised by marked lateral changes rendering the correlation between sections difficult.

**Stratigraphy and lithology**
The basal part of the McDermott Formation (Unit 1), exposed at the reference section (Figure 7) consists of a 30 m thick sequence of red or white, medium-grained, cross-bedded quartz sandstone and dolomitic sandstone with interbeds of shale. It is followed by 80 m (over 100 m in the type section) of sandy dolarenites and fine-grained sandstones (Unit 2) containing ooliths, pisoliths, intraformational breccia and conglomerate. Small-scale trough cross-bedding, ripple-marks and
### Table 5  Chemical analyses of Tawallah Group igneous rocks.

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- not detected

pseudomorphs after evaporitic minerals are often seen. The dolomitic beds also contain stratiform and columnar stromatolites.

The overlying unit (Unit 3), best exposed in the Horse Creek area is about 45 m thick and consists of cherty breccia. It contains ferruginous and manganiferous boxworks, botryoidal structures, quartz veins and cavities filled with large crystals of quartz. Remnants of sedimentary structures indicate that the formation occurred after deposition of the original carbonate sediments. Due to the resistant nature of the chert, this unit forms a prominent topographic feature. Jackson and others (1987) considered that this unit represents a significant stratigraphic break during which the dolostones were uplifted, eroded and silicified to considerable depth.

The uppermost unit (Unit 4) is about 200 m thick and comprises alternating 5-15 m thick intervals of thin- to medium-bedded, flaggy sandstone, and dolomite. It is exposed in the Horse Creek, Blackfella Creek and Sandy Creek areas, but is absent towards the southeast. The sediments contain gypseum pseudomor-
Figure 7 Sections of the McDermott Formation.

The upper 30 m also contain disseminated crystals of pyrite.

Unit 4 is overlain by conglomerate and quartz sandstone of the Sly Creek Sandstone with which it forms a sharp contact.

Depositional environment
Sedimentological features of the carbonate facies of the McDermott Formation indicate a shallow-water, marginal-marine environment of deposition ranging from subtidal to supratidal, and representing a carbonate bank-shoreline facies.

The shallow-water environment resulted in sedimentation of a variety of subfacies reflecting local changes in depositional conditions. Oolite- and pisolite-bearing sediments were deposited in the high-energy environment of carbonate banks. Facies containing algal mats and columnar stromatolites originated in less energetic conditions. The presence of evaporite relicts indicates that the shoreline had an arid, sabkha-like character.

The interbedded sandstone facies do not contain distinctive, environmentally diagnostic features. Fine grain size, good sorting, lamination and the occasional presence of glauconite suggests, however, a relatively quiet environment of deposition, probably deeper than that of the carbonates. Coarser facies, containing ripple-marks, small-scale trough and planar cross-bedding, rare desiccation cracks and coarsening-upwards cycles indicate a shallower, shoreline environment.

The alternation of dolostone and sandstone facies, which is characteristic of the McDermott Formation, reflects unstable tectonic conditions in the marginal part of the McArthur Basin. The sedimentation may have responded to minor but frequent tectonic movements along the Tin Hole Hinge Line. Each uplift was marked by an influx of terrigenous material which was eventually reversed by advancing marine conditions. Tectonic activity along the basin margin contemporaneous with sedimentation is also indicated by the considerable thickness of McDermott sediments which, in the south, were probably eroded before the deposition of the Sly Creek Sandstone.

Sly Creek Sandstone (Etf)
The Sly Creek Sandstone is well exposed along the southern edge of the McArthur Basin. The sequence reaches a maximum thickness of 900 m in the Batten Range, on BAUHINIA DOWNS, (Jackson and others, 1987). In the Calvert Hills region the Sly Creek Sandstone was first differentiated as a separate formation by Roberts and others (1963). It conformably overlies the carbonate rocks of the McDermott Formation and toward the top it gradually changes into glauconitic sandstone of the Aquarium Formation.
Stratigraphy and lithology

The Sly Creek Sandstone has a blanket-like geometry, and is characterised by lateral and vertical uniformity. In the Calvert Hills region the best outcrop is located in Little Calvert River gorge, where the sequence has a thickness of some 320 m. The sediment consists of fine- to medium-grained, laminated sandstone, subangular to subrounded and well sorted, occasionally containing coarser bands with dark-purple, flat, clayey clasts. The rocks in the lower part often have angular cavities, probably after weathered out fine material.

The sandstone is often silicified. Small symmetric ripple-marks, mud-cracks and small-scale (0.1–0.3 m) solitary cross-bedding (planar and trough) occur in places.

The most extensive outcrops of the Sly Creek Sandstone occur in the Branch Creek area but low dips (0°–5°) do not allow a complete section to be measured. A continuous, 65 m thick section through the upper part of the Sly Creek Sandstone has been studied 5 km south of the Wollongorang Homestead. The sequence consists mostly of medium-grained sandstone with symmetric ripple-marks, desiccation cracks and small-scale trough cross-bedding. In one place megaripples (amplitude 0.5 m) have also been observed. The middle part of the section contains a 5 m thick unit of coarse, gritty sandstone with flat clasts of red, silty material. The upper part of this section contains angular cavities similar to those in the Little Calvert River gorge section. In both sections the upper part of the Sly Creek Sandstone gradually passes into the Aquarium Formation. The boundary between these two formations is marked by the appearance of glauconite.

The direction of palaeotransport measured on current bedded sets is polymodal (Figure 8).

Petrography

The main mineral component is monocrystalline igneous quartz with straight extinction. Rarely, grains show undulose extinction as evidence that they have undergone strain. A small percentage of monocrystalline quartz grains contains abundant fluid inclusions suggesting a hydrothermal origin.

There is less polycrystalline quartz in the Sly Creek Sandstone than in the Westmoreland Conglomerate and the quartz is present as unstretched polygonal grains only.

Some grains of chaledony and more rarely chert also occur. Small numbers of volcanic fragments, closely resembling Cliffdale Volcanics, as well as fine siltstone or tuff, are ubiquitous components of the sandstone.

Feldspar appears only in outcrops located south of the Calvert Hills homestead. It consists predominantly of moderately weathered orthoclase and subordinate amounts of relatively fresh microcline. Occasional grains of muscovite are also present.

The matrix content varies considerably and consists of undefined clay minerals. Generally the amount of matrix, decreases with increasing content of silica cement, suggesting gradual substitution. In some cases the matrix is ferruginous.

Accessory zircon and greenish-blue tourmaline occur commonly in small amounts. In some cases these minerals, together with opaque grains, are concentrated in thin, discontinuous laminae indicating winnowing.

Environment of deposition and provenance

The polymodal pattern of palaeotransport, the well-sorted character of the sediment, and the presence of ripple-marks, evidence of winnowing, occurrence of desiccation cracks and geometry of the Sly Creek Sandstone all suggest a near-shore environment of deposition, with the shoreline probably following the Murphy Tectonic Ridge.

The provenance of the clastic material composing the Sly Creek Sandstone (and younger clastic formations of the Tawallah Group in the Calvert Hills region) is not clearly established. The petrography and lithology of this formation are similar to those of the Westmoreland Conglomerate and it is possible that the igneous and metamorphic rocks of the Murphy Inlier constituted the source for both.

Aquarium Formation (Etq)

The Aquarium Formation crops out in a belt 50 km long and up to 10 km wide along the south-eastern flank of the Settlement Creek valley. Smaller outcrops occur north of the Little Calvert River and Horse Creek confluence and southeast of the Foelsche River in the northwestern corner of CALVERT HILLS.

In a section south-west of the Calvert Hills homestead the Aquarium Formation is some 70 m thick. It conformably overlies the Sly Creek Sandstone, with a transitional contact marked by appearance of glauconite, and it is conformably overlain by the Settlement Creek Volcanics.

Stratigraphy and lithology

Since only limited time was devoted to the study of this formation, the available data on sedimentology and petrography are scanty. Most of the formation consists of medium to coarse, moderately sorted, subangular to subrounded, glauconitic sandstone.

The sandstone contains rare and often obscure small-scale cross-bedding including herring-bone type, and small-scale ripple-marks; it is commonly laminated.

During deposition of the upper part of the sequence the influx of terrigenous material must have decreased as the rock changes into dolomitic siltstone and dolomite, both containing glauconite.

Petrography

The main constituent is quartz, which is mostly monocrystalline, with minor amounts of the polycrystalline variety (polygonal, non-stretched), as well as chert and chaledony. Subordinate fabric constituents are fine, grey siltstone or tuff, muscovite, orthoclase and microcline.

Glaucnite grains comprise up to 7% of the rock volume but the distribution is uneven with patches rich in glauconite and parts where it is almost absent. The glauconite is partly oxidised, imparting a common purple-brown colour on the sediments.

Feldspar was observed in only one thin section made from a sample which was taken from an outcrop in the northwestern part of CALVERT HILLS.

In some cases iron oxide coating prior to silification is observed. The content of clayey matrix varies widely.

Depositional environment

The presence of glauconite and the specific nature of the sedimentary structures indicate shallow-marine,
Figure 8 Direction of paleotransport in the clastic sediments of the Tawallah Group, Constance Sandstone and Masterton Sandstone.

slightly reduced low-energy conditions, with a slow rate of deposition.

The transitional change between the Sly Creek Sandstone and the Aquarium Formation suggest a common source of the clastic material for these two formations. The supply of clastic material decreased toward the top of the sequence. Glaucophane-bearing dolomitic siltstone and dolomite concluding the sedimentation of the Aquarium Formation were probably deposited in a quiet, shallow-marine environment.

Settlement Creek Volcanics (Ete)
The Settlement Creek Volcanics occur along the northwestern side of the Settlement Creek valley and in the vicinity of the Calvert Hills homestead. They conformably overlie the Aquarium Formation and underlie the Wollogorang Formation. Due to poor outcrop, accurate thickness measurements are not possible; however, a total thickness of between 100 and 150 m is indicated. Although Roberts (unpublished manuscript) suggested the headwaters of the Settlement Creek in CALVERT HILLS as the reference area for the formation, Jackson and others (1987) have nominated the Mallapunya Dome (NB8911) in the WALLHALLOW as the type area.

The Settlement Creek Volcanics consist of a series of lava flows, sills, siltstone interbeds and pyroclastic material. Vesicular and amygdaloidal varieties occur locally and volcanic breccia and agglomerate occur at the top at several localities. The volcanic material exhibits a considerable range in grain size, including aphanitic, porphyritic and medium grained varieties. Vesicular and amygdaloidal varieties occur locally, generally toward the top of the flows. A sill-like body is seen at QA 9891. At this locality the base is medium to coarse grained, becomes medium to fine grained in the middle and fine grained to glassy at the top. The presence of vesicular cavities and some pahoehoe-like structures suggest that it may be an extrusive.

Petrography and geochemistry
Petrography and geochemistry of the Settlement Creek Volcanics was described by Darby (1986). Representative chemical analyses are given in Table 5. The finer grained samples tend to be more severely altered and consist predominantly of relic feldspar laths, 0.05 — 0.2 mm long, altered to sericite and chloride. The groundmass is made up of a turbid irresolvable mass of chloride and iron oxides. Veins and amygdales contain quartz, chlorite, chalcedony, carbonates, celadonite and, rarely, sulphides.

The fresher samples show a holocrystalline rock with ophitic textures comprising plagioclase (An30—An55) laths 0.2 — 0.8 mm long and augite. Scanning electron microprobe (SEM) analysis shows the augite to be ferro-augite. Small grains of biotite 0.1- 0.3 mm long occur interstitially, as do carbonate, quartz, chlorite and sericite.
Figure 9 Sections of the Wollogorang Formation and the Gold Creek Volcanics.

Trace amounts of apatite, sphene, zircon, and clinzoisite are present in the groundmass. Based on modal composition, Darby (1986) classified the Settlement Creek Volcanics as latite and suggested that while the Seigal Volcanics have tholeiitic affinity, the Settlement Creek and Gold Creek Volcanics have more alkaline characteristics but all three may have been derived from the same source.

Wollogorang Formation (Pt0)
The name Wollogorang Formation was first applied by Firman (1959) to carbonate rocks and overlying impure ferruginous sandstone in the Redbank/Wollogorang area. Part of this carbonate sequence, however, was later recognised as the McDermott Formation. Roberts and others (1963) redefined the Wollogorang Formation which now refers only to the carbonate and sandstone sequence between the Settlement Creek Volcanics and the Gold Creek Volcanics. A detailed sedimentological investigation of this formation was done by Jackson (1982).

The Wollogorang Formation crops out extensively in the southern part of the McArthur Basin. Within CALVERT HILLS it is exposed mostly along the northwestern slopes of the Settlement Creek Valley. Jackson and others (1967) nominated a stratotype section located some 10 km southeast of the Redbank mine at the Seven Mile Creek. Smaller outcrops also exist east of the Calvert Hills homestead and near the Robinson and Foelsche rivers in the northwest corner of the sheet area.

The formation reaches a maximum thickness of some 150 m in the Foelsche River area and near the Seven Mile Creek southeast of Redbank. Between these two areas the thickness ranges between 40 - 60 m. The formation is characterised by a great lateral continuity of facies and certain horizons can be followed for many tens of kilometres without significant change.

Jackson and others (1987) subdivided the Wollogorang Formation into four lithological units dominated by red siltstone (unit 1), crystalline dolostone (unit 2), dolomitic siltstone (unit 3), and dolomitic sandstone and quartz sandstone with minor dololutite and siltstone (unit 4). This subdivision is in this publication further simplified and now consists of a lower unit dominated by carbonate rocks (Pt0.1) and an upper unit with prevailing arenaceous rocks (Pt0.2). These two units have regional continuity (Figure 9) and are readily mappable.

Stratigraphy and lithology
The lower unit begins with locally developed, red siltstone facies, comprising laminated red siltstone, dolomitic siltstone and dololutite, oolitic in parts. This basal sequence conformably overlies the Settlement Creek Volcanics and is 2 — 3 m thick.

In places where the basal sequence is absent, the Settlement Volcanics are covered by a usually 5-10 m thick sequence of crystalline dolostone facies comprising brown dololutite, often laminated, with wavy and columnar stromatolites, and in places silicified. Locally it contains ooliths and dolomitic breccia. It is succeeded by thin but laterally very persistent block shale facies comprising, dark grey, thinly laminated dololutite and siltstone with grey to black, often bituminous ovoid nodules ('ovoid beds'). This sequence is a few metres thick and is present in most of the sections. It reaches a maximum thickness of 15 m in the Seven Mile Creek section.
It is followed by a grey dolostone facies up to 95 m thick and consisting of grey to brown, silty dololutite and dolarenite with columnar and wavy stromatolites, intraclast breccia and locally oolites. It also contains halite casts and desiccation cracks. This sequence terminates the sedimentation of the lower, mostly calcareous part of the Wollogorang Formation.

The upper unit is up to 45 m thick and consists of two sandstone sub-units divided by a dolomitic siltstone sequence varying in thickness from a few to several metres. The lower sandstone is commonly coarse, with gritty and conglomeratic interbeds. The framework consists mostly of moderately sorted subrounded to rounded grains of quartz, with minor feldspar and other lithic fragments. Occasional small-scale trough cross-beds are observed. In the Seven Mile Creek section the sandstone contains some 5 m of breccia consisting of angular clasts of sandstone and dolomite up to 0.3 m in size. Toward the top the grain size decreases, the sandstone becomes ferruginous, and also contains ripple-marks and shale interbeds.

The carbonate sequence which divides the two sandstones comprises mostly purple dololutite, minor siltstone and dolomitic siltstone. Columnar and wavy stromatolites, in places silicified, are common.

The top beds are often strongly ferruginous. In the Calvert Hills area, this sequence thins to 2 m of breccia consisting of fragments of dololutite cemented by coarse dolomite and it is often even absent.

The top sandstone is brown, ferruginous, medium to coarse-grained and occasionally contains pebbles. The fabric consists of moderately well sorted, subrounded to rounded grains of quartz and rare feldspar (moderately altered microcline and orthoclase) set in clayey matrix. In places the sandstone has interbeds of micaceous siltstone. Small-scale planar cross-beds, including herring-bone type, are common. This unit is conformably overlain by the Gold Creek Volcanics or, where the volcanics are absent, by the Masterton Sandstone.

The Wollogorang Formation has two horizons containing minor copper mineralisation — one within the stromatolitic dolostone near the base of the formation, and a second one within the coarse-grained sandstone near the top. Disseminated lead-zinc mineralisation also occurs in black dolomitic shale near the base.

**Depositional environment**

The basal red siltstone was deposited on the uneven surface of the Settlement Creek Volcanics and is absent in elevated areas. Its oxidised character and common lamination indicate a quiet and shallow lagoonal environment.

The overlying dolostones contain a range of sedimentary features including chertified stromatolites, tepee structures, oolites, small-scale cross-bedding, ripple-marks and intraclast breccias, all evidence for a shallow-water, high-energy environment, possibly a carbonate bank.

A thin but very persistent horizon of dark grey, laminated dololutite and dolomitic siltstone with bituminous nodules (‘ovoid beds’) was deposited under quiet, euxinic conditions. A detailed sedimentological study of this unit was carried out by Jackson (1982) who related fine lamination of the sediment to annual seasonal variations of climate (varves). He also considered the bituminous nodules to be the result of dewatering.

The ‘ovoid beds’ are followed by a thick sequence of grey or brown, often silty dololutite and dolarenite containing stromatolites, breccia, and oolites. It is indicative of marginal marine, high-energy sedimentation with occasional emergence recorded by the presence of evaporitic halite casts and desiccation cracks.

The coarse character of the sandstone that begins the sedimentation of the upper, predominantly clastic part of the Wollogorang Formation (Et2), and the presence of conglomeratic interbeds and trough cross-bedding suggest a shallow marine near shore environment.

The sedimentary features of the thin sequence of purple, ferruginous dolomite and siltstone dividing the sandstone units and comprising silicified stromatolites, brecciated parts and halite clasts suggest sedimentation in supra-tidal conditions.

The top sequence of medium-grained and ferruginous sandstone, with herring-bone cross-bedding and occasional interbeds of micaceous siltstone represents shallow-marine, intertidal deposition.

The palaeocurrent directions measured in both sandstone units indicated 2 dominant directions: toward the northeast and toward the west-northwest. These directions suggest that during the time of deposition the palaeoslope was generally rising toward the Murphy Inlier.

**Gold Creek Volcanics (Et2)**

Previous publications have included the Gold Creek Volcanics, Hobblechain Rhyolite and Packaddle Microgranite as members of the Masterton Formation (Smith, 1964; Roberts and others, 1963; Plumb and Sweet, 1974). However, Jackson and others (1987) considered each of these units readily distinguishable and mappable, and have therefore accorded them formation status. Previous mapping in ROBINSON RIVER and in the northwestern corner of CALVERT HILLS showed the Gold Creek Volcanics sandwiched in the Masterton Sandstone. Plumb (pers. comm.) is of the opinion that the sandstone below the Gold Creek Volcanics may belong to the Wollogorang Formation. The bottom sandstone, however, looks very similar to the Masterton Sandstone and additional work is required to solve this problem.

The upper contact appears to be conformable in the Redbank area and has been intersected in several diamond drillholes. The Gold Creek Volcanics are about 225 m thick in the Redbank area (Figure 9) but become thinner to the northeast and southwest. At the southern end of the Camp Creek valley they are about 30 m thick and are probably absent farther up the valley. The same appears to be the situation in the area north of the Wollogorang homestead. Roberts (unpublished manuscript) has chosen the area 16-20 km southwest of the Redbank mine as the reference area which appears to be quite appropriate as the formation is best exposed in this area.

Trachytic lavas comprise the bulk of the Gold Creek Volcanics, though trachyandesitic lavas and a wide variety of volcanioclastic interbeds are also present, including coarse and fine tuffs, tuffaceous and lithic sandstone, and siltstone. The lavas, which include aphonitic, porphyritic and amygdaloidal varieties are invariably weathered and severely altered.
In the Redbank area the lower sequence comprises trachyte, mudstone and siltstone while the middle sequence consists almost entirely of trachyte flows and agglomerate. Clastic rocks comprising lithic tuffs, lithic sandstone and quartz sandstone are common in the upper part (Figure 9).

The regional dip of the Gold Creek Volcanics is to the northwest at very low angles, but on a small scale the structure is complicated by numerous shallow domes and troughs which have been considered as Jura-type folds resulting from movements along a decollement at the base of the Wollogorang Formation (Rod, 1977, 1978).

**Petrography and geochemistry**

Petrographic and geochemical characteristics of the Gold Creek Volcanics have been described by Knutson and others (1979), and Darby (1986). Some selected chemical analyses are given in Table 5. Alkali feldspar laths occur in a cryptocrystalline groundmass of alkali feldspar, chlorite, celadonite and silica. Most samples are strongly altered, however, a vague trachytic texture is just discernible in some thin section (Darby, 1986). Amygdales contain chlorite, quartz, chalcedony, hematite, celadonite and often pyrobitumen and sulphides. The rocks are highly altered and substantial removal of Na and addition of K has occurred as a result of reactions with volatile-rich fluids, enriched in Fe, Mg, K and possibly Al (Knutson and others, 1979).

**Intrusives and eruptive centres**

Several volcanic vents have been mapped in the area north and northwest of the Wollogorang homestead. They consist of pink brecciated trachyte, are similar in appearance to the mineralised breccia pipes at Redbank and range in diameter from about 4 to 80 m.

A mushroom-shaped intrusive body seen at the Eagle Nest (Rod, 1978), southwest of the Redbank Mine, probably represents a breccia pipe which did not break through to surface.

**Discussion**

Most trachyte flows appear to be sub-aerial extrusives but the presence of agglomerates and sedimentary interbeds, at least in the upper part, suggests submarine environment. The interbedded sandstone contains abundant herring-bone cross-beds and rare ripple-marks, suggesting a tidal influence.

The marked increase in the thickness of the Gold Creek Volcanics in the Redbank area suggests that major extrusive centres were close to this locality.

**Pungalina Member (Etu)**

Yeates (1963) and Roberts (unpublished manuscript) defined a sequence of siltstone and fine sandstone, separating the Gold Creek Volcanics from the Masterton Sandstone, as the Pungalina Member of the Masterton Formation. Jackson and others (1987), however, included this member into the Gold Creek Volcanics. Based on data given in Orridge and Mason (1975) and Rod (1978), Jackson and others (1987) considered the arenaceous succession overlying the Gold Creek Volcanics in the Redbank area as belonging to the Pungalina Member. Our field work and that of Smith and others (1974) show that in the Redbank area this sequence is made up of rhyolite flows, rhyolitic agglomerate and volcanic arenite and has been assigned to the Hobblechian Rhyolite Member.

In the Redbank area there is a thin (up to 2 m) reddish brown siltstone horizon at the base of the Masterton Sandstone. This may represent the Pungalina Member but owing to the small outcrop area, could not be shown on CALVERT HILLS.

**Hobblechian Rhyolite (Eth)**

Although the Hobblechian Rhyolite is exposed in the northeastern corner of CALVERT HILLS, its main exposure occurs in ROBINSON RIVER. It has a maximum thickness of about 70 m and, apparently, conformably overlies the Gold Creek Volcanics. It comprises red-brown or pink-weathering, fine-grained porphyritic rhyolite, cobble conglomerate of reworked porphyry, tuff, sandstone and siltstone.

In the Redbank area, rhyolite flows are confined to the bottom. The upper part contains mainly volcanic arenite and rhyolitic agglomerate.

Although the Rb-Sr isochron age for the Hobblechian Rhyolite is estimated at 1575±120 Ma with an initial Sr$^{87}$/Sr$^{86}$ ratio of 0.7084±0.0139 (AMDEL, 74), this age is considered to be unreliable, probably due to Rb-Sr open system behaviour in acid volcanics, and it is not in accord with the much older (1690 Ma) U-Pb age obtained for the tuffs from the HYC Pb-Zn deposit hosted by the overlying sediments of the McArthur Group (Page, 1981).

**Petrography and geochemistry**

The lavas have a predominantly spherulitic texture and contain phenocrysts of quartz and altered plagioclase. The groundmass consists of graphic intergrowths of quartz and K-feldspar. The tuffs include welded ignimbrite which contains phenocrysts of quartz and feldspar in a groundmass of needle-shaped devitrified shards and opaques (Darby, 1986).

**Packsaddle Microgranite (Egr)**

The Packsaddle Microgranite intrudes the Wollogorang Formation and the Gold Creek Volcanics which have been domed up and dip radially away from the contact at angles of up to 20°. Vertical flow banding occurs in some places along the margin and some recrystallisation of the Wollogorang Formation has taken place near the contact (Roberts and others, 1963).

The Packsaddle Microgranite is exposed in a northwest trending belt of approximately 70 km$^2$ in the northeastern margin of CALVERT HILLS. The headwaters of the Rocky Creek (lat. 17°03′S, long. 137°54′E) have been nominated as the type area (Jackson and others, 1987).

A Rb-Sr age from a single sample yielded 1520 Ma (McDougall and others, 1965), but a more precise U-Pb age of 1690 Ma was obtained from tuffs in the HYC deposit situated in the overlying McArthur Group (Page, 1981).

**Petrography and geochemistry**

Resorbed phenocrysts of bipyramidal quartz and intensively altered alkali feldspar total 5—15% of the rock volume. The feldspar phenocrysts have euhedral to subhedral outlines and are replaced by sericite, green pleochroic chlorite and hematite. The phenocrysts range in size from about 0.5 mm to over 5 mm. Small
flakes of biotite are a minor constituent and hematite
stains and spherulites are also present. The groundmass
consists of graphic intergrowths of quartz and alkali
feldspar, and fine dusting of opaques (Darby, 1986).
The Packsaddle Microgranite and Hobblechain
Rhyolite are probably co-magmatic and may represent
highly differentiated end products of magma which
gave rise to the Seigal, Settlement Creek and Gold
Creek Volcanics (Darby, 1986).

**McARTHUR GROUP**

Although the McArthur Group overlies the Tawallah
Group unconformably throughout most of the McAr-
thur Basin, on CALVERT HILLS there is no well
pronounced unconformity. There is, however,
evidence of a unconformity at the Camp Creek Valley
where the underlying Gold Creek Volcanics lense out
possibly due to nondeposition. There is a major
unconformity between the Masterton Sandstone and
the Karns Dolomite. The Masterton Sandstone records
the beginning of a new sedimentary cycle and is the
oldest formation of the McArthur Group. The stratigra-
phic position of the Karns Dolomite is uncertain — it may represent, as discussed later, either the
McArthur or the Nathan Group.

**Masterton Sandstone (Ems)**
The Masterton Sandstone crops out extensively in the
southern part of the McArthur Basin between the
Queensland border and the Linmen Bight River. It
reaches a maximum thickness of some 650 m in the
Mulholland Creek area on BAUHINIA DOWNS
(Jackson and others, 1987), but both thickness and
lithology show great lateral variations.

Only the marginal, southernmost part of this unit is
exposed in CALVERT HILLS. The sandstone
overlies, the Gold Creek Volcanics, the Hobblechain
Rhyolite or, where these are not developed, the
Wollogorang Formation.

**Stratigraphy and lithology**
The Masterton Sandstone is widespread and was
deposited in a variety of environments. There is no
exposure of a complete Masterton Sandstone section in
CALVERT HILLS. The best sections were observed
near the Redbank mine (W0880980) and in the vicinity
of the Robinson River (SC967175). The latter section
clearly shows a vesicular basalt flows in between two
sandstone horizons. The earlier maps show these flows
as belonging to the Gold Creek Volcanics but in view of
the recent subdivision of the Masterton Formation
(Jackson and others, 1987) this interpretation is doubt-
ful.

In CALVERT HILLS the Masterton Sandstone
can be subdivided into two distinctive units: a lower
marine and an upper fluvial unit.
The base of the lower unit in some places is
marked by a red, micaceous siltstone (QB936068). The
remaining part of the lower unit consists of medium-
grained pebble-free sandstone, often with small-to
mega-scale trough cross-bedding. Planar cross-bedded
sandstone, laminated sandstone and sandstone with
common symmetric small-scale ripple-marks occur in
this unit. The basal part in places contains mud cracks,
oxidation spots and herring-bone type cross-bedding.
There are two palaeotransport directions; northeast
and north-northwest (Figure 8).

The upper unit is dominated by medium to coarse
sandstone with scattered beds of clast-supported con-
glomerate. The clasts consist of vein quartz, grey
sandstone, volcanics and orange chert. The clast size
ranges commonly from 10 to 50 mm; the maximum size
recorded was 0.2 m. Small- to medium-scale solitary
trough cross-bedded sets occur in places.

Palaeotransport directions measured on trough
cross-bedded sets show, in contrast with the lower unit,
very regular, unidirectional flow toward the north
(Figure 8).

**Petrography**
The two units of the Masterton Sandstone have a
similar composition. The sediment mostly consists of
sublitharenite, quartz arenite and lithic arenite with a
minor amount of quartzwacke. The average grain size
ranges from 0.2 to 0.5 mm (excluding conglomeratic
beds). The grains are commonly subangular to
subrounded and the framework is moderately sorted.

The content of clayey, often sericitic and ferrugin-
ous matrix varies widely from less than 1 % to as high
as 50%. The matrix content is often inversely propor-
tional to the amount of silica cement suggesting that the
original matrix content was higher than at present.

The main framework component is monocryst-
alline quartz. The dominant variety is of an igneous
type, readily recognisable due to its almost complete
lack of fluid inclusions. The second, less common type,
is vein quartz having a cloudy appearance caused by
abundant inclusion.

Polycrystalline quartz is less common and is
represented almost exclusively by an unstretched type
with mosaic-like extinction. The stretched type is
extremely rare.

Other lithic fragments comprise acid volcanics,
grey siltstone and quartz-mica schists. Chert and
chalcedony are minor constituents of the framework.

The feldspar content reaches several percent. It is
represented by altered microcline and orthoclase occurr-
ing only locally, as single grains or as a constituent of
detrital volcanic fragments.

**Depositional environment**
The Masterton Sandstone was deposited in a variety of
environments including alluvial fan, fluvial, marine and
aeolian (Jackson and others, 1987).

In CALVERT HILLS, where only the southern-
most part of the present Masterton Sandstone is
exposed, the following environmental interpretation is
proposed:

The lower unit consisting of pebble-free medium-
grained cross-bedded sandstone, in places ripple-
marked and containing mud cracks and also displaying a
bimodal palaeotransport pattern, was probably de-
posited in supratidal to shallow-marine environment.
Jackson and others (1987) have also postulated an
aeolian origin for some of these sediments.

The upper unit, comprising sediments with scat-
tered pebbles and conglomeratic beds, showing a
strongly unimodal direction of transport, indicates a
fluvial environment of deposition — probably by distal
gravelly rivers of the Donjek-type.

The clastic framework material of the Masterton
Sandstone probably has a local origin and was recycled
from the older sediments deposited in this region.
Karns Dolomite (Emk)
The Karns Dolomite crops out extensively in the northern part of CALVERT HILLS. Roberts and others (1963) estimated the thickness at about 130 m. Because the upper part of the formation always has undergone some erosion, the above figure represents only a minimum thickness.

A 40 m thick section of the Karns Dolomite, exposed on the Borroloola to Wollongorong road crossing at the Calvert River (QB520265), was proposed by Jackson and others, (1987) as a type section. The same authors suggested a reference section located on the Little Calvert River, 6km southwest of the Calvert Hills homestead (QB438896).

The Karns Dolomite overlies the Masterton Sandstone with a major unconformity and is unconformably covered by sediments of the Roper Group (north of the sheet area) or by the Bukalara Sandstone.

The stratigraphical relationship of the Karns Dolomite to the McArthur and Nathan groups is not clear. Roberts and others (1963) considered the Karns Dolomite as an equivalent of the McArthur Group which, in turn, is correlative with the Fickling Group (Sweet and Slater, 1975).

The Karns Dolomite also shows considerable sedimentological and geochemical similarities to the Balbirini Dolomite of the Nathan Group, exposed in central and northwestern part of the McArthur Basin. Both formations consist of basal clastic sediments overlain by evaporitic and stromatolitic carbonate rocks. The two formations also have an anomalously high manganese content and host lead and copper mineralisation. The above evidence prompted Jackson and others (1987) to suggest that the Karns Dolomite may be correlative with the Nathan Group.

Stratigraphy and lithology
The sedimentation of the Karns Dolomite commenced in depressions in the uneven surface of the Masterton Sandstone. The basal facies types vary widely, being strongly dependent on local palaeotopography. Considerable lithological differences, controlled by basement palaeotopography, were also maintained during the later sedimentation of this formation. The following description of the Karns Dolomite is based mainly on the type section.

The initial deposition was mostly clastic, and comprised an up to 10 m thick sequence of grit and sandstone with lithic fragments of chert, dolarenite and dark-grey shale. The sandstone is cross-bedded and contains mainly symmetrical ripple-marks. In places it is malachite-stained. Above this unit the amount of clastic material gradually decreases.

The basal sandstone is followed by some 4 m of grey dolomite interbedded with medium to coarse-grained, cross-bedded and ripple-marked quartz sandstone. At the top of this unit small domal stromatolites and halite casts occur.

The next unit is about 13 m thick and consists of coarse- to fine-grained sandstone, pebbly in places, with halite and gypsum casts and, locally, cauliflower chert. It is interbedded with dolomitic sandstone, intraclast conglomerate and beds of domal and conical stromatolites. The sandstone is cross-bedded, rarely ripple-marked, and locally contains malachite staining. Dolarenite commonly hosts finely disseminated chalcopyrite.

The overlying unit, at least 13 m thick, comprises alternating beds of dolomite with shaly and silty dolostone. It contains abundant conical and domal stromatolites, silicified ooliths, intraclast conglomerate and, in places, gypsum pseudomorphs. It also locally hosts galena mineralisation and hydrocarbons.

The top unit of the Karns Dolomite consists of some 30 m of purple to dark-green silty dolomite and shale.

Depositional environment
The characteristic feature of the Karns Dolomite sediments is their evaporitic and shallow-water nature. The abundance of evaporitic pseudomorphs, desiccation cracks and truncated stromatolites suggest frequent subaerial exposure.

Drilling carried out by the Carpentaria Exploration Company just north of CALVERT HILLS (Dennis, 1981) revealed distinctive evaporitic cycles consisting of an upper crust of white dolomite, 10-20 mm thick, commonly with halite pseudomorphs, underlain by quartz dolarenite or quartz arenite up to 1m thick, underlain by basal layer of variable thickness up to 0.3 m containing anhydrite pseudomorphs.

This suggests that, except for the basal unit, representing a local infill of palaeogeographic depressions, the Karns Dolomite was deposited in a coastal sabkha environment.

LAWN HILL PLATFORM SEQUENCE

Wire Creek Sandstone (Eti)
The Wire Creek Sandstone lies unconformably on the igneous and metamorphic complex of the Murphy Inlier and is conformably overlain by the Peters Creek Volcanics. Although it is correlated across the Murphy Inlier with the Westmoreland Conglomerate, there is no evidence that these two formations were connected.

Only a small portion of the Wire Creek Sandstone crops out within CALVERT HILLS; along the south eastern edge of the Murphy Inlier. Its major exposures are located farther east, within WESTMORELAND in Queensland. The formation is up to 70 m thick (Grimes and Sweet, 1979) and consists of medium to coarse sandstone with scattered pebbles, mostly of quartz and volcanics. Lenticular conglomeratic beds composed of clasts up to 30 cm in size are common. A 2-3 m thick bed of basal conglomerate is often developed at the bottom. Near the One Hen prospect in the WESTMORELAND, the basal conglomerate contains pebbles of greisened granite suggesting local derivation from the Murphy Inlier.

The sandstone is commonly cross-bedded. Sweet and others (1981) considered that deposition of the Wire Creek Sandstone and the Westmoreland Conglomerate took place in similar environments i.e. braided rivers and alluvial fans.

Peters Creek Volcanics (Ptp)
Minor exposures of the Peters Creek Volcanics occur in the southeastern corner of CALVERT HILLS but the most complete sequence was mapped in WESTMORELAND where the volcanics are exposed in a 50 km long and 10 km wide west-trending belt which also contains the type section nominated by Carter and others (1961).
The Peters Creek Volcanics probably conformably overlie the Wire Creek Sandstone and are overlain by the Fish River Formation with an angular unconformity. Together with the Wire Creek Sandstone, they are considered to be equivalent of the whole of the Tawallah Group and have been divided into eight members with the combined thickness of up to 2000 m (Sweet and Slater, 1975; Sweet and others, 1981). Only the lower two members are exposed in CALVERT HILLS and as they are bounded by faults and an unconformity, their real thicknesses remain unknown.

The lower part (up to 600 m thick) has been named the Buddawadda Basalt Member (Sweet and others, 1981) and it is considered to be the equivalent of the Seigal Volcanics. It includes vesicular and massive basaltic lavas with interbeds of fine and medium feldspathic and glauconitic sandstone. Most lavas are strongly altered but in fresh samples, phenocrysts of clinopyroxene, plagioclase and minor pigeonite have been noted suggesting tholeiitic affinities (Sweet and Slatter, 1975). The major element chemistry of this member is almost identical to that of the Seigal Volcanics.

The sequence above the Buddawadda Basalt Member is made up of rhyolite, rhyodacite, minor basalt, tuff, shale, siltstone, dolomite and conglomerate. The volcanics are distinctly more felsic than either the Settlement Creek or the Gold Creek volcanics and they resemble the Hobblechlain Rhyolite.

The Peters Creek Volcanics have been correlated with the Carters Bore Rhyolite (Plumb and others, 1980), and the latter unit has been dated by the U-Pb method as being 1678 Ma old (Page, 1981).

**FICKLING GROUP**

**Fish River Formation (Eff)**
The Fish River Formation crops out discontinuously along the southern edge of the Murphy Inlier. More extensive exposures occur on WESTMORELAND. The formation progressively overlies toward the west older rocks and consists mainly of sandstone with conglomerate lenses. On WESTMORELAND a siltstone and sandstone unit occurs in the middle of this formation dividing it into three members. This unit, however, thins westward and grades into ferruginous sandstone on CALVERT HILLS and the three members become indistinguishable.

In the type section at the Wire Creek on WESTMORELAND the Fish River Formation is 250 m thick (Sweet and others, 1981). The thickness varies widely within CALVERT HILLS; near the Gorge Creek it is more than 200 m thick, farther west, between Pandanus Creek and the Fish River the formation is 50-70 m thick, 8-12 km west of the Fish River it is 170 m thick but farther west it thins rapidly to 10-20 m.

The conglomeratic horizons present in the eastern part of the exposure thin westward and on CALVERT HILLS most of the formation comprises medium-grained quartz-rich sandstone with ripple-marks, mud cracks and herring-bone type cross-bedding suggesting a shallow-marine, tidal-flat environment of deposition. The conglomeratic beds were deposited in a local higher energy environment, probably by rivers. The clast composition indicates derivation locally from the Wire Creek Sandstone, the Peters Creek Volcanics and possibly the Clifordale Volcanics. The thinning of the formation toward the west is probably a result of a transgression on the Murphy Inlier.

**Walford Dolomite (Pbw)**
The Walford Dolomite conformably overlies the Fish River Formation and is conformably overlain by the Mount Les Siltstone. It forms a series of disconnected outcrops south of the Murphy Inlier. In the type section located some 4 km east of CALVERT HILLS near the Gorge Creek, the formation is 400 m thick but farther west it thins to 250 m (Sweet and others, 1981).

The Walford Dolomite consists of oolitic,stromatolitic, and intraclastic dolomite with minor black shale and dolomitic, glauconitic sandstone. It is commonly silicified at the surface. The relation of silicification to the present land surface and lack of this feature at less than 10 m below the surface, suggests that the silicification is related to a Mesozoic or Tertiary deep-weathering event (Sweet and others, 1981). The presence of ooliths, stromatolites and intraclast breccias indicates a shallow-marine sub- supratidal environment of deposition.

**Mount Les Siltstone (Pfl)**
The Mount Les Siltstone crops out east of the Pandanus Creek and extends eastward for some 30 km across the Queensland border. It is about 90 m thick at the type section about 5 km east-northeast of the Mount Les prospect in WESTMORELAND. It conformably overlies the Walford Dolomite and is conformably overlain by the Doomadgee Formation (Sweet and Slatter, 1975). It consists of dolomite, siltstone, shale and minor interbeds of flaggy dolomite with pseudomorphs of limonite after pyrite and dolomite after gypsum indicating evaporitic conditions of supratidal environment. The deposition of the Mount Les Siltstone was followed by a slight uplift which was probably greater in the western part of the map sheet area.

**Doomadgee Formation (Pfd)**
The Doomadgee Formation is about 400 m thick in the type section which is situated about 1 km northeast of the Gorge Creek in WESTMORELAND (Sweet and Slater, 1975). It occupies the southeast corner of CALVERT HILLS and crops out extensively farther eastward. It conformably overlies the Mount Les Siltstone, at least in the western portion of the exposure, and is overlain unconformably by the South Nicholson Group. The Doomadgee Formation consists of conglomerate, sandstone, siltstone, shale and dolomite. On CALVERT HILLS the basal part of the formation consists of poorly sorted conglomerate with subangular clasts of chert up to 0.2 m in size. It is followed by a sequence of flaggy quartz sandstone, dark grey to black fissile carbonaceous shale and siltstone. The top part comprises coarse intraclastic dolomite or fine-grained sandstone.

Erosion has removed the Doomadgee Formation west of Pandanus Creek and the South Nicholson Group rests in this area directly on the Mount Les Siltstone or the Walford Dolomite. The sedimentation of the Doomadgee Formation marked a renewed transgression. The depositional environments were
more heterogenous than for the other formations of the Fickling Group and they probably included fluvial and marine environments.

SOUTH NICHOLSON BASIN SEQUENCE

Constance Sandstone (Esa)
The Constance Sandstone is the basal formation of the South Nicholson Group and crops out in the southern part of CALVERT HILLS but major exposures occur on MOUNT DRUMOND. Carter and others (1961) nominated the type section in the western part of LAWN HILL area about 39 km south of the Bowthorn homestead. The Constance Sandstone conformably overlies the Doomadgee Formation in WESTMORELAND. Uplift and erosion of the underlying sequence was more pronounced in CALVERT HILLS and in this area the Constance Sandstone overlies with angular unconformity all units of the Fickling Group. The thickness of the Constance Sandstone increases from 650 m in the western part of CALVERT HILLS to over 1000 m in south-western part of WESTMORELAND. The dominant rock type of the formation is a medium-grained quartz sandstone or lithic sandstone. The sandstone sequences are separated by three lenticular siltstone bodies which allowed division of the formation into seven members (Sweet and others, 1981).

The oldest member (Esa1) thickens eastward from some 10 km near the Fish River to about 90 m between Hedley and Wire creeks on WESTMORELAND.

The lower part of this member consists of conglomerate containing well rounded quartz and quartzite pebbles and subangular to subrounded fragments of chert.

The remaining part of Esa1, is composed of cross-bedded friable medium to coarse sandstone, with occasional grit and pebble beds.

The Pandanus Siltstone Member (Esa2) consists of fissile and flaggy, green, purplish-brown and grey coarse siltstone with shaly partings and thin interbeds of very fine to fine-grained sandstone and greywacke. The middle part of the member often contains a prominent bed of blocky sandstone. The type section, nominated by Sweet and Slater (1975), is located about 5 km northwest of the confluence of the Pandanus Creek and the Nicholson River.

The thickness of Esa2 increases eastward from 50 m, east of Wallis Creek, to some 130 m, in western part of WESTMORELAND. It thins again farther east and finally lenses out toward the southeast.

The next member (Esa3) is the thickest member of the Constance Sandstone. It consists of up to 320 m of medium to coarse lithic sandstone, quartz sandstone and greywacke. Some beds have a bimodal grain size distribution.

The Wallis Siltstone Member (Esa4) in its type section, some 7 km west-southwest of the Fish River and Tin Hole Creek conjunction, is 96 m thick. It thins and lenses out some 15 km west and appears again farther westward. East of the type section the member has a constant thickness, but it thins out and disappears southward, just south of the boundary with WESTMORELAND. The dominant rock types of this member are siltstone, shale, lithic sandstone and greywacke.

The overlying member (Esa5) consists of cross-bedded, medium to coarse lithic sandstone and greywacke. It thickens eastward, from 100 to 160 m. As is the case with Esa2, some beds of Esa5 show bimodal distribution of grain sizes.

Higher members of the Constance Sandstone, the Bowthorn Siltstone Member (Esa6) and overlying member Esa7 are not exposed within CALVERT HILLS.

Depositional environment
The immature character of most of the sandstones suggests short distances over which the sediments have been transported and therefore points to a local source rock. Palaeotransport direction is toward the northeast (Figure 8).

The sedimentary structures of the Constance Sandstone — common cross-bedding and presence of ripple-marks, current lineations, skip casts and clay pellets in some beds — are all indicative for a shallow marine environment. The sandstones were deposited in a high energy regime and the siltstones were laid down in a quieter environment.

Clear bimodal grain size distribution of some sandstones in members Esa2, Esa3 and overlying Mullera Formation indicate an aeolian origin of the sediment (Folk, 1968).

Mullera Formation (Es1)
The Mullera Formation conformably overlies the Constance Sandstone. It consists of coarse, medium and fine grained quartz sandstone, greywacke, and siltstone. The sediments are often rich in iron oxides. No complete section of the formation is exposed in CALVERT HILLS area, but in MOUNT DRUMMOND it is some 2400 m thick (Smith and Roberts, 1963).

Mittlebah Sandstone (Es2)
The Mittiebah Sandstone conformably overlies the Mullera Formation and crops out in the south-western corner of CALVERT HILLS but major exposures are located on MOUNT DRUMMOND where the formation reaches a maximum thickness of 2700 m. It consists of quartz sandstone, feldspathic sandstone and arkose, and it is commonly ripple-marked and cross-bedded.

PHANEROZOIC STRATIGRAPHY

CAMBRIAN

Bukalara Sandstone (Clb)
The Bukalara Sandstone crops out extensively in the northwest quadrant of the sheet area where it unconformably overlies various Proterozoic units and is overlain unconformably by Mesozoic rocks.

It consists of an about 100 m thick sequence of red fine to very coarse feldspathic sandstone and pebble or cobble conglomerate. The sediments are strongly jointed and commonly show trough cross-bedding and ripple-marks.

Muir (1980) described five localities on MOUNT YOUNG containing trace fossils including Skolithos, and possibly Charniodiscus Ford 1958 and Dickinsonia Glaessner 1966, which indicate an Early Cambrian age for this formation.
LATE JURASSIC TO EARLY CRETAEOUS

Mullaman Beds (Kj)
The Mullaman Beds, up to 70 m thick in CALVERT HILLS, are part of an extensive belt of fluvial and shallow-marine sandstone and siltstone covering vast areas of the Northern Territory and western Queensland. The Mullaman Beds form dissected plateaux and isolated mesas capping older rocks. The main sediment comprises medium-grained quartz sandstone and conglomerate near the base, overlain by interbedded fine clayey sandstone and siltstone. Siltstone is dominant in the upper part of the formation. Fossil flora and fauna has been recorded from this formation by Skwarko (1962, 1966).

CAINozoIC
The Cainozoic sediments cover most of the southwestern, central and northeastern areas in CALVERT HILLS.

Majority of the Cainozoic sediments consists of lateritic soil, laterite (Czl), soil and sand (Czs). Southwestern corner of the sheet area is occupied by an extensive cover of black soil (Czb). Alluvial sediments (Qa) occur along the Nicholson River and along some creeks.

Also included in the Cainozoic are remnants of valley-fill conglomerate best preserved on the northern slopes of a valley located some 2.5 km southwest of Redbank mine along the main road. The conglomerate is clast-supported or matrix-supported and is very poorly sorted. The largest clasts are 0.5 m in size, the most common size, however, ranges between 10 and 100 mm. Rounding of clasts is extremely variable. Clasts of vein quartz, sometimes containing feldspars, are very well rounded and are probably recycled from conglomerates of the Masterton Sandstone. Well rounded to subangular clasts of pink vesicular trachyte and fine sandstone probably originated from the Gold Creek Volcanics and the Masterton Sandstone respectively. The conglomerate also contains large, up to 0.5 m in size, very angular fragments of feldspathic sandstone which show no evidence of transport and are derived from the Masterton Sandstone or Mullaman Beds. Matrix of the conglomerate consists of coarse sandstone. A similar conglomerate occurs near the Southern Comfort uranium prospect (RA145570) filling bottom of a local valley within sediments of the Westmoreland Conglomerate, and in other places.

Black soil (Czb)
Black soil plains developed in the south-west corner of the sheet area, covered by silt and clay.

Alluvium (Qa)
Alluvial deposits are closely related to recent drainage systems, including sandy and silty overbank deposits as well as stream bed deposits.

STRUCTURE
The structural setting is dominated by the Murphy Inlier, which is the exposed part of the Murphy Tectonic Ridge (Figure 3). The Murphy Inlier extends eastward into WESTMORELAND and is covered farther west by the sediments of the Carpentaria Basin. The northwestern margin of the Murphy Tectonic Ridge is defined by the Tin Hole Hinge Line, the southern margin, however, is not well defined and probably coincided with the Fish River Fault zone from the beginning of the Fickling Group time, but may have been farther south before that (Sweet and others, 1981).

The Murphy Inlier sequence formed basement to the overlying McArthur Basin, Lawn Hill Platform and South Nicholson Basin. There is no direct evidence regarding the basement configuration on either side of the Murphy Inlier. To the north, gravity data show a series of lows trending east and roughly following latitude 17°30'. A well pronounced gravity low is located in the centre of CALVERT HILLS. Geophysical modelling suggests this to be due to a palaeohigh of granitic composition.

MURPHY INLIER
The Murphy Metamorphics are isoclinally folded along east-west axes and dip sub-vertically to the north. This folding episode represents the earliest deformation phase and was probably associated with regional metamorphism. Gneissic layering and coarsening of muscovite in the vicinity of fault or shear zones, suggests the presence of a younger deformation (and metamorphic) episode.

The flat-lying Clifftide Volcanics are in some areas folded or tilted to the north probably as a result of granite intrusions. Faulting and vein ing is intense in Ec but Ec is relatively less deformed.

The Ec phase of the Nicholson Granite Complex clearly intruded the Ec sequence showing in several localities zones of lift-par-lit injection. The relationship between Ec and Ec is not clear.

TAWALLAH GROUP
The regional dip of about 10° to the northwest is reversed and steepened in several places by local folding, doming and faulting. The axes of folds have a predominant northwest trend suggesting a compression in a northeast-southwest direction. The Westmoreland Conglomerate is folded near the El Hussen uranium prospect and at the western extremity of the Westmoreland Conglomerate belt, probably as a result of faulting. In the central and northwestern part of the sheet the McDermott Formation occurs in the core of elongated domes.
McARTHUR GROUP

The Masterton Sandstone and Karns Dolomite are practically undeformed and occur as sub-horizontal beds with a maximum dip of about 3-5° due north. A major unconformity separates these two formations.

FICKLING AND SOUTH NICHOLSON GROUPS

In the Fickling Group the regional dip of about 5° to the south is reversed at several places due to broad anticlinal folds along east trending axes. The degree of deformation is low and comparable to that of the McArthur Group.

The South Nicholson Group shows very little or no folding but minor faults and joints are common.

CALVERT FAULT

The Calvert Fault trends northwest and has a near vertical dip. It can be traced for a distance of over 200 km as a zone of silicification up to 100 m wide.

Attitude of this contact can not be precisely predicted (being an intrusive contact) the displacement figures are doubtful. At RA010440 the contact between the Westmoreland Conglomerate and the Cliffdale Volcanics-Nicholson Granite Complex shows a horizontal displacement of about 2 km. Farther north the Seigal Volcanics-Westmoreland Conglomerate contact is displaced by about 1 km and the direction of displacement is reversed. The Carolina Sandstone Member shows a similar displacement but displacements of the McDermott-Sly Creek contact are insignificant. It appears that major movements along the Calvert Fault took place during the deposition of the Westmoreland Conglomerate and Seigal Volcanics. Later movements were restricted to minor vertical adjustments.

TIN HOLE HINGE LINE

The Tin Hole Hinge Line was considered to be a zone of flexuring and uplift during sedimentation of the Westmoreland Conglomerate (Roberts, unpublished manuscript). This interpretation is now no longer adopted as the palaeocurrent directions suggest a north-easterly source for the Westmoreland Conglomerate. It probably represents a thrust fault along which the Westmoreland Conglomerate moved southward. This interpretation could be used to explain the marked decrease in the thickness of the Westmoreland Conglomerate south of the hinge line.

Along the hinge line the Westmoreland Conglomerate dips steeply to north at angles exceeding 60° (Plate10) but the dips flatten to about 45° some 100 m north of this line. Steepening of dip is not seen eastward of the confluence of Rocky Creek.

FISH RIVER FAULT ZONE

The Fish River Fault Zone forms the boundary between the Murphy Tectonic Ridge and the Lawn Hill Platform in the southwestern part of the sheet area. The zone comprises a series of east-trending faults along which mainly vertical movements have occurred. The north block has been uplifted 500-1000 m relative to the south (Sweet and others, 1981).

OTHER MAJOR FAULTS

Other faults conform to either a northwest or east-west trend. Two major northwest trending faults could be traced running parallel to the Calvert Fault and situated about 15 and 25 km north of it. Their trend more less coincides with the axes of the El Hussen and the Camp Creek anticlines.

The east-southeast trending faults passing through the Redrock and Jackson Pit prospects have been proved to be reverse faults. Along these faults a wedge of the Westmoreland Conglomerate has been thrust under the Cliffdale Volcanics (Pietsch and Tucker, 1972; Darby, 1985).

GEOLOGICAL EVOLUTION

The Early Proterozoic metasediments of the Murphy Metamorphics were deposited under geosynclinal conditions. Metamorphism and deformation of these sediments took place prior to the extrusion of the Cliffdale Volcanics and intrusion of the stocks associated with the Nicholson Granite Complex i.e. prior to 1840 Ma. This deformation phase probably represents the 1855-1890 Ma Barramundi Orogeny — an
orogenic event recognised over much of the northern Australian Craton.

Extrusion of the Cliffdale Volcanics and intrusion of the granitoids of the Nicholson Granite Complex represent post-orogenic felsic igneous activity and they also mark the transition of the area from an orogenic to a cratonic domain. This 1870-1700 Ma felsic igneous event is also recognised over most of the northern Australian continent.

Uplift, erosion, minor folding and extensive faulting followed crystallisation and several kilometres of strata were stripped off the surface prior to the sedimentation of the McArthur Basin and the Lawn Hill Platform sequences. A topographic barrier (Murphy Inlier) separated these two sequences throughout most of the Proterozoic.

The total area covered by the McArthur Basin is about 200,000 km². Its palaeogeography and structure is dominated by fault bounded troughs and shallow stable shelves. The troughs received up to 12 km of sediments, the shelves 1.5 — 4 km. Sedimentation in the Calvert Hills area occurred in a shallow north-sloping shelf (Wearyan Shelf).

The Westmoreland Conglomerate is a result of fluvial accumulations derived from a northeastly source and, although the Murphy Inlier existed as a topographic high, it apparently did not act as a source rock for the Westmoreland Conglomerate. This fluvial sedimentation was terminated by the outpouring of large volumes of basaltic lava (Seigal Volcanics). A pattern of marine sedimentation, at times interrupted by volcanism, characterises the conditions under which the remaining sediments of the Tawallah Group were deposited. The nature of volcanism, changed with time, from basalt via trachytandesite and trachyte to rhyolite as a result of magmatic fractionation. The palaeocurrent directions in the clastic sediments of the Tawallah Group except the Westmoreland Conglomerate, indicate a southerly source and suggest a configuration of the Wearyan Shelf with Murphy Inlier forming the shore line and the shelf sloping gently to the north.

Volcanism virtually ceased after the outpouring of the Hobblechain Rhyolite and minor erosion and uplift occurred in some parts of the Wearyan Shelf, prior to the deposition of the fluvio-marine Masterton Sandstone, the basal formation of the McArthur Group. The other formations of the McArthur Group were probably never deposited in the area of CALVERT HILLS. A prolonged period of erosion preceded the deposition of the Karns Dolomite which took place under shallow-marine conditions on the uneven post-Masterton erosion surface.

South of the Murphy Inlier, deposition of basalt fluviatile arenites (Wire Creek Sandstone) was followed by more or less uninterrupted volcanism (Peters Creek Volcanics). The volcanics range from mafic to felsic and are time equivalent of virtually the entire Tawallah Group.

A period of uplift and erosion followed the volcanism and preceded the deposition of the Fickling Group in a shallow-marine tidal-flat environment which in turn, was terminated by yet another period of uplift and minor folding.

The Fickling Group sediments were partly eroded before the development of the South Nicholson Basin which received predominantly arenaceous sediments under shallow-marine conditions.

Since the Middle Proterozoic the region has been stable and except for some minor adjustments along pre-existing faults has not experienced any tectonic disturbances. The Phanerozoic was mainly characterised by weathering and erosion, except for marine transgressions during the Cambrian and Cambrian-Jurassic time which deposited a thin veneer of sediments over the entire area.

ECONOMIC GEOLOGY

Copper was first reported from the Settlement Creek area in 1899. In 1916 W. Masterton discovered copper at Redbank and subsequently at a number of other nearby deposits. In 1956 uranium was discovered by R. T. Norris at the Eva mine and by A. R. Blackwell at Cobar-2 (Roberts and others, 1963). Tin at Crystal Hill was probably discovered at about the same time.

Since these early discoveries the area has witnessed considerable mineral exploration activities. Three periods of extensive exploration can be recognised:

1956-1960: most exploration was directed toward locating uranium deposits,

1968-1971: most exploration was directed toward uranium but extensive exploration for copper also took place in the Redbank area,

1978-present: most exploration has been directed toward uranium and diamonds. A strong gold-uranium association was identified in a number of previously discovered uranium deposits.

As a consequence of these exploration activities over a hundred occurrences of uranium, copper, tin and manganese are now known. Details on these occurrences are given in individual Mine Data Sheets.

URANIUM

The early ground discoveries at the Eva and Cobar-2 mines were followed by an airborne radiometric survey by the BMR (Livingstone, 1957). From 1956 to 1960, the area underwent intensive exploration (Morgan, 1959 a,b; North Australian Uranium Corporation, Field Reports, 1957; Batrey, 1957; Brooks, 1960). Another surge in exploration activity occurred from the late sixties to the early seventies (Taylor, 1968; Taylor and others, 1968; Hills, 1969 a,b, 1970; Tucker 1970 a,b,c; Tucker and Hills, 1970; Hills and Thakur, 1975; Cook, 1975). A slight pause in exploration was followed by yet another period of intensive activity which started in 1979.

Exploration efforts, so far, have outlined a number of uranium occurrences. Most of these were located during initial exploration efforts (1956-60) by prospectors who combed the region on horesback and used geiger counters to detect areas of higher radioactivity. A number of occurrences were later inspected by geologists who provided brief field descriptions. Follow-up work in the late sixties and seventies included airborne and ground radiometric surveys, drilling, mapping and geochemical studies. Although early work showed a strong gold-uranium association, it is only recently that samples from a number of uranium occurrences have been analysed for gold.
**Classification**

Ahmad (1987a) has used a combination of geologic and hydrogeologic settings to classify these occurrences into the following types (Figure 10).

**Type A**

Pervious strata underlie relatively impervious strata:

A₁ — Reverse-faulted contact, Clifftdale Volcanics overlie Westmoreland Conglomerate.

A₂ — Normal contact, Seigal Volcanics overlie Westmoreland Conglomerate.

**Type B**

Near-vertical more or less impervious rocks (basic dykes) in contact with pervious strata (Westmoreland Conglomerate).

**Type C**

Pervious strata (Westmoreland Conglomerate) may have overlain relatively impervious strata (Clifftdale Volcanics) but have since been eroded.

**Type D**

Similar to subtype A₂ but situated along fractures in impervious strata (Seigal Volcanics) some distance away from the impervious/pervious boundary.

**Type E**

Occurrences in the Murphy Metamorphics. Salient features of these occurrences are summarised in Table 6.

**Type A**

These occurrences lie at the volcanic (Seigal or Clifftdale) — Westmoreland Conglomerate interface. The volcanics or the Westmoreland Conglomerate or both are mineralised. The mineralised area seldom exceeds a few metres in width but enhanced radioactivity can be traced for several tens of metres along the contact. In both subtypes, the Westmoreland Conglomerate underlies the volcanics. In subtype A₁ this has happened as a result of reverse faulting, whereas in subtype A₂ it is due to the normal stratigraphic succession.

Topographically, the mineralised occurrences lie at relatively low elevations along the flank of the hills formed by the Westmoreland Conglomerate. The Westmoreland Conglomerate can be considered a major aquifer with a catchment area at a relatively higher elevation than the surrounding country. This situation has resulted in the formation of several perennial and intermittent springs along the base of the hills.

**Subtype A₁**

The known occurrences are associated with east-trending reverse faults: the Redrock Fault, the Main Range Fault and the Main Range Fault as mentioned in various company reports. Drilling at the Redrock and Main Range Fault indicated a dip to the south of about 50° (Pietsh and Tucker, 1972; Darby, 1985).

At the Redrock anomaly radioactivity, associated with a zone of hematitised and brecciated volcanics, extends discontinuously for about 2 km along the strike. The Main Range Fault contains the Jackson Pit, Jim Beam, Jacques and Southern Comfort occurrences which together define a narrow zone of patchy radioactivity over a strike length of about 2 km.

**Subtype A₂**

The known occurrences are associated with the conformable Seigal Volcanics — Westmoreland Conglomerate contact. In many places a reddish brown siltstone horizon, a few metres thick, is observed along this contact. The host rock to these occurrences is either the Westmoreland Conglomerate or the Seigal Volcanics or the siltstone horizon. A large number of these occurrences are situated along both flanks of the El Hussen anticline.

At the El Hussen prospect very rich but patchy uranium mineralisation is seen along a straight line approximately 1.5 km long. This line represents a northeast-trending fault just within the Seigal Volcanics and parallels the steeply dipping contact with the Westmoreland Conglomerate. Drilling, costeaming and exploratory mining has been carried out but no reserves have been outlined. At the McGuinness prospect, costeaming has indicated very patchy but rich uranium mineralisation along the sandstone/volcanics contact. Other occurrences included in this sub-type contain patches of high radioactivity often associated with secondary uranium minerals.

**Type B**

This type contains the most economically important occurrences in the study area. The mineralisation occurs as sub-horizontal lenses in the Westmoreland Conglomerate, in close proximity to basic dykes which are also mineralised. The dykes are tholeiitic in composition, up to 10 m wide and occupy northeast-trending near-vertical joint zones. They are distributed in an en-echelon pattern and bifurcate around sandstone blocks in the fault zone (Hills and Thakur, 1975). The dyke material is heavily altered, particularly along the contact zones. No age determinations have been carried out on the dyke material but the dykes could have the same age as the Seigal Volcanics.

Sweet and others (1981) have mapped several basic dykes which cut the Nicholson Granite Complex and the Clifftdale Volcanics. One such dyke extends in a northeasterly direction virtually all the way across SEIGAL. It is possible that this dyke represents the southwestern extension of the Northeast Westmoreland dyke (see below). Similarly, a dyke in the Clifftdale Volcanics south of the Moongooma prospect could be correlated with the Redtree dyke system. No uranium mineralisation has ever been reported in the vicinity of these dykes and it appears that the combination of the Westmoreland Conglomerate and basic dykes is of the utmost importance in localising the uranium mineralisation. In the mineralised areas, preferential erosion of the dyke zone has resulted in deep and narrow rubble-filled gullies bounded by cliffs of the Westmoreland Conglomerate.

Three such fault-associated dyke zones have been identified. From west to east they are: the Northeast Westmoreland, the Redtree and the El Nashfa dyke zones. The last two are in the adjoining WESTMORELAND but are included here for the sake of completeness.

The Northeast Westmoreland dyke zone has a known strike length of about 5 km. Drilling on profiles across this zone has indicated uranium values ranging from 0.4 to as high as 24 kg/tonne and gold values ranging from 1 to 16 g/tonne (Kratos Uranium N.L., 1981). No reserves have been announced and further work is in progress. This zone has been divided into
Figure 10  Geological setting and types of uranium occurrences.
three prospective areas, namely Mageera, Intermediate and Oogoodoo.

The Redtree dyke zone extends over a strike length of about 20 km. The prospective areas in this zone from south to north are: Moongooma, Namalangi, Redtree, Huarabagoo, Januguna, Wangerango, Embayment and Pat’s Find. The Namalangi deposit contains probable reserves of 4745 tonnes contained U$_3$O$_8$ (average grade 0.17% U$_3$O$_8$). In addition, possible reserves totalling 5650 tonnes contained U$_3$O$_8$ (average 0.25% U$_3$O$_8$) are also available. About half of this possible ore is from the Januguna deposit (Queensland Mines Ltd., 1979). Some reserves are also available from the Huarabagoo deposit, but no figures have been announced. Although Mount Isa Mines Ltd has carried out considerable exploration in the areas covered by the Redtree leases, no reserves have been announced. Brooks (1972) considered that reserves at the Redtree leases are substantial, though probably much less than those of Queensland Mines Ltd. Exploration in the northern prospects of the Redtree zone has, so far, proven unsuccessful. The El-Nashfa dyke zone is approximately 10 km long. There is extensive surface mineralisation at the Long Pocket deposit but drilling by Queensland Mines Ltd, has shown that it does not persist at depth. Reserves were estimated at about 2200 tonnes of contained U$_3$O$_8$ with an average grade of 0.045 kg/tonne (Brooks, 1972).

No reserves have been identified from the other prospects, but dyke rocks are known from the El Nashfa and Flying Fox prospects.

Type C
The uranium occurrences of this type are situated in the Clifford Volcanics, not far from their contact with the unconformably overlying Westmoreland Conglomerate (Plate 11). It is possible that the Westmoreland Conglomerate once covered these occurrences and was subsequently eroded. An observation of the Westmoreland Conglomerate escarpments, from the Eva mine to about 6 km southwest of this locality, shows several springs originating from points close to the unconformity. The hydrological setting is that of very pervious sub-horizontal strata unconformably underlain by relatively impervious strata. The groundwater movement is probably downward (through the Westmoreland Conglomerate) and then horizontally outward along the unconformity.

At the Eva mine, the orebody is 60 x 10 m in size and is associated with a northeasterly-trending body of quartz-epidote rocks (Morgan, 1965; Taylor, 1968). During 1960-62, South Alligator Uranium N.L. produced some 336 tonnes of ore averaging 8.37% U$_3$O$_8$. The Crippled Horse occurrence is associated with a near-vertical quartz-filled fault zone. The Duccio’s occurrence is not related to any structures.

Type D
The known occurrences are associated with fractures in the Seigal Volcanics. The contact of the Seigal Volcanics with the underlying Westmoreland Conglomerate is some 100 m below the surface at the Cobar-2, Old Parr and King’s Ransom areas and may be as much as 200 m below the surface at the other occurrences. The Seigal Volcanics are estimated to be about 1600 m thick (Sweet and others, 1981) but the uranium occurrences are confined to the basal part.

The hydrological setting is similar to that of subtype A2. The catchment area of the underlying pervious aquifer (Westmoreland Conglomerate) is at higher elevation. The Cobar-2 occurrence is associated with a north-trending near-vertical fracture which probably extends down to the Westmoreland Conglomerate (Tucker, 1970b). It has yielded some 78 tonnes of hand-picked ore assaying 4.77 kg/tonne U$_3$O$_8$.

At Old Parr and King’s Ransom mineralisation is associated with north-trending near-vertical fractures similar to those at the Cobar-2 occurrence.

Other occurrences of this type are very small and very little work has been done on these. They are areas of higher radioactivity often containing secondary uranium minerals.

Type E
These occurrences are situated in the Murphy Metamorphics and are associated with faults and fractures. Drilling has indicated minor mineralisation at Anomaly 1, 30 and 4901.

Mineralogy
Reported uranium minerals at various occurrences are listed in Table 6. No information is available on a number of occurrences and in many cases the description “secondary uranium” or “uranium ochres” is used. The mineralogy of the Namalangi, Eva mine, Cobar-2, El Hussen and Northeast Westmoreland occurrences
### Table 6 Summary of uranium occurrences.

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<th>NAME</th>
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<td>Btw</td>
<td>Sec</td>
<td>Hem,Q,Cl</td>
</tr>
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<td>Carn</td>
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<td>Ptb,Gum,Py,Cpy</td>
<td>Hem</td>
</tr>
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<td>Ecc</td>
<td>-</td>
<td>Hem,Q</td>
</tr>
<tr>
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<td>A2</td>
<td>Bts/Btw</td>
<td>Carn?</td>
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<td>C</td>
<td>Ecc</td>
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<td>Bts/Btw</td>
<td>Ptb, Carn</td>
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<tr>
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<td>Aut,Torb,Ptb</td>
<td>Q,Ser,Epd</td>
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<td>A2</td>
<td>Bts/Btw</td>
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<td>Bts</td>
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<td>Jacques</td>
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<td>Ecc/Btw</td>
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<td>Ecc/Btw</td>
<td>-</td>
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<td>Q</td>
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<td>Bts/Btw</td>
<td>Carn</td>
<td>Hem</td>
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<td>Btw/DI</td>
<td>Torb,Ptb</td>
<td>Hem,Q</td>
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<td>Btw/DI</td>
<td>Torb,Ptb</td>
<td>-</td>
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<td>(Dyke,intermediate)</td>
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<td>Btw/DI</td>
<td>Torb,Ptb</td>
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<td>Bts</td>
<td>Sec</td>
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<td>Sec</td>
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<td>White Label</td>
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<td>Bts/Btw</td>
<td>Carn</td>
<td>-</td>
</tr>
</tbody>
</table>

36
Table 6 (continued)

| White Heather | A₂ | Ets | Sec | Hem,Ο |
| White Horse   | Α2 |  Ets/Етш |     |   |

Abbreviations: Aut = autunite; Br = branerite; Carn = carnokite; Cl = chlorite; Gum = gummite; Epid = epidote; Hem = hematite; Kao = kaolin; Pb = pitchblende; Q = quartz; Sec = unidentified secondary uranium minerals; Ser = sericite; Torb = torbernite; Dl = dolerite; Ecc = Cliffside Volcanics; Egn = Nicholson Granite Complex; Etw = Westmoreland Conglomerate; Ets = Seigal Volcanics; — = not known or not described.

has been described in some detail (Morgan, 1965; Newton and McGrath, 1958; North Australian Uranium Corporation, 1957; Hills, 1973; Hills and Thakur, 1975; Manning, 1979). A number of samples were also examined during the course of the present study. There are two basic styles of ore mineralisation
1. Open-space filling and replacement of vein walls in the volcanics and rarely in the sandstone (Plate 12).
2. Replacement of matrix in the sandstone (Plate 13).

Pitchblende is the dominant primary uranium mineral. It occurs as the massive structureless variety or as colloform masses. Some rare euhedral grains have also been found, and Hills (1973) described thin films of sooty pitchblende. Hematite is almost invariably associated with pitchblende and together they are replacing clay or quartz matrix in the Westmoreland Conglomerate. In the volcanics, pitchblende occurs as replacement along the edges of the veins which often are filled with quartz.

Hills (1973), Hills and Thakur (1975), and Pohl (1970), have reported minor branerite from the altered dyke rocks at the Namalanagi deposit. Its formation is attributed to replacements of titanomagnetite.

Most specimens studied contain abundant specular hematite but a finely disseminated earthy variety of hematite is also present. Hematite and pitchblende are closely associated and were probably deposited simultaneously.

Hills (1973) and Hills and Thakur (1975) described galena inclusions in pitchblende and considered that it had been derived by radiogenic decay of uranium and that it did not constitute a primary mineral.

Rare grains of pyrite, marcasite, chalcopyrite and bornite have been observed. Hills (1973) and Hills and Thakur (1975) also describe the presence of gersdorffite (NiAs) and safflorite (CoAs₂).

Gold is visible in a few samples as small globular bodies and as nugget-like grains up to 10 microns in size. It is often associated with pitchblende. Free gold is reported from the Eva mine (Morgan, 1965). It is also present in the sediments of the streams draining the Westmoreland Conglomerate (Ahmad and others, 1984). Most gold grains are either free of Ag and Cu or contain trace amounts of Ag.

Secondary uranium minerals are seen at almost all the occurrences. The most abundant minerals are torbernite, carnotite and metatorbernite. A host of other minerals have also been reported.

Amongst the silicates, quartz, sericite, muscovite and chlorite are common. Quartz occurs as overgrowths in optical continuity with the quartz clasts. This is considered to be a replacement of clay matrix (Wygralaik and others, 1988). It also occurs as small thin veinlets. Sericite occurs as small flakes along the vein edge or replacing the matrix. Chlorite is a green pleochroic variety and occurs as patches or masses replacing the matrix or it occurs along the altered area close to the vein edge. Kaolinite and ilite have also been reported (Manning, 1979). They are probably diagenetic in origin. Sericite, epidote, talc and topaz have been reported from the Eva mine (Morgan, 1965).

Plate 12 Hematite and pitchblende vein (dark areas) in the Seigal Volcanics. A thin vein quartz stringer passes through the hematitised area. Location: Cobar 2 mine, sample No. 196.
Alteration
The alteration in the rocks at these occurrences have been variously described as hematitisation, chloritisation, silicification and sericitisation. In most occurrences the characteristic alteration minerals in the order of abundance are hematite, quartz, sericite, muscovite and chlorite. Petrological observations indicate that in the barren samples, hematite (and other iron oxides) constitute less than half a percent whereas in the mineralised samples it constitutes up to 10% and average about 5%. This strongly suggests additions of iron. Formation of sericite, muscovite and chlorite appears to be at the expense of authigenic clay minerals in the case of sandstone. In the volcanics it appears to be at the expense of feldspar and ferromagnesian minerals. The alteration at the Eva mine is different. The mineralisation occurs in sericite-epidote-quartz rocks within the Cliffdale Volcanics. Minor talc has been noticed in the orebody and hematite is rare (Morgan, 1965). About 100 m north in the strike direction of the uraniferous sericite-epidote-quartz rock an exposure of quartz-topaz rock is seen. Quartz-cassiterite-topaz veins are also seen to the east of the ore zone. These observations suggest that the host rock at the Eva mine may have gone through a period of greisenisation. The age of this event may be the same as that of the Crystal Hill greisen, i.e. 1621±28 Ma (Ahmad, 1986).

Chemical composition of the ore
Chemical analyses of ore samples from selected occurrences are given in Table 7. Strong enrichment in vanadium and copper is apparent; silver and gold are present in most of the samples and might be an important by-product of uranium mining. It must be noted that the samples analysed were randomly selected and precious-metal values may be higher in certain portions of the orebodies. The presence of mercury and arsenic in the ores could have considerable utility in exploration, since these elements may be used as pathfinders. Selenium and molybdenum are present in some occurrences.

Oxidation state of the rocks
Some idea of the oxidation state of the rocks in the area can be obtained from the FeO/Fe₂O₃ ratios. The available bulk rock analyses are summarised in Table 8 and frequency histograms of FeO/Fe₂O₃ ratios are given in Figure 11. FeO was determined by chemical methods and this was subtracted from the total iron oxides values, determined by XRF, to obtain the Fe₂O₃ values.

The average FeO/Fe₂O₃ ratio for the unmineralised Westmoreland Conglomerate is 1.22. This is taken as a reference in drawing the oxidised-reduced boundary in Figure 11. It appears that the blue-black ignimbrite and andesite of Ec, the granite of Eg and the Seigal Volcanics have a more reducing mineralogy than the Westmoreland Conglomerate whereas red brown ignimbrite of Ec, rhyolite Ec, and some granite stocks of Eg are more oxidised than the Westmoreland Conglomerate. Almost all the mineralised occurrences are situated on or along the contact of the Westmoreland Conglomerate with the rocks of more reducing mineralogies.

Age determination
Hills and Richards (1972) gave results of U-Pb dating on 12 uraninite samples from mineralised occurrences in the study area (5 samples from the Namalangi deposit, 5 from the Cobar-2 deposit and 2 from the Eva mine). Their data suggest two periods of uranium deposition about 820 and 430 Ma ago.

Pidgeon (1985) dated 8 samples from the Namalangi deposit by the U-Pb method, which gave a single episode of uranium mineralisation at 812±55 Ma ago.

Uranium abundances
A number of uranium analyses are available from the Murphy Metamorphics, Cliffdale Volcanics, Nicholson Granite Complex, Westmoreland Conglomerate and Seigal Volcanics (Darby, 1986; Mitchell, 1976; Mason 1980; Uranerz Australia Ltd, unpublished data). Uranium in the Murphy Metamorphics was determined by fluorometry followed by HNO₃/HClO₄ extraction of 50 g of sample. The detection limit was 0.5 ppm. Other samples were analysed by XRF with a detection limit of 3 ppm.

The averages given in Table 9 should be treated with caution since a number of samples yielded values below the detection limits. Furthermore, a few analyses above 10 ppm U have been excluded, since these high values may be due to secondary enrichment processes.
<table>
<thead>
<tr>
<th>Deposit: Sample No</th>
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<th>Jim Beam</th>
<th>King's Ransom</th>
<th>El Hussen</th>
<th>Namalangi</th>
<th>Northeast</th>
<th>Westmoreland</th>
<th>Southern</th>
<th>Comfort</th>
<th>Eva mine</th>
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<td>198</td>
<td>188</td>
<td>208</td>
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<td>218</td>
<td>219</td>
<td>224</td>
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<td>0.8</td>
<td>1.7</td>
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<td>15</td>
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X: Below detection limit
NA: Not Analysed
All analyses in ppm except where indicated otherwise.

Detection limits: Se, Te = 0.02; Au = 0.03; Hg = 0.005; Ag, Cd = 0.1; As, Co, Ni, Sb, Sn = 1; Bi, Mo = 2; U = 3; Th = 4; Cu, Mn, Pb, Zn = 5; W = 10 ppm.
Table 8 FeO/Fe₂O₃ ratios of rocks from the Murphy Inlier region.

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<th>Rock Type</th>
<th>No of analyses</th>
<th>Fe₂O₃% range</th>
<th>average</th>
<th>FeO% range</th>
<th>average</th>
<th>FeO/Fe₂O₃ range</th>
<th>average</th>
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<td>0.84-4.07</td>
<td>2.03</td>
<td>0.90-4.26</td>
<td>2.76</td>
<td>0.75-3.15</td>
<td>1.61</td>
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<td>Blue-black ignimbrite</td>
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<td></td>
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<tr>
<td>Red-brown ignimbrite</td>
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<td>0.41-2.15</td>
<td>1.29</td>
<td>0.75-1.10</td>
<td>0.87</td>
<td>0.75-1.84</td>
<td>0.92</td>
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<tr>
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<td>5.05</td>
<td>2.67-3.07</td>
<td>2.87</td>
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<td>Cliffdale Volcanics (Ecco₂)</td>
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<td>Westmoreland Conglomerate</td>
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<td>2.62</td>
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<td>9.81</td>
<td>3.43-5.76</td>
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Source: Mitchell (1976), Gardner (1978) and Ahmad (1987)

Table 9 Uranium abundances in the Murphy Metamorphics, Cliffdale Volcanics, Nicholson Granite Complex, Westmoreland Conglomerate and Seigal Volcanics (all values in ppm).

<table>
<thead>
<tr>
<th>Rock unit</th>
<th>Range</th>
<th>No of Samples</th>
<th>Average</th>
<th>Standard deviation</th>
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<td>2.77</td>
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<td>Westmoreland Conglomerate</td>
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<td>Seigal Volcanics</td>
<td>3-11</td>
<td>13</td>
<td>5.41</td>
<td>2.57</td>
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</table>

Hochman and Ypma (1984), on the basis of thermoluminescence measurements on 800 samples from the Westmoreland Conglomerate, concluded that the original concentration of uranium could have been at least 10 ppm. This implies that more than half the original content of this element has been leached since the deposition of the Westmoreland Conglomerate.

The average crustal abundances of uranium is 2.7 ppm; for granite 5.0 ppm, for basalt 0.5 ppm, for shale 3.5 ppm (Krauskopf, 1979) and for sandstone ranges between 0.4 — 3.2 ppm (Wedepohl, 1978). This suggests that the Murphy Inlier region contains enhanced concentrations of uranium.

Origin
Morgan (1965) described the mineralisation at the Eva mine as hydrothermal in origin. A similar origin was suggested by Newton and McGrath (1958) for the Type D deposits described in this report. Hills and Thakur (1975) considered that the deposits associated with the Redtree dyke system are of hypogene origin. Schindlmayr and Beerbaum (1984) advocated a similar origin, resulting from convection cells generated by the thermal energy of repeated dyke reactivation. Manning (1979) considered the mineralisation as epigenetic and post-diagenetic. He classified the mineralisation in the Redtree area as a peneconcordant (nearly concordant) sandstone type. Hochman and Ypma (1984), on the basis of thermoluminescence studies, concluded that uranium was leached from the Westmoreland Conglomerate and was precipitated where suitable reducing conditions existed close to the basic dykes and volcanics. Ahmad (1987a) advocated a similar origin and has elaborated on the precipitation mechanism. The higher oxidation state of the Westmoreland Conglomerate permitted leaching and mobilisation of uranium and gold which were then precipitated along the reduction boundary at the interface of the Westmoreland Conglomerate and the volcanics. A coupled charge transfer reaction involving reduction of uranium from U⁶⁺ to U⁴⁺ and oxidation of iron from Fe²⁺ to Fe³⁺ has been suggested as a possible precipitation mechanism. Such an origin is possible for type A, Type B and probably also for Type C, but could not explain the Type D occurrences which are not situated at or along oxidised/reduced strata boundary. Obviously the fractures in the Type D occurrences pre-date the uranium precipitation. These fractures already may have had magnetite and sulphides which could have acted as reducing agent (Ahmad, 1987a).

COPPER
Classification
On the basis of orebody shape and composition of the gangue minerals, the copper occurrences within CALVERT HILLS can be classified as:
A. Breccia-pipes
B. Veins:
B₁-without vein quartz
B₂-with vein quartz
C. Stratiform
A. Breccia pipes
Breccia pipes are only seen in the Redbank Copper Field (RCF) where they occur as essentially steeply plunging cylindrical structures up to 75 m in diameter.
Figure 11 Frequency histograms of FeO/Fe₂O₃ ratios in various rock formations.

and with a vertical extent of about 350 m (Figure 12). Often the only surface expression of pipes is a circular capping of brecciated Masterton Sandstone (Plates 14 and 15). Pipes of smaller size, down to a diameter of about 4 m, are also known (Orridge and Mason, 1975; Rod, 1978). The majority of pipes occurs in the Gold Creek Volcanics, but in the area close to the Wollogorang homestead, breccia pipes have also been observed piercing through the Wollogorang Formation and the Settlement Creek Volcanics. A volcanic plug piercing the Seigal Volcanics (Plate 9), about 2 km north of the King’s Ransom prospect, probably also belongs to this category. It thus appears that pipes have pierced the entire stratigraphic section from the Seigal Volcanics to the Hobblechain Rhyolite. Not all of them, however, carry copper mineralisation.

Although a number of copper bearing breccia pipes have been located, mineralisation of economic grade has been proved only at the Bluff and Sandy Flat pipes. The Redbank, Azurite and Prince deposits, from which the bulk of the past production has come are apparently not related to breccia pipes.

The pipe boundary commonly represents a complex of minor shears with narrow zones of fracturing extending beyond the limits of the pipe, giving in detail an irregular and transitional boundary to the structure (Orridge and Mason, 1975). Rod (1978) considered that the pipes have crooked stems, and mushroom-like caps where they have domed-up the sediments. In the RCF, the rocks within the pipes typically dip toward the centre of the structure and are generally collapsed to a level more than 100 m below their normal stratigraphic position.

Detailed studies on the Bluff-type pipes by Knutson and others (1979) showed that the pipes contain two types of breccia: (a) in situ or autochthonous breccia and (b) allochthonous breccia. Type (a) breccia forms the outer part of the pipes and consists of very angular fragments of the local rocks viz., the Gold Creek Volcanics. Type (b) breccias form the axial zone of the pipes and contain large, subrounded fragments of the underlying Wollogorang Formation and the Settlement Creek Volcanics. The matrix in both types of breccia is similar. Associated fracturing often extends beyond the pipe boundaries. The matrix and the material filling the fractures consists of various combinations of dolomite, calcite, quartz, K-feldspar, apatite, celadonite, hematite, rutile and clay minerals. Chalcopyrite is the dominant sulphide, but some pyrite, galena, sphalerite and covellite is also present. Barite occurs as a minor constituent.

The oxidised zone extends to a depth of about 30 m and contains high-grade mineralisation ranging from 1.7 to 5.8% Cu. The main minerals in this zone are malachite, azurite, chalcocite and chryscolla. The main mineral in the primary zone is chalcopyrite (Plate 16). The average grade of the primary zone is about 1% Cu (Hobourside Oil N.L., 1974).

Hopwood (1971) is of the opinion that the tectonics of the Gold Creek Volcanics are characterised
by contemporaneous sedimentation and faulting, with common sediment-filled graben. The breccia pipes appear to be localised at the intersection of two graben zones which became the locus of subsequent fumarolic vents and associated copper mineralisation. Orridge and Mason (1975) considered that the primary structural control was the breccia which provided a permeable channel for hydrothermal solutions. They considered the initial brecciation of the pipes to be related to explosive activity, with trachyandesite magma rising into vertical zones of weakness controlled by intersections of major fractures.

Knutson and others (1979) on the basis of geochemical, petrological and stable isotope studies, concluded that the breccia pipes were formed as a result of high-level igneous activity and associated magmatic hydrothermal processes. Subsequent circulation of non-magmatic brines through fractures in igneous and sedimentary rocks is considered to have left a sedimentary imprint (which is evident in the
stable isotope values) on what was originally an igneous event. They believe that the breccia pipes formed by explosive release of fluid following the build up of overpressure in a postulated carbonated, K-rich trachytic magma at a depth of roughly 2 to 3 km.

B. Veins

Vein-type copper occurrences are of two subtypes: B₁ those in which vein quartz is lacking, and clayey, chloritic or micaceous gangue dominate and, B₂ those in which vein quartz is one of the major gangue minerals.

Subtype B₁ veins mostly occur in the RCF and include the Redbank, Azurite, Prince and Black Charlie prospects. Some copper occurrences in the Seigel Volcanics also belong to this category (e.g. Dianne, St. Barb prospects). Some reports of exploration companies suggest that the vein-type occurrences in the RCF may be breccia pipes but this is not confirmed by available evidence. The mineralisation is controlled by ill-defined steeply dipping fractures or shear zones and consists of secondary copper minerals such as malachite, azurite, chalcocite and chrysocolla. As in the breccia pipes, chalcopyrite is the only important sulphide in the primary zone along with minor pyrite. Similarity in ore and gangue minerals and close spatial relationship of the veins and the breccia pipes suggest a similar origin for both. In the case of these veins evidence of collapse is lacking and they may

Plate 15 Sandstone breccia capping San Manuel prospect. QA 937984.
Table 10  Chemical composition of copper ore.

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<th>Element</th>
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<th>121 (SF)</th>
<th>127 (SF)</th>
<th>140 (SF)</th>
<th>151 (SF)</th>
<th>38 (CV)</th>
<th>33 (AZ)</th>
<th>34 (AZ)</th>
<th>35 (AZ)</th>
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<th>212 (SB)</th>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>270</td>
<td>980</td>
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</table>

Analyses by ANALAB, Perth by Atomic Absorption method. All analyses in ppm except where indicated.

Abbreviations
BL Bluff  AZ Azurite  NR Norris
SF Sandy Flat  DN Dianne  CP Chapman Copper
CW China Workings  SB St. Barb
- Not analysed  X Below detection limit

Detection limits are same as in table 7

represent hydrothermal conduits probably connected to the breccia pipes.

Subtype B3 veins occur in the Nicholson Granite Complex and in the Cliffdale Volcanics. Mineralisation is controlled by well-defined steeply dipping faults, generally occurs in vein quartz as vug, fillings and, usually includes malachite, chalcocite, chrysocolla, minor azurite and rare galena. These veins may have been derived from hydrothermal fluids associated with the late phases of the Nicholson Granite Complex. Chemical analyses from some selected copper occurrences are given in Table 10. Copper appears to be the only element of economic importance along with some silver. Traces of gold also occur in vein-type copper deposits.

C. Stratiform copper mineralisation
Anomalous copper concentrations of up to a few thousand ppm have been noted at several stratigraphic horizons over several kilometres strike length and sometimes, even basin-wide. Visible mineralisation

Plate 16  Chalcopyrite (white massive) and pyrite (subhedral small grains) filling intergranular space between K-feldspar laths and vesicles in the Gold Creek Volcanics. Location: DDH SE8, depth 224 m, Sandy Flat deposit, sample No. 298.
consists of malachite, azurite, chrysocolla, and chalcopyrite.

Although a stromatolitic dolomite bed in the McDermott Formation, just below the Sly Creek Sandstone, shows consistently elevated copper and cobalt values over a few kilometres, south of Calvert Hills Homestead, sampling did not yield encouraging results (Allison and Dennis, 1982).

The Wollogorang Formation has several copper-rich horizons, occurring more or less throughout the basin. A stromatolitic dolostone near the base contains visible chalcopyrite. Rock chip samples gave around 250 ppm Cu (locally up to 5%), as well as anomalous lead and zinc values. Azurite and malachite fill vugs in sandstone near the top of this formation (Rod, 1977; Wyatt, 1977; Ashton Mining Ltd., 1983; Jackson and others, 1987). Nodular, organic-rich black shales, located immediately above the dolostones (“ovoid beds”), have regionally anomalous lead, zinc, and copper values (Ashton Mining Ltd., 1983) in a lacustrine facies similar to the host shales of the HYC deposit (Jackson and others, 1987).

TIN AND TUNGSTEN

Nicholson Granite Complex and Clifftide Volcanics contain a number of greisenised tin/tungsten-bearing occurrences.

The Crystal Hill deposit is situated on the northern flank of a conical hill known as Crystal Hill. This hill is about 500 m in diameter and rises to some 100 m above the surrounding country. It is composed largely of quartz-muscovite greisen (Plate 17). The strongly greisenised area on the southern flank of the hill is about 60 m long and 20 m wide. It is enveloped by a moderately greisenised zone of more than 100 m wide. This deposit has been worked intermittently, and cassiterite has been recovered mainly from the adjacent eluvium; production has been small but no records are available. Cassiterite is commonly disseminated throughout the greisen but in places it occurs in small rich pockets (up to 20% SnO₂) scattered erratically throughout the greisen. Occasional small pods and veins of cassiterite and wolframite bearing quartz occur within the greisen (Plates 18, 19). At Tracy’s Table traces of cassiterite are present in a number of quartz-
Plate 19 Wolframite crystal in quartz vein from the Crystal Hill deposit, sample No. 1863.

MUSCOVITE GREISEN LODES WITHIN THE CLIFFDALE VOLCANICS.

The greisenised outcrops are elliptical in plan and range in size from 6 x 12 m to 48 x 15 m. Many more occurrences of such greisenised outcrops are known from an area which extends some 3 km radially around the main Tracy's Table greisen, and it is possible that this area is underlain by a greisenised granite stock, similar to the one at Crystal Hill.

A few quartz veins containing traces of cassiterite and wolframite occur in an area about 1 km south of the Chapman copper prospect. The host rock belongs to the Nicholson Granite Complex. The veins have a northerly to north-easterly trend, a subvertical dip and may be 0.1 m wide and up to 50 m long. There are several patches of greenish grey greisenised material in the Dry Creek area. They are seldom larger than 5 m across and often contain quartz veins or patches with traces of cassiterite and/or wolframite. The host rock likewise belongs to the Nicholson Granite Complex.

About 150 m east of the Eva uranium deposit, a greisenised vein of about 0.1 m wide runs in a north-northeasterly direction for about 100 m. The host rock is a quartz-feldspar porphyry.

Muscovite from the Crystal Hill greisen was dated by the Rb-Sr method by Fanning and Webb (1986b). It contains 4460 ppm Rb and about 32 ppm Sr. It was assumed that most of the Sr is derived from radiogenic decay. The strong preponderance of Rb gave a calculated age which is insensitive to any geologically assumed initial ratios. Fanning and Webb (1986a) gave a calculated age of 1621±28 Ma for the formation of the muscovite. The age of greisenisation thus appears to be a least 100 Ma younger than the age of the enclosed Nicholson Granite Complex.

Six kinds of fluid inclusions are present in vein quartz within the greisens: Type A (liquid +<10% vapor), Type B (liquid + 10-30% vapor), Type C (vapor only or liquid +>80% vapor), Type D (liquid + halite +<10 % vapor), Type E (liquid + halite) and Type F (liquid only). Early 'primary' inclusions represented by Types B and C have higher temperatures (range 190-400°C, mean 300°C) and lower salinities (range 0.3 — 12 wt% eq. NaCl, mean 6 wt% eq. NaCl) than the late pseudosecondary inclusions represented by Types A, D and E (temperature range 90-330°C, average 165°C, salinity range 0.5 — 40 wt% eq. NaCl, mean 24 wt % eq. NaCl). Co-existing vapor and liquid + vapor inclusions in most samples indicate that solutions were boiling which is substantiated by vapor phase homogenization of many inclusions. The late high salinity — low temperature fluids were probably caused by extensive boiling.

In the early high temperature — low salinity fluids, tin was predominantly transported as a stannous hydroxide complex and precipitation caused by an increase in oxidation and decrease in temperature, both of which are attributed to boiling. The late low temperature — high salinity fluids carried tin predominantly as stannic hydroxide and precipitation was essentially due to lowering temperature (Ahmad, 1989).

MANGANESE

A number of small manganese occurrences are located in the vicinity of the Calvert Hills Homestead. They are underlain or hosted by the Karns Dolomite. Plsolumeane is the main ore mineral but pyrolusite, cryptomelane and wad also occur. Assays of up to 51% Mn have been recorded (Shannon, 1971, Campe and Gausden, 1970). Shannon (1971) speculated that the Masterton-2 prospect could contain about 200,000 tonnes of ore but this remains unsubstantiated.

The deposits have residual, bedding or joint/fault-controlled features and their origin is uncertain. Campe and Gausden (1970) conducted a regional geochemical survey in order to identify a suitable host rock and found that (a) all high grade deposits were underlain either by shale and siltstone or by chert, and that these rocks had low manganese values and (b) there were no high grade deposit in areas of pure dolostone. They concluded that the original Mn content of the underlying rocks was not a factor that controlled the manganese occurrences.

DIAMONDS

A systematic exploration program is currently carried out over most of the sheet area and detailed work by the Australian Diamond Exploration N.L. (1985) has resulted in the identification of several pipe-like bodies
west of Benmara Homestead. Scattered microdiamonds are also common in the drainage samples collected from this area. Ashton Mining Ltd (1986) also referred to a sedimentary rock abundant in microdiamonds, but no other details were given.

LEAD AND ZINC
Sediments of the Karns Dolomite and Fickling Group contain disseminated lead-zinc mineralisation but exploration efforts have, so far, failed to identify significant concentrations.

GOLD
Roberts and others (1963) mentioned the presence of small amounts of gold in the Tin Hole Creek and Gold Creek area but no references were given. Small quantities of gold occur also in the ores of the Eva, King’s Ransom and Cobar-2 uranium mines and a majority of uranium prospects are aurifereous (Table 7). Ahmad and others (1984) reported detrital gold from the Westmoreland Conglomerate.

HYDROCARBONS
Roberts and others (1963) described a sample of dark grey shale from sediments of the Fickling Group which had an average porosity of 20%, a residual water saturation of 12.4% of the porosity, and a residual oil saturation of 1.8% of the porosity. Dixon (1957) described imposotive (a solid hydrocarbon) occurring in the Karns Dolomite in the Bluey Creek area.

GROUNDWATER
There are several water bores in the Benmara area where water is obtained from weathered granite. In the Wollogorang Homestead one bore taps an aquifer in the Aquarium Formation. A few water bores have been drilled recently in the area of the Seigal Creek, Dry Creek and the Nujuburra Aboriginal settlements.

ACKNOWLEDGEMENTS
The authors gratefully acknowledge the contribution from other members of the Northern Territory Geological Survey in the preparation and publication of this report. Special thanks are due to C.P. Hallenstein and A.W. Mackie who mapped some parts of the area during the field work. Messrs. G. Webb, B. Kiwi Kiwi, M. Rhode and B. Butler provided assistance in the field.

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### Appendix 1

**MINERAL DEPOSIT DATA SHEETS**

**Explanatory Notes**

The accompanying data sheets have been largely compiled from unpublished reports held by the Northern Territory Department of Mines and Energy. Many of the mineral occurrences were inspected in the field and part of the information comes from these inspections.

The data sheets are designed to present brief, factual information on each deposit but some subjective interpretation is unavoidable.

**General Data**

Where available names of the mineral occurrences are shown, otherwise they are marked as unnamed. The names shown are either the most commonly used or the most recently known. Other names are shown in brackets. The number given to the deposit is arbitrary and generally progresses from west to east commencing from the northwestern corner of the 1:250,000 sheet. Compiler and date show the name of the geologist(s) extracting the information, and the date on which the information was placed on the computer file. Commodities are shown by chemical symbols. For extractive minerals full names are given. Locality gives the names and number of the 1,250,000 and 1:100,000 map sheets. Universal Grid Reference shows the 100km square identification followed by six digit grid co-ordinates. Length, width and depth refer to the overall size of the orebody. When more than one orebody is present, only the largest is mentioned here, others are described in the remarks column. Similarly, strike, dip and plunge refer to the overall attitude of the largest of the orebodies. Status of the deposit distinguishes between mineral occurrences, prospect, operating or abandoned mine.

**Size**

The size classification is based on the total tonnage (production + reserves) of the orebody or orebodies and is shown on the map by the size of the rings. The colours on the ring are proportionally divided if more than one commodity is present. For some deposits, with incomplete production or reserve figures, the size of the deposit is determined by the compiler. Four classes of deposits have been established. Three of these are given in Table 11 and are based on internationally recognisable size categories (e.g. as shown on the metallogenic maps of North America, South Africa and the Circum Pacific Mineral Resources Map). The category which contains only the ‘occurrence’ has been added to show mineral occurrences which appear to be very small and which have never been mined or delineated in great detail.

**Shape**

The shape classification is primarily geometric, emphasizing the relationship of the ore deposit to the host rock. Two genetic classes, superficial and placer, which are not determined by the above relationship are also included here.

- **Irregular deposits**: of irregular and undefinable shape, e.g. patchy greisenised bodies like the Crystal Hill deposit.
- **Vein or shear-zone fillings**: crosscutting or concordant epigenetic deposits in any type of host rock generally filling a fault or a shear-zone, e.g. Norris Copper, gold-bearing veins in the Pine Creek area.
- **Pipes**: essentially cylindrical deposits with long vertical axes such as breccia pipe, e.g. Sandy Flat and Bluff deposits.

Note 1. These data sheets have been superseded by the mineral occurrences database MODAT. Copy on CD DIP003.
Table 11  Deposit size, limits in tonnes of metal or mineral contained unless otherwise specified.
Past production and/or reserves totaled.

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<th>Medium</th>
<th>&gt;</th>
<th>Small</th>
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<td>Precious gems</td>
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<td>Semi-precious gems</td>
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<td></td>
<td>Silver</td>
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<td></td>
<td>Tungsten</td>
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<td></td>
<td></td>
<td>500</td>
</tr>
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<td></td>
<td>Uranium (U₂O₆)</td>
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<td></td>
<td></td>
<td>100</td>
</tr>
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<td></td>
<td>Vanadium</td>
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<tr>
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<td>Zinc</td>
<td>1,000,000</td>
<td></td>
<td></td>
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- **Stratiform deposits**: more or less rigorously confined to one or more layers in stratified (sedimentary or volcanic) rocks. Usually considered to be syngenetic, e.g. the McArthur River deposit.
- **Stratabound deposits**: occur more or less at the same horizon in stratified rocks. May be partly concordant, partly discordant with regard to the enclosing rocks. Usually considered to be of epigenetic origin, e.g. uranium deposits associated with the Westmoreland Conglomerate.
- **Superficial blanket type deposits**: usually consist of concentrations of residual material, e.g. bauxite at Gove, manganese deposits near Calvert Hills homestead.
- **Placer alluvial or eluvial deposits**: usually deposits resulting from mechanical concentration.
- **Others deposits**: those which could not be accommodated in one of the above categories.

**Origin**
The assignment of mineral deposits to genetic categories is rather subjective and speculative. Most of the Northern Territory deposits can be accommodated in seven categories which are slightly modified versions of those shown on the Metallogenetic Map of Europe (Carte, metallogenique de l'Europe, 1:2 500 000).

- **Sedimentary**: deposits formed entirely by sedimentary processes, e.g. iron ore deposits of Roper Bar and Constance Range; manganese deposits at Groote Eylandt.
- **Exhalative sedimentary**: deposits formed by issuance of volcanic fluids onto the sea floor or into the sea. e.g. Cosmo Howley gold deposit, McArthur River, Pb-Zn-Ag deposit.
- **Magmatic**: deposits formed by either magmatic segregation or by late-stage residual magmatic fluids e.g. Crystal Hill tin deposit.
- **Hydrothermal**: deposits formed by hot aqueous solutions, with or without demonstrable association with igneous processes, e.g. Redbank copper deposits.
- **Pegmatitic**: deposits occurring within pegmatite and formed concurrently. e.g. Bynoe tin-tantalum deposits.
- **Superficial enrichment**: deposits formed by residual or mechanical concentrations, e.g. most alluvial deposits, bauxite deposits at Gove.
- **Reduction boundary**: deposits formed by leaching by groundwaters at near surface temperatures and precipitation at oxidised-reduced interface e.g. Westmoreland uranium deposits.
- **Origin unknown**: deposits without enough data for a genetic classification.
Geologic setting
Gives names of the major tectonic unit(s), sub-unit, stratigraphic group, formation, member as well as their respective ages. Informal names are not used. When a particular deposit covers the boundary of two units, both units are mentioned.

Lithology and metamorphism
Describes the lithology of the host rocks and subsidiary host rock. For veins, such as a quartz vein for example, the wall rock lithology is also given. Metamorphic age is in Ma (million years) and type distinguishes between regional, contact or retrograde metamorphism. Facies: the following individual metamorphic facies are recognised: the zeolite, prehnite-pumpellyite, albite-epidote hornfels, greenschist, hornblende-hornfels, pyroxene hornfels, amphibolite and granulite facies.

Structure
Structure defines the ore controlling feature. Some of the structural elements that have been taken into account are: bedding, fault or shear zone, joint, cleavage, schistosity, synclinal hinge or basin, saddle reef etc. The principal structure is given first followed by the subsidiary structure. Strike, dip and plunge are in degrees (0-360°); if not accurately known, terms like NE, SW etc. are used. Mineralisation relative to age is indicated by the prefixes syn-, pre- or post-.

Mineralisation
Principal and other primary and secondary minerals are given. Except when otherwise indicated all sulphides are included in the primary ore minerals. Terms to describe gangue minerals have been selected from the following: host rock, quartz, other silica, calcite, dolomite, siderite, muscovite, sericite, epidote, K-feldspar, chlorite, clay minerals, talc, tourmaline, barite, fluorite, anhydrite, iron oxides and other minerals as specified.

Grain size refers to primary ore minerals only and it is defined as microscopic (less than 0.1 mm), fine (0.1-0.5 mm), medium (0.5-2 mm), coarse (2-10 mm) and very coarse (more than 10 mm).

Age of mineralisation refers to the actual age determination on one or more of the ore minerals and is given in Ma (million years).

Macroscopic ore textures are described by selecting one or more of the following terms: cataclastic, schistose, recrystallised, massive, disseminated, banded granular, nodular, vein, veinlet (stringer), open space filling, breccia filling, calloform and radiating. Other structures given are defined in the remarks.

If weathering effects have had a significant impact on the deposit, either adversely or favourably, then this result is added to the type of weathering effect (supergene enrichment, oxidation, leaching, etc.); the depth to which weathering has penetrated is also mentioned.

Wall rock alteration
The type of wallrock alteration is indicated by one or more of the following terms: propylitic, chloritic, zeolitic, argillic, sericitic, potassic, albitionisation, carbonitisation, silification and greisenisation.

The location relative to ore is indicated by reference to the footwall, hanging wall, and is farther described as proximal (in mineralisation), distal (fringe). Relative age is indicated by the prefixes pre-, post- or syn-.

Exploration and mining
Exploration methods include geochemistry, geophysics, geological mapping, drilling, costeaming and shallow pitting. Only methods are named here and users requiring more information should consult the reference or appropriate Exploration Series Maps.

Mining methods include open cut, underground, dredging, sluicing etc. Length, width and depth of the largest open cut working is given. Other information is included in the remarks.

Past production
Past production is given for up to three identifiable periods, all data are in metric tonnes. In many cases grade is not known. If more than one commodity has been mined, and if the other commodity is considered to be significant, it also is shown.

Ore reserves
Most data on ore reserves are as published in the reports, but in some cases an assessment has been made by the NTGS staff. Status denotes two categories: identified (measured, indicated, and inferred) reserves, and undiscovered (hypothetical and speculative) reserves. Both, identified and undiscovered reserves have been added, for the purpose of size classification.

References
Two categories of references are used: production and reserves, and exploration and general. Company report (CR) numbers used in the references are those assigned by the Geoscience Resource Section of the NT Geological Survey.

Remarks
This column includes data which the compiler considers important and which could not have been given elsewhere on the data sheet.
**MINERAL DEPOSIT DATA SHEET**

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<tr>
<td>Dip:</td>
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</tr>
<tr>
<td>Plunge:</td>
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</table>

**GEological SETTING**

| Major tectonic unit(s): | Sub-unit: |
| Group: | Age: |
| Formation: | Age: |
| Member: | |

**LITHOLOGY AND METAMORPHISM**

| Host rock: | |
| Subsidiary host rock: | |
| Wall rock: | |
| Subsidiary wall rock: | |
| Age of metamorphism: | |

**STRUCTURE**

| Type: | |
| Strike: | |
| Dip: | |
| Plunge: | |
| Age relative to mineralisation: | |

**MINERALISATION**

| Principal primary ore mineral: | Grain size: |
| Other primary ore mineral(s): | (of primary ore mineral) |
| Principal secondary ore mineral: | |
| Other secondary ore mineral(s): | |
| Principal gangue mineral: | Age of mineralisation: |
| Other gangue mineral(s): | |

**Macrosopic ore textures:**

| Weathering effect(s): | |
| Depth of weathering: | |

**WALLROCK ALTERATION**

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<th>Age relative to ore</th>
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**EXPLORATION AND MINING**

| Exploration methods: | |
| Mining methods: | |
| Open-cut workings - Depth: | Length: |
| | Width: |

**PAST PRODUCTION**

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**ORE RESERVES**

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**REFERENCES**

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**REMARKS**
REFERENCES

(AUTHORSHIP SHEETS)


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