Pine Creek Orogen: field excursion guide.
Chief Government Geologists Conference,
28 April–2 May 2003

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ITINERARY

DAY 1 WEDNESDAY, 30 APRIL 2003
DEPART DARWIN 0800 SHARP – ARRIVE AT FIRST STOP 0900

Stop 1-1 Beestons Formation/Archaean unconformity
Stop 1-2 Browns Polymetallic Deposit
Stop 1-3 Rum Jungle Creek South Uranium Mine and recreation area
Stop 1-4 Coomalie Dolostone stromatolites/Winchester Magnesite Deposit

LUNCH AT ADELAIDE RIVER 1300–1400

Stop 1-5 Burrell Creek Formation - road cutting
Stop 1-6 Gerowie Tuff in Howley Anticline - road cutting
Stop 1-7 Union Reefs Gold Mine

OVERNIGHT AT KATHERINE

DAY 2 THURSDAY 1 MAY 2003

Stop 2-1 Tollis Formation
Stop 2-2 Katherine Gorge - Kombolgie Subgroup
Stop 2-3 Edith Falls

LUNCH AT PINE CREEK

Stop 2-4 Allamber Springs Granite
Stop 2-5 Folding in the Mount Bonnie Formation
Stop 2-6 Nourlangie rock tourist stop

OVERNIGHT AT GAGUDJU LODGE / COOINDA

DAY 3: THURSDAY 2 MAY 2003

Stop 3-1 Wetland environment-Yellow Water Cruise
Stop 3-2 Ranger Uranium Mine (Mine visit with Mr Lorry Hughes, Chief Geologist)

LUNCH AT KAKADU NATIONAL PARK HQ - 1300–1400

Stop 3-4 Mount Bundey Dimension Stone Quarry

BACK TO DARWIN 5:30 PM
INTRODUCTION

The purpose of this excursion is to examine some of the Archaean and Palaeoproterozoic rocks and mineral deposits of the Pine Creek Orogen (previously referred to as Pine Creek Geosyncline or Pine Creek Inlier). Excursion stops are shown in Figure 1. The Pine Creek Orogen contains about 1500 mineral occurrences and is one of the most important metallogenic provinces of the Northern Territory. It hosts the world class uranium deposits of the Alligator Rivers Region (Ranger, Jabiluka, Koongarra and Nabarlek) and also a variety of other mineral commodities including Au, Pt, Pd, Sn, Ta, Pb, Zn, Cu, Ni, Co, Fe, and magnesite. Significant mineral deposits and regional geology are shown in Figure 2. The region contains about 20% of the world’s low-cost uranium resources, has a known resource of about 8.5 million ounces of gold and has produced approximately 2.5 million ounces of gold since its discovery in the late 1800s.

HISTORY

Early geological investigations in the Pine Creek Orogen (PCO) were carried out towards the end of the 1800s and provided a brief documentation of the geology, rock types and mining practices. In the period 1935-1939, the Aerial, Geological and Geophysical Survey of Northern Australia (AGGSNA) mapped several of the mines and mining fields. Sullivan and Iten (1952) compiled most of this information in Bureau of Mineral Resources (BMR) Bulletin 12.

In the period 1953-1958, BMR1 conducted a systematic regional mapping program at 1:63 000 scale. Walpole et al (1968) produced a comprehensive account summarising the results of this mapping. Between 1971-1981, the region was jointly re-mapped at 1:100 000 scale by BMR and the Northern Territory Geological Survey (NTGS).

Gold was discovered in 1865 and by 1881 gold mining activity was fairly widespread in the region. Nearly all pre-1980 gold production occurred in the period 1884-1915. Copper was discovered in 1872 at the Copperfield Creek Mine near Pine Creek. Tin was discovered at Mount Wells in 1879 and was followed by a number of other discoveries in the same region. Tin-tantalum bearing pegmatites in the Bynoe area were discovered in 1886. Lead-zinc-silver mineralisation was discovered in 1886 at the Evelyn Mine.

It was the discovery of uranium at Rum Jungle in 1949 that prompted systematic geological mapping of the PCO (Walpole et al 1968). Several small uranium and base metal deposits were discovered in the Rum Jungle Region in the following decade. The Browns polymetallic deposit was discovered in 1954 and is currently being assessed for feasibility. Geological similarities between the Alligator River Region and the Rum Jungle Region led to intensive exploration for uranium in the late 1960s, resulting in the discovery of the Koongarra, Nabarlek, Ranger and Jabiluka deposits between 1969 and 1971. The Nabarlek and Ranger 1 No.1 deposits are now exhausted (mined out). Mining is active at the Ranger 3 No. 1 deposit. Because this uranium-rich region is wholly within the Kakadu National Park, stringent environmental safeguards are enforced. The Koongarra and Jabiluka deposits are still awaiting clearance for mining.

A significant increase in exploration activity during the early 1980s resulted from an increase in the gold price and improvements in gold exploration, mining and extraction techniques. This led to the opening of the first modern gold mining venture, the Enterprise mine, in October 1985. Several other mining operations, including Brocks Creek, Cosmo Howley, Golden Dyke, Goodall, Moline, Mount Todd, Rustlers Roost, Union Reefs, Tom’s Gully and Woolwonga followed shortly afterwards.

REGIONAL GEOLOGY

The Pine Creek Orogen represents a Palaeoproterozoic sedimentary basin occupying an area of at least 66 000 km² (Figure 2). It forms part of the North Australian Craton and is correlated with other Palaeoproterozoic successions of Northern Australia (eg Tanami Region, Tennant, Murphy and Arnhem Inliers, and Halls Creek Orogen). Younger strata conceal its margins and the total extent is unknown. The PCO succession is unconformably overlain by the Palaeo- to Mesoproterozoic McArthur Basin to the west and southwest. Mesozoic and Cambrian sediments of the Bathurst Terrace and Arafura Basin lie to the north. Unconsolidated sand, silt and clay of Tertiary age cover much of the region. During the Late Cretaceous to Middle Tertiary, much of the land surface was subjected to intense chemical weathering, leading to laterite formation.

The PCO succession is up to 14 km thick and is considered to have been deposited in an intracratonic ensialic structure formed as a result of rifting of Archaean basement. Previous workers (Needham et al 1980, Walpole et al 1968) have divided the PCO into seven structural entities: Chilling Platform, Western Fault Zone, Batchelor Shelf, South Alligator Trough, South Alligator Hinge Zone, Nanambu High and Kakadu Shelf. These have little or no expression either in regional-scale gravity or airborne magnetics data. The gravity data shows two depocentres: a northwest-trending depression between South Alligator and Darwin, and a narrow belt west of Jabiru. Basement (granite and gneisses) in these centres is up to 4 km deep, but elsewhere, it is less than 2 km deep. It is exposed at the Rum Jungle and Nanambu Complexes and is subcropping at the Woolner Complex. On the basis of gravity data, Ahmad and McCready (2001) divided the PCO into four depositional domains: Batchelor Shelf, Central Trough, Nanambu Shelf and Eastern Trough. The Pb-Zn-Cu-Ni-Co±U-rich Rum Jungle Mineral Field represents depositional basement highs on the Batchelor Shelf and a similar situation is apparent in the Alligator River uranium province bordering the Nanambu Shelf.

1 now Geoscience Australia (GA).
The western PCO (formerly Litchfield Province) represents an area of isoclinally folded amphibolite to greenschist facies metamorphic rocks. The Batchelor Shelf and Central Trough exhibit sub-greenschist facies metamorphism and simple structures dominated by upright northwest- or north-trending folds. The Rum Jungle Region surrounds Archaean metamorphic and granitic basement inliers and exhibits polyphase upright folds, domes and basins. The Nanambu Shelf and Eastern Trough (formerly East Alligator Rivers Region) is characterised by amphibolite facies metamorphism and upright to recumbent folds (Johnston 1984). These areas are also characterised by different styles of mineralisation. The western PCO show extensive development of tin-tantalum-bearing pegmatites. The Rum Jungle Shelf and Central Trough contains Au, U, Cu, Ni, Co, Au-Pt-Pd, Sn and Pb-Zn-Ag deposits. The Nanambu Shelf hosts world-class uranium deposits at Ranger, Jabiluka, Nabarlek and Koongarra.

Peak deformation and regional metamorphism ascribed to the Nimbuwah Event of the craton-wide Barramundi Orogeny occurred at 1865 Ma. A period of granitoid intrusion, thermal metamorphism and minor volcanism dated at 1800-1850 Ma followed the regional metamorphism and deformation. Based on age and composition, Stuart Smith et al (1993) recognised three broad groups of granites in the Central Region: an older group dominated by more mafic granitoid phases, followed by concentrically zoned granites and leucogranites, and a youngest felsic granite phase. Stuart-Smith et al (1993) summarised geochronological data on these granites and concluded that U-Pb zircon ion probe ages are in the range 1800-1835 Ma and are more precise than either Rb-Sr whole rock (about 1780 Ma) or conventional U-Pb zircon ages (1860-1750 Ma). Granites of the Central Region have predominantly I-type characteristics and have magnetite as a common accessory. Many of these granites appear to be minimum melts and indicate crystal fractionation (Ferguson et al 1980). Mineralogical and petrological data on granites in the Litchfield Province suggest affinity to S-type granites (Ahmad et al 1993, Ahmad 1995).

**Palaeoproterozoic Stratigraphy**

The Pine Creek Orogen comprises an alternating succession of psammitic and pelitic sediments, tuff and minor volcanic rocks. Stratigraphic subdivisions in the Central and Rum Jungle regions are fairly well established, but due to poor exposure, intense

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**Figure 1.** Regional geology and locations of excursion stops.
deformation and high-grade metamorphism, those in the Litchfield Province and Alligator Rivers Region have not been established in sufficient detail. The stratigraphic succession is summarised in Table 1 and the regional geology and correlations are given in Figures 2, 3.

Table 2 details the geological history of the PCO.

Archaean basement

Archaean rocks are exposed in broadly domed inliers in the Rum Jungle (Rum Jungle Complex) and Nanambu Shelf (Nanambu Complex) areas. More is known about the Rum Jungle Complex because of better outcrop that shows the different rock types within the complex and relationships with the surrounding sediments.

The Rum Jungle Complex consists predominantly of granite, granodiorite, quartz-monzonite, quartz-monzodiorite and rare tonalite and monzonite. These granitoids intrude earlier metasediments comprising schist, metadiorite and banded iron formation. The granitoids are usually foliated and minor pegmatites and aplites are generally the only non-foliated rocks within the complexes. Both I- and S-type granitoids are present. In I-type granitoids, the pristine assemblage includes quartz, two feldspars, biotite ± hornblende ± sphene ± allanite ± zircon. The S-type granitoids assemblage does not contain hornblende and allanite but includes any or all of the following: garnet, muscovite, cordierite and sillimanite (Ferguson et al 1980). Granitic rocks have anomalously high uranium contents (average at 11 ppm) compared with the world abundances of 4.8 ppm in granitoids and 2.7 ppm in the crust (Ferguson et al 1980). S-type phases have relatively higher uranium concentrations than I-type.

The Rum Jungle Complex is exposed in two inliers named the Rum Jungle and Waterhouse domes (Lally 2002). The geometry of the inliers and updoming of surrounding sediments have been variously explained. Rhodes (1965) suggested that the Rum Jungle Complex represented a mantled gneiss dome. Stephansson and Johnson (1976) considered that both complexes correspond to Eskola’s type of mantle gneiss dome, but solid-state diapirism during the Palaeoproterozoic caused the doming of these complexes. Johnston (1984) interpreted the doming and oval shape to be a result of non-cylindrical folding modified by fold interference and late faulting. The contact with the Palaeoproterozoic sediments is clearly unconformable (Rhodes 1965) and in

Figure 2. Regional geology and locations of major mineral deposits. Geological key same as Figure 1.
many places is strongly deformed. It is exposed about 5 km northwest of Batchelor Township along the road to the Rum Jungle deposits (Stop 1-1). In this area, a granite phase is unconformably overlain by a basal conglomerate, which incorporates mineral grains and sub-angular pebbles of milky vein quartz derived from the basement.

U-Pb zircon and Rb-Sr total rock analyses gave ages of at least 2400 Ma for the crystallisation of granites from the Rum Jungle Complex (Richards et al. 1966, Page 1976, Richards et al. 1977). SHRIMP U-Pb zircon age dating of granites in the Rum Jungle is ongoing. To date, two samples from the Rum Jungle and Waterhouse domes have yielded ages of 2525 ± 5 Ma and 2535 ± 7 Ma, respectively.

Outcrop of the Nanambu Complex is very poor and different granite types are not able to be distinguished as at Rum Jungle. Geochemistry indicates both I- and S-type granites are represented, and as in the Rum Jungle Complex, uranium contents are anomalously high. U-Pb zircon and Rb-Sr dating give an age of about 2470 Ma (Page et al. 1980). Isotopic and structural evidence indicates that the Nanambu Complex has been remobilised at its margins, producing low-angle tectonic fabrics parallel to younger metasediments and Rb-Sr muscovite ages around 1800 Ma.

The Woolner Granite is subcropping beneath Cretaceous sediments of the Money Shoal Basin and has been sampled by drilling on a regional gravity low. SHRIMP U-Pb zircon dating of a granite sample yielded an age of 2675 ± 15 Ma (Williams and Compston 1983).

<table>
<thead>
<tr>
<th>Unit</th>
<th>Lithology</th>
<th>Thickness (m)</th>
<th>Age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor Dolerite</td>
<td>quartz dolerite dykes and small plug-like bodies.</td>
<td>1</td>
<td>1200 ± 35</td>
</tr>
<tr>
<td>Madgibberri Phonolite</td>
<td>phonolite dykes.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Munmarlary/Phonolite</td>
<td>phonolite dykes.</td>
<td>1</td>
<td>1316 ± 50</td>
</tr>
<tr>
<td>Tolmer Group</td>
<td>sandstone, dolostone, siltstone.</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Katherine River Group</td>
<td>sandstone, conglomerate, minor greywacke, siltstone, interbedded basal-andesite volcanics and pyroclastics.</td>
<td>3000-4500</td>
<td>1780-1700</td>
</tr>
<tr>
<td>Oenpelli Dolerite</td>
<td>layered tholeiitic dolerite lopoliths.</td>
<td>&lt;250</td>
<td>1720</td>
</tr>
<tr>
<td>Edith River Group</td>
<td>ignimbrite, microgranite, rhyolite, minor basalt and cherty sediments; basal sandstone, arkose.</td>
<td>1200</td>
<td>1820</td>
</tr>
<tr>
<td>Post-orogenic granite emplacement</td>
<td>biotite granite, quartz monzonite, syenite, granodiorite (numerous plutons).</td>
<td></td>
<td>1840-1800</td>
</tr>
<tr>
<td>EtSherana Group</td>
<td>rhyolite, greywacke, siltstone, sandstone, basalt.</td>
<td>1835</td>
<td></td>
</tr>
<tr>
<td>Nimbawuah Complex</td>
<td>granitoid migmatite, granite, gneiss, schist (anatexis of Early Proterozoic granite).</td>
<td>1865</td>
<td></td>
</tr>
<tr>
<td>Zamu Dolerite</td>
<td>layered tholeiitic dolerite sills and minor dykes.</td>
<td>&lt;250</td>
<td>1890</td>
</tr>
<tr>
<td>Myra Falls Metamorphics and Nourlangie Schist</td>
<td>layered schist, gneiss (metamorphosed and partly migmatised Early Proterozoic sediments).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Finniss River Group (flysch)</td>
<td>siltstone, shale, greywacke, arkose, quartzite, schist; minor interbedded volcanics.</td>
<td>1500-5000</td>
<td></td>
</tr>
<tr>
<td>South Alligator Group (shallow marine chemical, volcanics)</td>
<td>pyritic black shale and siltstone, chert-banded and nodular hematitic siltstone and black shale, algal carbonate, banded iron formation, jaspilite, tuff; greywacke near top.</td>
<td>&lt;5000</td>
<td>1885 ± 3 (tuff)</td>
</tr>
<tr>
<td>Mount Partridge Group (fluvialite, near-shore chemical, supratidal)</td>
<td>sandstone, siltstone, arkose, shale, conglomerate, quartzite, carbonaceous siltstone and shale, dolostone, magnesite; minor interbedded volcanics.</td>
<td>&lt;5000</td>
<td></td>
</tr>
<tr>
<td>Cahill Formation (supratidal, fluviatile)</td>
<td>quartz schist, pelitic and partly carbonaceous near base, with magnesite lenses.</td>
<td>&lt;3500</td>
<td></td>
</tr>
<tr>
<td>Namoona Group (shallow marine, chemical, detrital, supratidal)</td>
<td>pyritic carbonaceous shale and siltstone, calcareous in places, calcareous sandstone, tuff, agglomerate; arkose, sandstone and massive dolostone/magnesite in west.</td>
<td>3000</td>
<td></td>
</tr>
<tr>
<td>Kakadu Group (fluviatile)</td>
<td>sandstone, arkose, siltstone, conglomerate, quartzite, schist, gneiss.</td>
<td>&lt;1000</td>
<td></td>
</tr>
<tr>
<td>Nanambu Complex</td>
<td>granite, augen gneiss, leucogneiss, minor quartzite and schist (includes accreted Early Proterozoic metamorphics).</td>
<td>&gt;2470</td>
<td></td>
</tr>
<tr>
<td>Rum Jungle Complex</td>
<td>coarse, medium, and porphyritic adammellite, biotite-muscovite granite, migmatite, gneiss, schist, pegmatite, metadiorite, banded iron formation.</td>
<td>&gt;2525</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Summary of Archaean to Palaeoproterozoic stratigraphy of the Pine Creek Orogen
The stratigraphic relationships and correlation of rock units between different regional entities are given in Figure 3. The thickness of the Palaeoproterozoic strata in the Central Region is considered to be about 14 km, whereas in the Rum Jungle region it is only 1-2 km, suggesting an eastward-sloping basement configuration (Stuart-Smith et al. 1980). The thickness of Palaeoproterozoic strata in the Litchfield Province is not known.

A mafic volcanic unit at the top of the Namoona Group in the South Alligator Valley has been dated by SHRIMP U-Pb zircon at about 2050 Ma (Geoscience Australia, Ozchron database). Tuffaceous sediments higher in the Palaeoproterozoic succession (Gerowie Tuff and Mount Bonnie Formation) have been dated by U-Pb whole zircon method at 1885 ± 2 Ma (Needham et al. 1988). SHRIMP U-Pb zircon dating of ignimbrite in the Tollis Formation has given ages in the range 1900-1870 Ma (Page and Williams 1988).

Table 2. Summary of Palaeoproterozoic geological history.

<table>
<thead>
<tr>
<th>Platform Cover Succession</th>
<th>Age</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1720 Ma</td>
<td>Intrusion of dolerite lopoliths and sills (Oenpelli Dolerite).</td>
</tr>
<tr>
<td></td>
<td>1780-1700 Ma</td>
<td>Continental to shallow marine deposition of sandstone and minor siltstone. Mafic to felsic volcanism (Katherine River and Tolmer Groups).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unconformity</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Shoobridge Event” 1780 Ma</td>
</tr>
</tbody>
</table>

| Rifting phase 1825 Ma | Fluvial deposition of sandstone, felsic and minor mafic volcanism (Edith River Group), southern central PCO. |

<table>
<thead>
<tr>
<th>Unconformity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maude Creek Event 1830 Ma</td>
</tr>
</tbody>
</table>

| Rifting phase 1835 Ma | Valley-fill felsic and mafic volcanism and fluvial deposition of sandstone, followed by widespread turbidite facies deposition (El Sherana Group), southern central PCO. |

<table>
<thead>
<tr>
<th>Unconformity</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Nimbuwah Event” 1870-1860 Ma</td>
</tr>
</tbody>
</table>

| 1890 Ma | Intrusion of continental tholeiitic dolerite sills (Zamu Dolerite). |

| Sag phase sedimentation 1885 Ma | Shallow marine subtidal, semi-evaporitic deposition of pelite, distal felsic volcanism (South Alligator Group); evolves into flysch-turbidite deposition (Finniss River Group). |

<table>
<thead>
<tr>
<th>Unconformity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rift phase sedimentation start 2100 Ma</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Unconformity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basement &gt;2470 Ma</td>
</tr>
</tbody>
</table>
Figure 3. Stratigraphic correlations across regions of the Pine Creek Orogen.
Palaeoproterozoic Granitoids

The succession in the Pine Creek Orogen is intruded by a large number of granitoids. The majority of these intrusions are post-orogenic but some late- or syn-orogenic granitoids are also present.

In the western PCO, intrusive activity is reflected by the emplacement of at least 6 predominantly S-type granitoids. In the Central Trough, 19 phases constituting the Cullen Batholith have been identified. These intrusions are typically I-type, except in rare cases in which characteristic features straddle the I-S boundary. In the eastern PCO, synorogenic intrusions of the Nimbuwah Complex caused local migmatisation of the sediments. Age determinations reveal three different time periods of granitoid intrusion: Nimbuwah (eastern PCO) at 1870-1860 Ma; Litchfield (western PCO) at 1850-1840 Ma; and Cullen (Central Trough) at 1840-1820 Ma.

Regional Metamorphism

At least two regional metamorphic events are discernible in the Pine Creek Orogen:

- Archaean pre-2500 Ma metamorphism in the Rum Jungle Region prior to the intrusion of granitoids.
- Palaeoproterozoic Nimbuwah Event of the Barramundi Orogeny (1865 Ma) displaying:
  (a) high-grade regional metamorphism along the eastern and western margins
  (b) low- to medium-grade regional metamorphism in the centre.

Archaean metasedimentary units within the Rum Jungle Complex are metamorphosed to amphibolite facies. The minerals present include biotite, oligoclase, hornblende, muscovite, andalusite, tremolite, actinolite, epidote, diopside and relict garnet (Rhodes 1965, Pietsch 1986, 1989). The age of this metamorphic event is considered to be pre-2500 Ma and is constrained by the age of the Rum Jungle granites that intrude the metamorphic rocks.

The mineralogy of these rocks is not described in terms of stable mineral assemblages and P-T limits cannot be precisely determined, but the presence of biotite, muscovite, garnet, tremolite, diopside, quartz and oligoclase suggests a pressure range of 4-6 kbar and a temperature range of 550-650°C.

Granite of the Nimbuwah Complex at the eastern edge of the Pine Creek Orogen has been dated by the conventional U-Pb zircon method at 1866 ± 8 Ma (Page et al 1980). This provides the age of the earliest Palaeoproterozoic metamorphic event in the PCO, which is termed the Nimbuwah Event of the craton-wide Barramundi Orogeny. Metamorphism of the Hermit Creek and Welltree Metamorphics in the western PCO, and that of the Myra Falls Metamorphics and Nourlangie Schists in the eastern PCO probably took place during this early phase.

Complexly deformed pelitic to psammitic gneisses and metabasite of the Hermit Creek Metamorphics are metamorphosed to upper amphibolite or granulite facies (Pietsch and Edgoose 1988, Dundas et al 1987). The presence of biotite, cordierite and sillimanite in the assemblage and the absence of both staurolite and kyanite indicate low pressure-high temperature Buchan-type metamorphism. P-T estimates in the order of 3-4 kbar and 500-600°C are indicated by these mineral assemblages.

Deformation and metamorphism in the Welltree Metamorphics was less intense. Metamorphic grade ranges from greenschist to lower amphibolite facies. The presence of andalusite, albite, biotite and muscovite in the greenschist assemblage suggests a temperature range of 400-500°C. There are no diagnostic mineral assemblages to define the pressure, which was probably less than 3.5 kbar because of the absence of kyanite (Pietsch 1986). The presence of rare almandine, sillimanite, tremolite and diopside in the higher grade (amphibolite facies) assemblage suggests P-T conditions of 2.5-5 kbar and 530-650°C (Pietsch 1986).

Throughout the Central Trough, regional metamorphism of the pelites produced fine-grained, weakly foliated sericitic and microcrystalline quartz-bearing rocks which show a phyllitic texture. Psammitic rocks usually have fractured and strained quartz grains, which exhibit recrystallised, optically continuous quartz overgrowths. Minor metamorphic sericite, chlorite or muscovite are present in these sediments. Eutaxitic textures are commonly preserved in the tuffaceous sediments, which are devitrified and altered to chlorite, sericite and quartz (Stuart-Smith 1985). Calcareous units contain calcite + tremolite ± phlogopite ± talc and/or dolomite + calcite + magnesite ± tremolite assemblages (Ferguson 1980, Pietsch 1989). The absence of cordierite, staurolite and andalusite, and the presence of sericite, muscovite, chlorite and tremolite suggest P-T regimes of less than 2 kbar and 400-500°C (Ferguson 1980).

Around the Burnside and Shoobridge granites, metamorphic grade is slightly higher. The rocks in these areas are strongly foliated and commonly contain biotite. Calcareous rocks of the Koolpin Formation contain tremolite, garnet, quartz and biotite. Iron-rich sediments contain ferroactinolite, garnet, siderite and iron-rich chlorite.

Contact Metamorphism

Regional metamorphism was closely followed by a major period of late- to post-tectonic granitoid intrusions and in some instances, these two events partly overlapped. Palaeoproterozoic rocks have been contact-metamorphosed in the vicinity of these granitoids. Albite-epidote hornfels is present in all contact aureoles, commonly with a narrower, inner continuous zone of hornblende-hornfels (Stuart-Smith 1985). The effects of contact metamorphism are seen up to 10 km away from the exposed granite contact (Stuart-Smith 1985) and Pietsch (1986) described the contact aureole of the Two Sisters Granite as being up to
15 km wide. This emphasis on lateral distance may be misleading as geophysical data (Tucker et al. 1980) suggest that granitic rocks are virtually everywhere present in the Pine Creek Orogen at a depth of 1-4 km. However, the geophysical data cannot distinguish between Archaean basement and Palaeoproterozoic granitoids.

The boundary between the albite-epidote and the hornblende-hornfels facies is marked by the hornblende isograd, which lies at the surface within 2 km of the granitoid boundary. The presence of muscovite, quartz, diopside and rare K-feldspar and cordierite, and the absence of sillimanite suggests P-T regimes of 2-4 kbar and 550-680°C.

The albite-epidote facies may be divided into two parts by the biotite isograd (Stuart-Smith 1985). The inner high-grade biotite-bearing zone is generally massive and hornfelsic and contains visible muscovite, biotite and chloritoid. Pelitic rocks of the outer, lower-grade zone typically contain recrystallised foliated sericite, muscovite, chlorite and quartz. The presence of sericite, quartz, chloritoid, tremolite and calcite, and absence of diopside, K-feldspar and biotite suggests P-T regimes of 2-4 kbar and 500-600°C.

Pelitic hornfels rafts and xenoliths within the granitoids, and some pelitic rocks of the Burrell Creek Formation close to the McMinns Bluff Granite, contain cordierite, andalusite, K-feldspar, biotite, muscovite and quartz. The presence of K-feldspar and andalusite, muscovite and biotite, and the absence of sillimanite suggest temperatures higher than the albite-epidote facies, probably in excess of 650°C.

Local Post-tectonic Rifting

In the South Alligator River Valley area and extending south to Katherine, two cycles of felsic volcanism and clastic sedimentation accompanied the waning stages of post-orogenic granitoid intrusion. The oldest cycle, the El Sherana Group, consists of mostly coarse sandstone and conglomerate with interbedded rhyolite, ignimbrite and crystal tuff. The SHRIMP U-Pb zircon age of the rhyolite unit is 1825 ± 9 Ma. A probable equivalent of the El Sherana Group, the Tollis Formation, is exposed to the southwest of the South Alligator River Valley around the Mount Todd Goldfield area, and further south near Katherine. The Edith River Group unconformably overlies the El Sherana Group and extends from the South Alligator River Valley to Katherine. It consists of mostly felsic volcanic rocks and high-level subvolcanic felsic intrusives, with only minor sandstone. Felsic volcanics have been dated by SHRIMP U-Pb zircon at 1822 ± 6 Ma. Volcanism is linked to late-stage extensional reactivation of the South Alligator Fault Zone and other parallel structures (Needham et al. 1988).

Retrograde Metamorphism

The stable regional and contact metamorphic mineral assemblages are invariably altered by widespread retrograde or hydrothermal events. Such alteration effects are present throughout the PCO. Andalusite and cordierite porphyroblasts have been converted to muscovite and quartz. K-feldspar is commonly sericitised and biotite and hornblende have been converted to chlorite and quartz. Ubiquitous Rb-Sr ages of granitoids in the range 1770-1780 Ma probably record this event, which appears to have involved widespread thermal resetting.

Palaeo- to Mesoproterozoic platform cover

Palaeo- to Mesoproterozoic platform cover successions rest with a marked unconformity on the older rocks. The Katherine River Group covers PCO rocks to the east and southeast, and the Tolmer Group overlies these rocks to the west. These cover rocks are essentially unfolded and the strata are either horizontal or only gently dipping. They are commonly cut by major joint sets and dolerite intrusions.

The Katherine River Group includes arenites and interbedded mafic volcanic rocks and may be up to 4 km thick. It consists predominantly of white to buff, very coarse and pebbly quartz sandstone. The basal 20 m is conglomeratic with well rounded pebbles and boulders up to 40 cm in size of vein quartz, siltstone, shale, slate, argillite and chert, derived locally from underlying Archaean and Palaeoproterozoic rocks. Volcanics at the top of the group have been dated by SHRIMP U-Pb zircon method at 1705-1712 Ma (Kruse et al. 1994). The Katherine River Group does not host any economic mineralisation but the proximity of this formation to the uranium deposits in the Alligator Rivers Region has focused attention on the sandstone as a possible source of uranium or as a vital factor in uranium-ore genesis (Needham et al. 1980).

A similar situation probably existed in the Rum Jungle area where orogenic strata was covered by arenites of the Tolmer Group. The Tolmer Group outcrops extensively in the western PCO where it is about 1800 m thick and is divided into four formations. Like the Katherine River Group, the succession is not folded and comprises horizontal to gently dipping strata.

Structure

The earliest deformation, D1, caused north-trending monoclinal warping, recumbent north-trending isoclinal folding and tectonic sliding. Thrusting and recumbent folding, which is more common in the in the western PCO and Alligator Rivers Region, represents D2 deformation. The D2 deformation event is more widespread and is represented by north- to northwest-trending non-cylindrical, tight to isoclinal folds and the development of an axial planar slaty cleavage. These folds are an important structural control for vein-type mineralisation in the Central Trough. The D3 deformation phase was associated with post-tectonic granitoid intrusions and produced open, upright, small-amplitude large-scale east-trending folds, which are responsible for the structural control for vein-type mineralisation in the Central Trough.
for the formation of elongated basins and domes. The $D_5$ deformation produced steeply plunging polyclinal kinks and drag folds associated with dextral movements along major faults.

**STOP DESCRIPTIONS**

**Stop 1-1 Beestons Formation/Archaean unconformity**

*Location: Rum Jungle Uranium Field 1:100 000 Special MGA 718100mE, 8559400mN*

Originally the Rum Jungle and Waterhouse "Granites" were thought to be concordant intrusions which had domed the Palaeoproterozoic metasediments of the Pine Creek Orogen (Sullivan and Matheson 1952, Malone 1962). However, no clear evidence of contact metamorphism was recorded, though quartz-tourmaline veins cut both granites and metasediments.

In 1962, BP Ruxton and J Shields discovered an outcropping unconformity (Rhodes 1965), which showed beyond dispute that the Beestons Formation, the lowest stratigraphic unit in the Rum Jungle Region, lies unconformably on what Rhodes defined as the Rum Jungle Complex. Since then, French (1970) and Johnson (1974) have described several other exposures of the unconformity between granitic basement and Palaeoproterozoic metasediments.

At most exposures, the unconformable contact is sheared and dips more steeply than 70° (Stephansson and Johnson 1976). However, at this locality, the contact is undeformed and dips southeast at about 40°. The unconformity is exposed in three outcrops and can be traced for about 150 m (*Figure 4*). The unconformity surface is irregular and undulating, broadly concordant with the dip of the overlying sedimentary rocks (Eupene 1985).

The basement at this locality is a massive, pink leucocratic coarse equigranular granite of the Rum Jungle Complex. The granite comprises microcline, quartz, plagioclase, biotite, sericite and minor fluorite. Thin, irregular fine-grained leucogranite dykes and quartz tourmaline veins are common, and the quartz has a characteristic pale blue opalescent colour. This granite has recently been dated by SHRIMP U-Pb zircon at about 2525 Ma (Ahmad *et al* in prep).

The sedimentary rock in contact with the granite is poorly-sorted coarse to gritty arkose of the Beestons Formation. This arkose contains thin quartz pebble beds and lenses up to 3 m thick of chaotic clast-supported conglomerate, which is composed of angular white vein quartz fragments ranging up to 30 cm across in a gritty arkose matrix (*Figure 5*). Grains of blue opalescent quartz, like those in the granite basement, are common in the arkose. The arkose represents transgressive shallow water, possibly shoreline deposits, largely derived from the underlying granitic basement (French 1970). Inherited zircons from the arkose have been dated by SHRIMP 1. The age spectra ranges from 2500 Ma to 3615 Ma and is principally dominated by a mode between 2500 Ma and 2575 Ma (66% of grains). The weighted mean of the youngest six grains in the population yielded an age of 2506 ± 14 Ma (Ahmad *et al* in prep), and this indicates that the sediment is derived entirely from the underlying granitic rocks.

*Figure 4.* Geological map of the Beestons Formation/Archaean unconformity in the vicinity of Stop 1-1 (after Eupene 1985).
Stop 1-2 Browns polymetallic deposit

Location: Rum Jungle Uranium Field 1:100 000 Special MGA 716400mE, 8562610mN

Fine-grained galena was found in this area in 1954 in diamond core holes drilled by the Territory Enterprises Pty Ltd. In 1957, the Australian Atomic Energy Commission and Australian Mining and Smelting Ltd carried out further drilling and by 1958, a substantial low-grade lead deposit was identified (Fraser 1980). Further evaluation was carried out by underground development and diamond drilling which outlined an orebody up to 700 m long, 50 m wide and persisting to a depth of 450 m. CRA Exploration Pty Ltd carried out further exploration and evaluation during the 1980s. Allnutt (1985) gave a total resource at this deposit of 20 million tonnes grading 5.6% Pb, 0.3% Zn, 0.19% Cu, 0.1% Co and 0.145% Ni.

In the last decade, a joint venture between Compass Resources (75%) and Guardian Resources (25%) has carried out considerable exploration including several diamond drillholes, resource estimations and metallurgical tests. The current total resource estimate, including Browns East, is 66.7 Mt at 2.58% Pb, 0.82% Cu, 0.12% Co, 0.11% Ni and 10g/t Ag (Compass Resources 2001). A trial pit was excavated in 2000 to obtain fresh samples for metallurgical tests. These tests demonstrated that high recoveries are possible by using the Ausmelt technology. In 2002, Compass Resources reached an agreement with The Doe Run Company to provide funding and technical support for a definitive feasibility study.

Browns and other mineral deposits, including the Rum Jungle uranium mines, lie within a triangular area known as the Embayment (Figure 6). The southern boundary of the Embayment is defined by the Giants Reef Fault, and the northern boundary by a series of east-trending ridges of the Crater Formation. Five deposits are known from this area; from east to west these are: Dysons (U), Whites East (U), Whites (U) Intermediate (U, Cu) and Browns (Pb, Cu, Ni, Co, Zn). They are spaced 0.5-1 km apart and lie on a northeast-trending shear zone. These deposits (and the shear zone) are located on the northern limb of a northeast-trending, steeply southwest-dipping and gently southwest-plunging, asymmetric syncline with a shallowly-dipping northern limb and steeply-dipping southern limb. North- to northeast-trending faults cut across the area and the Dysons, Whites and Intermediate deposits are located at the intersection of the shear zone and these north-trending faults. All deposits are within the Whites Formation close to the contact with the underlying Coomalie Dolostone. The sediments have been intruded by a sill of amphibolite, which is a possible stratigraphic equivalent of the Zamu Dolerite.

At depth, the sheet-like orebody dips steeply (80°) to the south, but rolls into shallower dips (45°) near surface (Figure 7). Major sulfide minerals are pyrite, galena, chalcopyrite and siegenite. These generally occur as fine crystals, typically less than 50 microns across. However, in some places, coarse-grained (>1 cm) mono- or polymineralic patches may occur. Polymetallic assemblages crosscut slaty and crenulation cleavages at a variety of angles.

During the early stages of exploration in the area, lateral zoning was identified, with Pb-Co (±Zn) dominating in the southwest and Cu-Co in the centre and northeast. However, recent drilling and analytical work has revealed a more complex picture. In places, the deposit is vertically zoned, with Cu stratigraphically below Pb, while Co-Ni overlaps both. In many cases, zonation is either more complex or actually reversed, with Pb below Cu. No evidence of stratigraphic inversion is present.

The host rocks predominantly consist of quartz, sericite/muscovite and organic matter in various stages of graphitisation, with variable amounts of chlorite and biotite. Other minerals present include zircon, monazite, apatite, crandallite (Ca₆(PO₄)₂(OH)₃·H₂O) and xenotime. Carbonate minerals are rare.
Stop 1-3 Rum Jungle Creek South uranium mine

*Location: Rum Jungle Uranium Field 1:100 000 Special MGA 716500mE, 8557200mN*

At this stop we look at a fully rehabilitated uranium mine. The old open cut has been rehabilitated and turned into a recreational lake. Discovery of this blind orebody in 1959 was the result of grid percussion drilling in the vicinity of an airborne scintillometer anomaly, which had been recognised since 1953. Follow-up evaluation of the deposit included 150 diamond drillholes (totalling about 10 000 m), 45 percussion holes (totalling about 3600 m) and a 72 m deep exploratory shaft with drives. This work outlined an orebody that produced 663 500 t of ore grading 0.435% U₃O₈ and 115 800 t of low-grade ore grading 0.065% U₃O₈ (Berkman 1968). Total production from this mine was 2928 t U₃O₈.

The host rocks are pyritic and chloritic schist or phyllite of the Whites Formation. These overlie the Coomalie Dolostone and are in turn unconformably overlain by a succession comprising hematite-quartz breccia (HQB), sandstone, fine-grained apatite rock and apatite breccia (Geolsec Formation; Lally 2002). This succession forms small ridges (Castlemaine Hill) to the north of the open cut. The age of the Geolsec Formation is uncertain but it may be a stratigraphic equivalent of the Depot Creek Sandstone and lower Katherine River Group. This possible correlation highlights the similarities between the Rum Jungle and Alligator Rivers Regions and may have some bearing on the genesis of the uranium deposits.

Figure 6. Geology of the Rum Jungle Mineral Field near Batchelor.
Figure 7. Geological map of Rum Jungle deposits and cross-section through Browns Deposit.
Rehabilitation of the mine site was carried out by the Northern Territory Department of Mines and Energy in 1990/91 and included: scraping, removal and disposal of uranium ore and contaminated soil on the waste rock dump; excavation of soil and gravel used to replace removed material; reshaping of the waste rock dump and covering it with top soil; construction of a drainage system and revegetation. This rehabilitation project was particularly significant because of the intention to encourage members of the public to use the site for recreation. Hence the degree of care in the rehabilitation program was of necessity very high. The recommended annual dose level for members of the public is 1 mSv (milli Sievert) which is exceeded by the natural background level in many places. The lake water contains 20-23 mg/L filterable uranium with only a small proportion of uranium present in particulate form.

Stop 1-4 Coomalie Dolostone/Mount Grace Magnesite
Location: Rum Jungle Uranium Field 1:100 000 Special MGA 722300mE, 8556300mN

The Coomalie Dolostone conformably overlies the Crater Formation and is conformably overlain by the Whites Formation. It comprises algal dolostone, silicified dolostone, dolomitic marl and breccia. Dolomite and magnesite are the common minerals along with minor talc. The magnesite is coarse and well crystalline, whereas the dolomite is fine-grained with a sub-earthly lustre. The Coomalie Dolostone has an average thickness of about 300 m and was deposited in a littoral to neritic environment.

At this site, a typical outcrop of the Coomalie Dolostone has the appearance of an elephant and is located in otherwise flat black-soil plains. This outcrop contains well preserved Palaeoproterozoic stromatolites. The dolostone is thickly bedded and dips about 60° southeast. It consists of dark grey dolomitic to magnesian marble, with some talc. Stromatolites in the outcrop are hummocky in form and consist of alternating bands of carbonates and siliceous talc draped over each other in a mould-like fashion.

On the northwestern side of the outcrop, there are some aboriginal etchings and crude paintings on a prominent overhanging cliff 12 m high. Numerous aboriginal artefacts including small chipped tools are scattered on the ground.

Magnesite deposits

Magnesite was first noted in the Coomalie Dolostone in 1986 at the Mount Fitch Uranium Deposit. In 1977-78, Geopeko drilled two diamond holes in the Area 44 Magnesite Deposit, located about 1.5 km west-northwest of the Woodcutters Zn-Pb deposit. Between 1979 and 1983, BHP conducted extensive exploration for magnesite and identified the Celia and Coomalie2 Magnesite Deposits. This work included costeasing, mapping, drilling, resource estimation and feasibility studies. A possible resource of 10 million tonnes of low-silica magnesite was identified. The search was for low-silica zones or coarsely crystalline magnesite which could be easily beneficiated to a refractory grade material. Drilling identified some low-silica zones within both the Coomalie and Celia magnesite areas. In 1980, 7 kg of magnesite ore was sent to Grundstofftechnic in East Germany for beneficiation tests. These tests indicated that a low-silica product could be obtained, which might be suitable for refractory grade magnesite production. In 1981, an additional 115 kg of core from the Celia Magnesite Deposit and 15 kg of core from the Coomalie Magnesite Deposit were tested by flotation, calcining and sintering. These tests indicated that high-density low-silica magnesite bricks suitable for refractory purposes could be produced.

No major exploration for magnesite was undertaken until the early 1990s, when there were significant changes in the demand, supply and uses of magnesium metal. Although the traditional use of magnesite as refractory bricks continued, new uses became important. The new areas of demand for magnesite are aluminium alloying such as in beverage cans (44%); die casting, mainly in castings for automobiles (28%); and desulphurisation of iron and steel (14%).

With this change in demand, exploration for magnesite in the Rum Jungle Mineral Field was reinstated. Between 1990 and 1993, Aztec Mining Company Ltd carried out drilling programs over the Area 44, Celia and Huandot Prospects and concluded that the Huandot Deposit had the greatest potential for the production of magnesium metal. Aztec estimated a total resource at Huandot at 5.08 Mt magnesite (Barnes 1999). A resource of 0.5 Mt down to 40 m depth was also identified at the Celia Prospect. In early 1994, Aztec assets were sold to Normandy Mining Ltd and were explored by its subsidiary Normandy Industrial Mineral Ltd (NIML). In 1995, NIML sent 26 000 tonnes of Huandot magnesite to Quebec for evaluation and magnesite metal production. Although this sample did not meet Norsk Hydro’s stringent chemical specification, it was found suitable for magnesium metal production.

In the area surrounding the Coomalie Magnesite Deposit identified by BHP in the early 1980s, Mount Grace Resources (now New World Alloys Limited) commenced exploration in 1998 and identified the Mount Grace (Winchester) Deposit. Between 1998-2002, this company carried out extensive drilling and identified a total resource of 17 Mt at 41.5% MgO. In 2000, a trial pit was excavated and 2000 t of magnesite ore was stockpiled. A 200 t parcel was sent to Mitec in South Africa for testing.

At this site, we look at the ore stockpile from the Mount Grace trial mining pit. The pit lies about 2 km to the east and is now collapsed. Note that the majority of the magnesite is heavily brecciated and several generations of magnesite can be identified. Magnesite colour varies from dark brown to grey to pure white and possibly reflects variations in trace iron oxide contents. It is present as coarse euhedral crystals up to 1 cm across in two dominant morphologies – cleavage rhombohedron (211) and steep rhombohedron (110). These two forms have been referred as rhombohedral and bladed, respectively (Bone 1985).

2 Now known as Mount Grace Deposit.
The magnesite deposits are not associated with any known structural features. In situ brecciation is common and virtually all the drill core from the Winchester deposits, as well as the open cuts at Huandot, show extensive brecciation to the extent that there is very little material that is not brecciated (Figure 8). In many instances, the brecciated pieces can be put back together and are therefore derived locally. The size of brecciated fragments ranges from a few cm to almost half a meter. The interstices between the brecciated fine to medium magnesite fragments are filled by coarse to very coarse white magnesite or calcite. The coarse white magnesite has very sharp contacts with the host rock. Along this contact, the host rock appears to be dark brown, in comparison to the centre of the host fragments, which are light brown to brownish grey. This may suggest iron enrichment by percolating fluids along the margins of the magnesite fragments prior to infilling of the veins and open spaces with white coarse magnesite. A later generation of open-space fill is seen at places. This involves angular fragments of black shale in a fine carbonate matrix infilling fractures in the previously brecciated magnesite. The black shale fragments in this instance are not locally derived and may represent fragments of the Whites Formation, which were dropped down vertical cavities or fractures and cemented by a carbonate matrix. The resulting cavity fill material has a sharp contact with the host rock. Other fragments include medium crystalline magnesite and probably quartz. This type of breccia could be interpreted as relatively recent karst fill.

Fluid inclusions in magnesite represent moderate to hypersaline CO₂-CH₄-bearing aqueous fluids trapped at temperatures in the range 100-400°C (average 153°C). Calculated pressure from the fluid inclusion data is about 1.5 kbars (hydrostatic). These magnesite deposits were previously interpreted as recrystallised sedimentary magnesite (Bone 1983), but could also represent hydrothermal replacement of dolomite by magnesium-rich brines (Ahmad et al in prep). The latter hypothesis results in a net volume decrease. This volume decrease may be the cause of in situ brecciation of the magnesite ore. In certain places the overlying strata collapsed, giving rise to a variety of breccia types. The space between the fragments was subsequently infilled by late coarse rhombic magnesite. 

Stop 1-5 Burrell Creek Formation  
*Location: Batchelor Hayes Creek Region 1:100 000 Special MGA 746439mE, 8517238mN*  
The Burrell Creek Formation (Finniss River Group) is a monotonous succession of greywacke, siltstone and shale deposited in high-energy, deeper marine environments towards the end of sedimentation. It conformably overlies the Mount Bonnie Formation (South Alligator Group) and comprises interbedded shale, siltstone, greywacke, volcanilithic conglomerate and rare felsic to intermediate volcanics. Olive green to brown shale, slate, phyllite and siltstone are typically laminated to thinly bedded and form about 50% of the formation. Within the contact metamorphic aureole of post-tectonic granites, cordierite and andalusite can be seen. Fine to coarse greywacke forms either thin interbeds within the shale and siltstone or massive graded beds up to 1 m thick. Commonly, the AE, BCE and CE divisions of the Bouma Sequence are present. Based on textures and sedimentary structures, this succession is interpreted as a submarine fan deposit, in which turbidity flow was the main mechanism of sediment transport. Conglomerate horizons contain sub-rounded to rounded quartz granules, pebbles and in places, cobbles of sublitharenite fragments in a sandy matrix. In the vicinity of Mount Hayward, the conglomerate also contains large angular clasts of phyllite and metagreywacke and smaller clasts (less than 5 mm) of spherulitic metaphyllite and metadacite. Fine-grained sediments in the Burrell Creek Formation commonly preserve a slaty cleavage that is axial planar to large-scale, tight to isoclinal, north- to northwest-trending regional D₃ folding.

The Burrell Creek Formation is extensively exposed from the eastern margin of the Litchfield Province to the South Alligator River Valley. The thickness of the formation is difficult to establish, but it has been suggested that it is at least 1000 m thick (Pietsch and Stuart-Smith 1987).
Stop 1-6 Gerowie Tuff - Howley Anticline

**Location:** Batchelor Hayes Creek Region 1:100 000 Special MGA 751200mE, 8512200mN

The Gerowie Tuff is the middle unit of the South Alligator Group and has conformable lower and upper contacts with the Koolpin Formation and Mount Bonnie Formation, respectively. At this stop, low-grade rocks of the Gerowie Tuff are well exposed in the road cutting and exhibit the dominant structural features characteristic of the central PCO.

Rocks exposed in the cutting consist mostly of laminated to thinly bedded black crystal and vitric tuff with a spotted weathered surface (Figure 9), minor pelitic interbeds and thin bands of pyritic chert (silicified dolomite?). At this locality, the tuffs commonly form graded beds up to 50 cm thick, with laminated and microlenticular cross-bedded tops.

Tuffs are also present in the overlying Mount Bonnie Formation, where they have yielded U-Pb zircon ages of about 1885 Ma (Page 1983), dating deposition of the South Alligator Group and the “sag” phase of sedimentation.

The central part of the orogen is dominated by one period of folding, characterised by regional northwest- to north-trending tight folds with subhorizontal axes and a well developed axial plane cleavage. These folds are openly folded about widely spaced northwest- or northeast-trending regional flexures and are locally modified by granitoid intrusion. At this stop, the hinge of one such regional fold, the Howley Anticline, is exposed in the southeastern end of the road cutting (Figure 10). The anticline plunges about 40° to the south and has a well-developed axial planar cleavage striking 175° and dipping 78° to the west. Joints, commonly well developed in the relatively brittle tuff beds, form a prominent set striking 072° and dipping about 75° to the north-northeast. In places, these joints are infilled by quartz.

The Howley Anticline is an economically important structure and hosts the nearby Cosmo Howley gold mine (production 15.6 t gold) and many other gold deposits in the region. Most of these are stratigraphically controlled within the Koolpin Formation of the South Alligator Group. In places, quartz saddle reefs are present, but they contain only low-grade mineralisation and most mineralisation is in late-stage quartz-filled steeply dipping faults and shear zones, concentrated in the hinge or adjacent limbs of the anticline.

**Figure 9.** Crystal and vitric tuff of the Gerowie Tuff.

**Figure 10.** Howley Anticline.

Stop 1-7 Union Reefs Gold Mine

**Location:** Pine Creek 1:100 000 MGA 801929mE, 8482161mN

Gold was discovered at Union Reefs in 1873. This goldfield was extensively mined between 1880 and 1910 and produced 1.76 t of gold from 0.58 Mt of ore. Minor activity has continued sporadically since that time, but no major production was recorded until 1994 when Shell Australia completed a feasibility study and plant construction. In the same year, Shell Australia transferred its mineral interest to Acacia Resources. Total resources in 1994 were 11.4 Mt @ 2.35g/t Au. Gold processing commenced in September 1994. Total reserves as at 31 December 2002 were estimated at 2.5 Mt @ 1.07g/t Au (Anglogold Annual Report 2002).

The lodes at Union Reefs lie within the Pine Creek Shear Zone and are hosted by greywacke, slate, and minor conglomerate of the Burrell Creek Formation. The strike of the beds is in the range 330-340°. Steep dips may change over a short distance from east to west. The rocks are strongly deformed into a series of tight to isoclinal folds, overturned to the northeast and in many places dislocated by bedding-parallel faults or shears. The isoclinal folds are parasitic on a large-scale antiform with an average plunge of 25° to the south. In places, the sediments are intruded by dolerite, pegmatite and amphibolite dykes (Shields et al 1967).

The lodes generally outcrop as en echelon, pinching and swelling northwest-plunging lenses, parallel to subvertical shears trending 010°, 330° and 355°. Most workings are confined to the oxidised zone, which extends to a depth of about 50 m (Turner 1990). The primary sulfide minerals consist of pyrite, arsenopyrite, galena, sphalerite, marcasite and pyrrhotite. Gold is present as rare small grains and as submicroscopic inclusions in sulfides. Coarse visible gold is mainly confined to selvages of larger quartz veins. Gangue minerals comprise quartz and minor carbonates. In places, relatively small rich shoots, with grades of up to 60 g/t Au and 25 g/t Ag over a true width of 2 m were intersected at 100 m depth (Shields et al 1967, Turner 1990).
Ahmad et al (1993) and Wygralak (1996) carried out fluid inclusion and stable isotope studies on the Union Reefs Mine and several other gold deposits of the PCO. Au-quartz veins were formed at P-T regimes of about 1 kbar and 300°C from low to moderate salinity (1-2 molal NaCl) CO₂, CH₄, H₂O-Na-Ca-Mg-Cl brines. Sulfur isotope data are consistent with a magmatic source for the sulfur. Oxygen and hydrogen isotope data indicate a mixed metamorphic and magmatic source. An interpretation of this data suggests the presence of both magmatic and metamorphic fluids during the formation of gold veins. Mixing of oxidised auriferous magmatic fluids with reduced CO₂- and CH₄-bearing contact metamorphic fluid is considered the most likely cause for gold precipitation.

Stop 2-1 Tollis Formation (Katherine Gorge Road)

Location: Geology of the Edith River Region 1:100 000 Special MGA 220500mE, 8408000mN

Two unconformity-bounded groups of volcanic rocks and associated sediments (El Sherana and Edith River Groups) separate older Pine Creek Orogen metasediments from Palaeo- to Mesoproterozoic platform cover of the McArthur Basin. The lower El Sherana Group developed during an extensional phase at about 1825 Ma, which was centred on the South Alligator River region, where rift valleys were filled with rhyolite flows, ignimbrite, and poorly sorted arenite and rudite, and flyschoid sediments spread onto adjacent lands (Needham and Stuart-Smith 1985).

The Tollis Formation is the most widespread unit of the El Sherana Group and consists of about 2200 m of interbedded greywacke, siltstone, slate, argillite, cherty tuff, crystal tuff, and minor altered mafic to intermediate volcanic rocks. The volcanic rocks include pitchstone, chloritised and carbonated mafic lavas and chloritised porphyritic andesite. The andesite contains phenocrysts of plagioclase, augite, and minor magnetite and apatite in a fluidal devitrified groundmass. The basal part of the formation is devoid of distinctive volcanic rock types, and consists of greywacke, siltstone and argillite. Rock types typical of the basal part are exposed in the first road cutting at this stop, whereas those more typical of the upper part of the formation are exposed in the second road cutting, 500 m further east. At the second road cutting, rare carbonate breccia is present, and dark green volcanic agglomerate and deeply weathered, greenish grey altered mafic flows and tuff are the only volcanic rocks present.

Stop 2-2 Katherine Gorge

Location: Geology of the Edith River Region 1:100 000 Special MGA 222000mE, 8416100mN

The spectacular Katherine Gorge is developed in the Mamadawerre Sandstone, the basal formation of the Kombolgie Subgroup of the Katherine River Group, where the Katherine River cuts the plateau along major joints and faults (Figure 11). The formation is the basal unit of the Palaeo- to Mesoproterozoic platform cover of the McArthur Basin, which forms the eastern margin of the Pine Creek Orogen.

The Kombolgie Subgroup comprises a sandstone succession punctuated by two layers of intermediate to basic volcanic rocks (Walpole et al 1968). It is about 900 m thick on the Arnhem Land Plateau but is much thicker (up to 2000 m) in locally developed basins in the Katherine-El Sherana area. The gorge is cut into 250 m of the Mamadawerre Sandstone; the lower volcanic horizon (McAddens Creek Volcanic Member) is about 150 m up-section and is preserved on the top of the plateau 2 km from the gorge.

The Mamadawerre Sandstone unconformably overlies the Edith River Group. It oversteps onto the El Sherana Group and older Palaeoproterozoic rocks with a high-angle unconformity. The unconformity is located at the entrance of the gorge, but in this area is covered by talus.

Sandstone forms 80% of the formation and is mainly medium to coarse, moderately rounded, moderate to well sorted, and clayey or feldspathic in the basins, but mature to slightly clayey in plateau successions. The formation also contains minor siltstone. Labile conglomerates are common at the base; these are up to 10 m thick in the plateau increasing to 25 m thick in places in the basins. The most common clasts are vein quartz and quartzite, although in the basins, volcanic clasts are also common and indicate a largely local provenance. The sandstone is extensively cross-bedded and ripple-marked and was deposited as braided alluvial fans from a northwesterly provenance (Ojakangas 1979) on a relatively stable, peneplained, mostly metamorphic basement.

The greater thickness of the Kombolgie Subgroup in locally developed basins is indicative of considerable subsidence during sedimentation, and this is probably related to the reactivation of older faults bounding these basins. Interbedded volcanic rocks were mainly fissure-fed flood basalts, spread over at least 10 000 km², which were in places extruded subaqueously (Needham 1978).

Except for a suite of Precambrian dolerite dykes intruded along and parallel to east-northeast-trending faults, there is no evidence of geological processes in the region for about 1500 million years after deposition of the Katherine River Group. The region may have been subjected to erosion for much of this time. By the Mesozoic, Proterozoic rocks were exhumed almost to their present extent, at which time extensive continental to shallow sea sediments were deposited; the present sandstone scarp of the area possibly formed as sea cliffs. Faulting continued to be periodically active from the Mesoproterozoic onwards and has resulted in local folding adjacent to larger faults.
Figure 11. Aerial view and simplified geological map of Katherine Gorge.
Stop 2-3 Edith Falls
Location: Geology of the Edith River Region 1:100 000 MGA 197000mE, 8430500mN

Edith Falls is located at the contact of the Kombolgie Subgroup and the unconformably underlying Plum Tree Creek Volcanics of the Edith River Group (Figure 12). The contact is exposed at the top of a scree slope on the north side of a fault. Boulder conglomerate containing clasts derived from the underlying volcanics forms the base of the Kombolgie Subgroup.

Stop 2-4 Allamber Springs Granite
Location: Pine Creek 1:100 000 MGA 823500mE, 8485800mN

Syn- to post-orogenic granitoids (1800-1835 Ma) intrude Palaeoproterozoic metasediments and felsic volcanic suites of the El Sherana and Edith River Groups. The Cullen Batholith is the largest granitoid body in the Pine Creek Orogen and is surrounded by an extensive hornfels aureole up to 10 km wide. The batholith is overlain by Mesoproterozoic to Cambrian sediments in the west and by scattered residual cappings of Mesozoic sediments elsewhere.

At this stop, which is along the side of the Kakadu Highway, we look at some freshly broken samples of the Allamber Springs Granite. This is the largest pluton of the Cullen Batholith, which was emplaced about 1825 Ma. Most granite phases within this pluton are considered to be I-type.

The Allamber Springs Granite is mainly massive, largely homogenous and even-grained, although porphyritic marginal variants occur at several localities. On the basis of colour, grain size and mineral assemblage, Stuart-Smith (1985) described three main varieties: (a) pink and green coarse porphyritic hornblende-biotite granite; (b) pink coarse porphyritic biotite leucogranite; and (c) pink coarse equigranular biotite leucogranite. The texture is generally medium-grained equigranular. Mafic inclusions are generally rare but in some cases, country rock xenoliths have been observed.

The marginal fine-grained porphyritic variety is characterised by the presence of quartz or orthoclase phenocrysts or both, set in a quartzofeldspathic matrix. Quartz occurs as phenocrysts 1-3 mm in diameter and also as fine-grained aggregates in the matrix. Grain size increases steadily towards the interior of the intrusion where the minerals may be fractured or partly strained. Tabular plagioclase crystals (2.5 x 1.4 mm) occur as phenocrysts or fine laths in the matrix and are commonly sericitised. In fine-grained porphyritic varieties, orthoclase forms phenocrysts, which may have plagioclase inclusions; exsolution of albite lamellae, characterised by optical continuity, may also be observed. Orthoclase crystals show partly developed spindle-shaped twins, indicative of metastability of sanidine at high temperature and later inversion to microcline. Anorthite contents of plagioclase are variable in the range An$_{34}$-An$_{52}$. Medium- to coarse-grained equigranular varieties form the greater part of the Allamber Springs pluton and in these rocks, orthoclase concentrations may be as high as 40%. Microcline grains (3 mm across), characterised by well-terminated crystal shapes, constitute up to 20% of the rock.

Biotite is an ubiquitous mineral phase and may constitute up to 10% of the rock. It is strongly pleochroic (α = light brown, β = γ = chocolate brown or rarely green) and has inclusions of zircon and apatite. Chloritisation and sericitisation of biotite may be observed. Hornblende is generally confined to medium- to coarse-grained rocks, in which it forms subhedral to anhedral grains or poikilitic aggregates in the matrix and constitutes up to 10% of the rock. In some rocks, hornblende appears to replace biotite either completely or in part. Accessories are allanite, sphene, magnetite, zircon, apatite and fluorite.

Figure 12. Geological map of Edith Falls area.
Stop 2-5 Folding in the Mount Bonnie Formation

Location: Ranford Hill 1:100 000 MGA 191930mE, 8488577mN

This road cutting is close to the axis of a major, southeast-plunging overturned anticline within the Mount Bonnie Formation. At this outcrop, the Mount Bonnie Formation is thinly bedded and provides an excellent example of the nature of the folding and faulting that characterises the Pine Creek Orogen. The regional strike is northwest and the strata dips to the southwest.

Stop 2-6 Nourlangie Rock

Location: Cahill 1:100 000 MGA 261500mE, 8577500mN

More than 300 Aboriginal rock art sites are known in the Alligator Rivers Region. The art sites of Kakadu National Park are one of the greatest collections of ancient art. They are recognised as a major international cultural resource and are part of the reason that the Kakadu National Park is inscribed on the United Nations list of World Heritage properties. The Nourlangie Rock paintings are some of the best examples of Aboriginal art in Arnhem Land and among the best in Australia. In common with rock painting sites elsewhere in the region, their position is related to occupation shelters close to prolific food resources. Rock painting was a wet season occupation in shelters near to rivers, lagoons, billabongs and alluvial flats.

The name ‘Nourlangie’ is an anglicised version of Nawurlandja, the name of a larger area that includes an outlier to the west of Nourlangie. The upper part of Nourlangie Rock is known as Burrunggui; the lower areas are known as Anbangbang. According to aboriginal legend, the area was formed when two Creation Ancestors in the form of short-eared rock wallabies travelled through from east to west. They moved past Nourlangie Rock, across Anbangbang Billabong, and up into the rocks at Nawurlandja, where they cut two crevices in the rock as they passed. These crevices are visible today and rock wallabies are often seen there in the early morning and at dusk.

There are three main sites at Burrunggui: a rock shelter (Anbangbang shelter); several rock art sites, including the Lightning Man rock art site (Anbangbang gallery); and Gun-warddehwardde lookout. These sites can be reached by following a 1.5-kilometre circular walking track from the car park. The walk takes about an hour.

An archaeological dig at Anbangbang rock shelter in the early 1980s revealed that Aboriginal people have been using the shelter for at least 20 000 years. Excavated layers of soil contained a variety of stone artefacts and implements that had been discarded over time. By examining the number of artefacts in each layer, researchers concluded that the shelter was used occasionally from about 20 000 to 6000 years ago. It appears to have been used more frequently after this, probably as the area became estuarine and more food was available.

Nourlangie Rock is at the southwestern end of a larger outlier of Mamadawerre Sandstone called Mount Brockman. At this locality, the Mamadawerre Sandstone lies unconformably on deformed and metamorphosed pelites and carbonates of the Cahill Formation. The southeastern edge of Mount Brockman is part of the large-scale reverse fault system that controls uranium mineralisation at Koongarra.

Stop 3-1 Wetlands and waterways

Location: Cahill 1:100 000 MGA 231000mE, 8572000mN

The South Alligator River and its tributaries are the arteries of the floodplains as they meander to the sea. The rivers are a saltwater environment for up to 80 km distance from the sea, and in the wet season shallow freshwater spreads over the floodplains for hundred of square kilometres, triggering an explosion of aquatic plant and animal life. These are some of the most important tropical wetlands in the world, and are a refuge for migratory birds and other waterbirds such as magpie geese, brolgas and jabirus that were once widespread in Australia. Paperbark trees fringe the wetlands, billabongs and creeks. In the dry season, they are a good indication of the extent of wet season flooding.

As the floodplains dry out in the dry season, permanent billabongs (permanently or periodically filled stream channels), creeks and rivers reappear. Waterbirds become much easier to observe as they crowd the few remaining wet areas and as they wing from one waterhole to another in search of food. Chains of billabongs and sandy creek beds edged with pandanus and tall paperbark trees form a network of waterways through the woodlands between the escarpment and floodplains.

Stop 3-2 Ranger 1 Uranium Deposits

Location: Cahill 1:100 000 AMG 2-73-200E, 85-96-000N

The Ranger 1 uranium deposits are located 10 km east-southeast of Jabiru (Figure 13). They were discovered in 1969 by an airborne radiometric survey that defined 6 anomalies within a corridor 6 km long by 2 km wide (Eupene et al 1975). Drilling of the highest intensity anomalies resulted in the identification of two separate orebodies called No.1 and No.3. Mining of No.1 orebody began in 1981, ceased in 1995, and produced 60 960 tonnes of U3O8 from 18.036 Mt of ore. The Ranger No.1 pit is currently used for tailings disposal. The currently working No.3 orebody is located 1.5 km north of No.1 and contains resources of 39.11 Mt of ore grading at 0.32% U3O8.

The Ranger 1 deposits occur in the lower member of the Cahill Formation. Host rocks are comprised of quartz-mica schist, para-amphibolite, calc-silicate schist and carbonates. These rocks dip 15-40° towards the east, and have a strong schistosity sub-parallel to bedding. Lithologies within the mine lease area were informally subdivided into the footwall (FWS), lower-mine
(LMS), upper-mine (UMS) and hanging-wall sequences (HWS) by Geopeko geologists (Eupene et al 1975) during the exploration phase and this terminology is still in use at the mine. Quartz-feldspar-tourmaline pegmatite intruded mine sequence rocks after formation of the schistosity, but before mineralisation, and this has been dated at 1847 ± 1 Ma (Annesley et al 2002).

An important feature is the presence of thrust faults at a low angle to bedding and schistosity, which produced zones of strain slip cleavage and chevron folding that postdate the main schistosity. These structures have acted as conduits during mineralisation (Savory 1994).

No.1 orebody

The No.1 orebody within the LMS is confined to massive chlorite schist and lenticle schist, the latter being characterised by aligned lenticular nodules of chlorite. In this lower mine unit, chert and chert breccia are also present and both may contain some mineralisation. The UMS is about 500 m thick and has been altered to quartz-chlorite rock in the mineralised zone. Graphitic schist within the central disturbed zone hosts high-grade uranium mineralisation (>1% U₃O₈). A U-Pb isochron on pitchblende gives an age of 1737 ± 20 Ma for the Ranger uranium mineralisation (Ludwig et al 1987). This is considerably older than those obtained from other uranium deposits (Jabiluka, Nabarlek and Koongarra), which are in the range 1614-1650 Ma (Maas 1989).

Within the No.1 orebody, ore-grade mineralisation is confined to a discrete synformal structure, formed as a result of the thinning of carbonates associated with thrusting of mine sequence over footwall sequence. In the synformal structure, there are two styles of mineralisation (Kendall 1990). The first type occurs as veins averaging 1% U₃O₈ and is recognisable by intense brecciation and chloritisation within the upper mine sequence. The second type is patchy in the lower and upper mine sequences and averages 0.15% U₃O₈. Uraninite and pitchblende are the major ore minerals of both styles, but coffinite and brannerite are also present as minor phases (Kendall 1990, Savory 1994). Minor gold is present. Uranium mineralisation is accompanied by pervasive chloritisation, with sericitisation and hematitisation.

No.3 orebody

The No.3 orebody lies 1500 m to the north along strike from the No.1 orebody. The UMS is a monotonous succession of thinly laminated quartz-chlorite schist containing a few thin (<1 m thick) chert bands. LMS rock types include banded chert, chloritic
carbonate schist and magnesian marble. UMS and LMS sequence rocks have been intruded by pegmatite bodies that are either steeply dipping, northeast striking dykes 1-3 m wide, or variably deformed and altered pods up to 250 m wide.

A cross-section through the No.3 orebody (Figure 14), based on drilling and pit mapping, shows the broad ‘ramp-and-flat’ geometry of the LMS-UMS contact, which is steeper on the western and eastern sides and subhorizontal beneath the main orebody. The FWS-LMS contact also steepens to the west, but the ‘flat’ beneath the orebody is less pronounced than the LMS-UMS contact. In the western wall of the pit, a faulted outlier of hematite and chlorite-altered and brecciated sandstone of the lower Kombolgie Subgroup occurs between the LMS and UMS. The eastern side of this outlier is a reverse fault with UMS in the hangingwall and can be traced into the UMS-LMS contact down-dip. Local steep dips of beds within the sandstone (80°-90°) indicate folding associated with the reverse faulting (Lally and Bajwah in prep).

Reverse faulting, kink folding and mineralisation postdates development of the pervasive schistosity, intrusion of quartz-feldspar pegmatites, development of the Ranger Syncline, steeply dipping normal faults and deposition of lower Kombolgie Subgroup sandstone. The LMS-UMS contact is considered to be the principal fault surface in a west-directed thrust system. Dilation and brecciation is most intense along the low-angle ‘flat’ in the geometry of the fault plane. Changes in the geometry of the LMS-UMS contact, due to pre-mineralisation folding and faulting, controlled the fracturing of the UMS and therefore focused mineralising fluids to form the orebody (Lally and Bajwah in prep).

**Figure 14.** Cross-sections through the Ranger 1 No.1 and No.3 orebodies. Outline of mineralisation on No.3 orebody cross-section refers to higher grade zones; disseminated low-grade mineralisation occurs throughout UMS schist in pit area.
Stop 3-3 Mount Bundey Granite
Location: Mary River 1:100 000 MGA 780800mE, 8575800mN

At this stop we look at a granite/syenite quarry supplying crush rock aggregate and dimension stone for local, interstate and overseas markets. Tiles made from this granite are used extensively in the Northern Territory Parliament House and other buildings, including the NT Department of Mines and Energy.

The Mount Bundey Granite and Mount Goyder Syenite form a co-genetic plutonic complex that outcrops over an area of about 80 km² between Old Mount Bundey and Annaburroo homesteads. The Mount Bundey Granite forms the southern two-thirds of the complex, and outcrops as rugged bouldery hills rising over 140 m above the adjacent Mary River Flood plain. The Mount Goyder Syenite forms the northern third of the Mount Bundey pluton, and a separate small pluton east of the Mary River at Mount Goyder, 7 km north of Annaburroo homestead. The syenite also outcrops in places as rugged bouldery hills, but is mainly covered by thin sandy residual soils.

The granite and syenite have been described by Dow and Pritchard (1958) and Stuart-Smith et al (1984). The conventional U-Pb zircon age of this granite is 1831 ± 6 Ma.

The granite and syenite intrude a south-plunging folded belt of metasediments of the Mount Partridge and South Alligator Groups, which are hornfelsed in an aureole about 500 m wide. The contact is sharp and mostly discordant. On the eastern side of the Mount Bundey pluton, the contact is concordant and follows a shallow easterly dipping anticlinal limb; a drillhole at the Quest 44 Prospect showed that the contact dips outwards at about 40°. The Mount Bundey Granite intrudes the Mount Goyder Syenite.

Aplites, syenites, and minette dykes up to 3 m wide are common in the granite, syenite, and surrounding metasediments up to 10 km from the Mount Bundey pluton. Xenoliths of country rock are also common near the contact. Pritchards Lode (the Mount Bundey iron deposit), a hematite-martite body within the Mount Goyder Syenite, is thought to have formed in part by replacement of an iron-rich sedimentary raft or pendant.

Both the granite and syenite are well jointed in three predominant directions: 340-350°, 50-60° and 80-90°. The northeast- and east-trending joints correspond to some post deformational fault orientations in the Palaeoproterozoic metasediments. In places the joints are sheared and contain pyrite encrustations.

The Mount Bundey Granite comprises massive reddish-brown to pale pink granite and minor quartz monzonite. It is composed of potash feldspar, quartz, plagioclase, hornblende, biotite, and trace amounts of sphene, apatite, zircon, allanite, epidote, magnetite, hematite, leucoxene and pyrite.

The potash feldspar is microperthite and typically forms coarse (<2 cm) subhedral crystals, commonly rimmed by graphic intergrowths. Quartz; zoning is present in places and rounded inclusions of plagioclase, quartz, biotite, and hornblende are common. Quartz occurs as anhedral grains, and comprises 20-50% of the rock; inclusions of feldspar and accessory minerals are common. Plagioclase ranges in composition from An₃₅-₃₆ and forms zoned tabular crystals, commonly with cores altered to kaolin, sericite, carbonate, and epidote; the outer zones are more sodic and the borders of some crystals are probably pure albite.

Hornblende and biotite are present in minor amounts and decrease as quartz increases. In rocks containing over 40% quartz, hornblende is absent, biotite shows progressive alteration to chlorite and quartz-feldspar graphic intergrowths are common. Hornblende, where present, is green to pale brown, and forms euhedral prisms, granular aggregates and irregular grains moulding feldspar crystals; it is commonly corroded and partly altered to biotite. Rust-red biotite occurs as irregular grains or decussate aggregates showing partial alteration to chlorite. In places, euhedral hornblende, apatite, and anhedral quartz form the cores of biotite clots, which are surrounded by opaque rims.

The Mount Goyder Syenite is a medium to coarse, slightly porphyritic massive rock, compositionally similar to, but distinguished from the Mount Bundey Granite by its lower quartz content (<10%), higher hornblende content (>10%), and commonly the presence of clinoxyroxene.

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REFERENCES


