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Regional Geology and Metallogeny of the Eastern Arunta

2004 Chief Government Geologists Committee Field Excursion Guide

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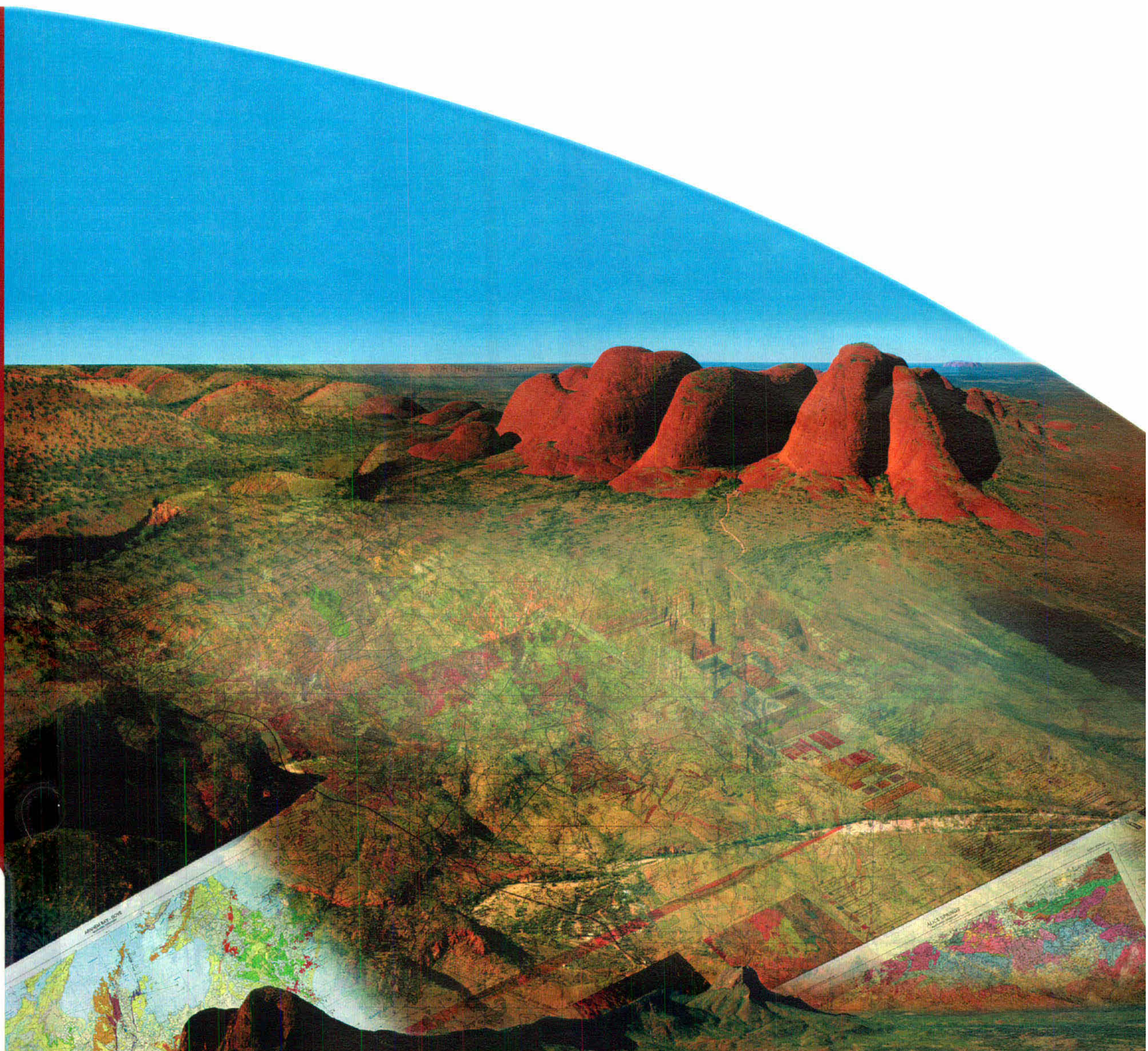

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REGIONAL GEOLOGY AND METALLOGENY OF THE EASTERN ARUNTA: 2004 CHIEF GOVERNMENT GEOLOGISTS COMMITTEE FIELD GUIDE

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1. INTRODUCTION

The last five to seven years have seen a major revision in our understanding of the geology of central Australia, with advancements in the field of geochronology redefining the geological framework and history of this area. Prior to about 1995, the eastern Arunta Region was thought to consist of moderate to high grade metamorphic Palaeoproterozoic rocks (the Arunta province) with a complex geological history. This basement was interpreted to be overlain by low grade, mainly sedimentary rocks of the Georgina and Amadeus Basins, which are part of the extensive Neoproterozoic to late Palaeozoic Centralian Superbasin (Walter et al., 1995). However, workers at Adelaide, La Trobe and Monash Universities found that rocks of the Harts Range Group (now mapped as the Irindina Supracrustal Assemblage [ISA]), have a Neoproterozoic to early Palaeozoic age and were intensely metamorphosed and deformed during the Ordovician (e.g. Miller et al 1998, Mawby et al., 1999). Since then, work by the Northern Territory Geological Survey (NTGS) and Geoscience Australia (GA) indicates that the Palaeoproterozoic part of the Arunta region can itself be divided into two discrete provinces: (1) the older (1840-1760 Ma) Aileron Province, and (2) the younger (1680-1610 Ma) Warumpi Province. Further work by the two geological surveys and the Australian National University suggests that in the eastern Arunta Region, the Aileron Province can be divided into two sequences, the older (1820-1800 Ma) Strangways Metamorphic Complex (SMC) and the younger (~1760 Ma) Oonagalabi Assemblage. Definition of these sequences became possible only because of the availability of a critical mass of geochronological data.

One of the purposes of this field trip is to illustrate the characteristics of the Palaeoproterozoic basement and the overlying Neoproterozoic to Palaeozoic rocks, with emphasis on the role of modern geochronology in resolving the newly defined terrains. The rocks of the eastern Arunta Region have also undergone multiple deformation and metamorphic events that are now being unravelled. This complex history will also be illustrated during the excursion. The second aspect that will be illustrated in this field trip is the metallogeny of the eastern Arunta Region. The eastern Arunta Region is characterised by a large variety of mineral deposits, including lode gold, volcanic-hosted massive sulphide (VHMS), carbonate replacement Zn-Cu, iron-oxide Cu-Au (IOCG), skarn W-(Mo-Cu-Au), carbonatite and aeolian/alluvial garnet deposits. However, most of the known deposits are small, with only the Molyhil W(-Mo-Cu-Au?) deposit, the Mud Tank vermiculite and the White Range Au deposits mined in recent times. Potentially the most economically important deposits are the garnet deposits.

2. GEOLOGY AND EVOLUTION OF THE EASTERN ARUNTA

The Arunta Region is one of the most geologically complex areas in Australia. A compilation by Scrimgeour (2003) identified nine metasedimentary packages and twelve discrete overprinting thermo-tectonic events in the Warumpi and Aileron provinces indicating this is an important geological building block of central Australia. Four of Scrimgeour's (2003) sedimentary packages are known to be present in the area covered by this excursion, and a fifth one is probably present. Although Scrimgeour's (2003) 1865-1820 Ma Lander package has not been definitively identified in the eastern Arunta Region, a correlative package might be present as ~1812 Ma mafic igneous bodies (Hoatson et al., 2002) intrude parts of the SMC and the Rankins Cu-Zn prospect has a Pb isotope model age of ~1822 Ma. In the western and northern Aileron Province, the Lander Package consists mainly of turbiditic pelites and psammites (Scrimgeour, 2003).

The Ongeva package, which includes the lower part of the SMC (excluding the Cadney Metamorphics) and the Bonya Schist, Deep Bore Metamorphics, Cacklebery Metamorphics, the Kanandra Granulite and the Bleechmore Granulite further to the east, is the main supracrustal package in the eastern Arunta Region. Geochronological data from the SMC, Bonya Schist and Deep Bore Metamorphics indicate ages between 1810 and 1800 Ma (Scrimgeour, 2003; J.Claoué-Long, pers. comm., 2003) for the Ongeva package. Lithologically, the Ongeva package consists of pelitic and psammitic rocks with subordinate calc-silicate, marble and felsic and mafic orthogneiss (Scrimgeour, 2003). Intercalated, turbiditic sandstone and mudstone, previously mapped as Lander Rock beds, occur in the Reynolds Range region and have a maximum age of 1805 ± 5 Ma (Claoué-Long, 2003). These turbiditic units are thought to be chronological equivalents of the Ongeva package, however, unlike the volcaniclastic units that have been dated so far in the Ongeva package, this low grade turbiditic unit has a protracted detrital provenance pattern with a typical Northern Australian Craton signature. These so-called "not-the-Lander Rock beds" appear to post-date the Stafford Event. It is suggested that the Ongeva package is a separate rift-fill basin, distinct from, though possibly overlapping in space to the Lander package basin.

Scrimgeour (2003) interpreted his Cadney package, which includes marbles and calc-silicates of the Cadney Metamorphics, to have an age of 1780-1760 Ma. However, age data from this unit is lacking, and it may be part of the SMC, having an age of ~1800 Ma.

Scrimgeour (2003) defined the 1760-1740 Ma Ledan package to include pelitic and psammitic metasediments that uncomformably overlie the SMC. Recent geochronological data suggest that the Oonagalabi assemblage, which hosts the Oonagalabi deposit, has a similar (maximum depositional) age (1768 ± 4 Ma: J. Claoué-Long, pers. comm., 2004). This sample was characterised by a single population of zircons, suggesting that the Oonagalabi assemblage contains a significant volcaniclastic component.

Of the twelve thermo-tectonic events affecting the Arunta region, four (Strangways [1730-1700 Ma: mainly in the Strangways Ranges, but low-grade effects extend throughout most of the Arunta to the Tanami and Davenport regions], Liebig [1640-1630 Ma: Warumpi Province and southern Aileron Province], Chewings [1590-1560 Ma: central-southern Aileron Province and Warumpi Province], and Larapinta [500-460 Ma: mainly in the ISA; very weak effects on adjacent Palaeoproterozoic rocks]) have involved high-grade (upper amphibolite to granulite) metamorphism (Scrimgeour, 2003). Most of the high grade events have been dated using metamorphic zircon overgrowths on zircons that define depositional ages, or by dating of zircons within leucosomes formed during metamorphism. Of the high grade events, the Strangways (SMC) and Larapinta (ISA) events have affected the areas visited during this field trip. Localised low to high grade metamorphism, deformation and retrogression are associated with the 450-300 Ma Alice Springs Orogeny. The lower metamorphic grade events are generally recognised through ^{39}Ar-^{40}Ar geochronology, SHRIMP U-Pb dating of monazite or by Sm-Nd dating of mineral separates

Three major and three minor igneous events have affected the eastern Arunta Region. The oldest, the ~1810-1800 Ma Stafford Event, involved the intrusion of mafic and felsic bodies and the emplacement of extensive felsic volcaniclastic units in the Ongeva package, including the SMC. Geochemistry of rocks within the Bonya Schist also indicates these rocks have a significant mafic source component. The SMC has been extensively intruded by ~1780-1770 Ma granitoids of the Yambah Event, and rocks of the Ledan package have been intruded by 1760-1740 Ma granitoids of the Inkamulla Igneous Event in the southeast. Small(?) subcircular 1730-1700 Ma granite bodies are recognised in central and northern parts of the Aileron province. The Mordor Igneous Complex is the main manifestation of the 1150-1130 Ma Teapot Event in the eastern Arunta Region (Scrimgeour, 2003). The Mud Tank carbonatite and related rocks intruded at ~732 Ma (Black and Gulson, 1978).

3. MINERALISATION

Mineral deposits in the Arunta Region vary in both style and age. This excursion visits a variety of mineral deposits with ages ranging from about ~1800 Ma to those formed in the Cainozoic. Although base metal and gold deposits in the Arunta are relatively widespread and geologically interesting, to date these deposits have been economically insignificant. The economically most important deposits are industrial minerals: vermiculite associated with the deeply weathered rocks in the Mud Tank carbonatite complex, and garnet-amphibole-rich sands concentrated by aeolian and alluvial processes to the north of the Harts Ranges. With the exception of Oonagalabi-type Zn-Cu-Pb-Ag deposits, this excursion visits examples of all geologically or economically significant mineral deposits in the eastern Arunta Region.

The oldest deposits in the eastern Arunta are base metal and gold deposits hosted by the SMC, Bonya Schist and Cadney Metamorphics. These deposits were grouped together by Warren and Shaw (1985) into their Oonagalabi-type and interpreted as VHMS deposits. Our recent work, however, suggests that there are systematic differences within Warren and Shaw's (1985) Oonagalabi-type. Although most of these deposits are associated with marble lenses, our data suggest that there are important differences in the age of the host rock, the abundance of magnetite, metal assemblages and the composition of the dominant alteration assemblage. Hence, we have divided the Oonagalabi-type of Warren and Shaw (1985) into three sub-types: (1) the Utnalanama-type, which we interpret as VHMS deposits, (2) the Johnnies-type, which we interpret as IOCG deposits, and (3) the Oonagalabi-type, which we interpret as either carbonate-replacement or VHMS deposits. Table 1 summarises the characteristics that distinguish these three groups.

Utnalanama-type deposits, which constitute the majority of known Palaeoproterozoic deposits in the SMC, are Zn-Pb-Cu(Ag-Au) deposits characterised by the extensive development of asymmetric alteration zones dominated by quartz-cordierite ± orthopyroxene ± biotite ± orthoamphibole ± garnet gneiss. Feldspar is typically absent in these rock types. Most of the quartz-cordierite rocks lack magnetite and have a very low magnetic susceptibility. Although magnetite is present in these deposits, it is not a major component of the ores or alteration assemblage. However, localised magnetite rich zones do occur. Geochemical analyses suggest that the quartz-cordierite rocks had a quartz-chlorite ± muscovite/illite protolith, which we interpret to be the alteration assemblage associated with mineralisation. Other minerals thought to be commonly present in the altered protoliths at these deposits include talc, tremolite and carbonate. These rocks are Mg-rich with (Mg/Mg+Fe) values typically between 60 and 100. The altered rocks have $\delta^{18}O_{whole\ rock}$ between 1.8 and 7.0‰ (most values between 2.5 and 4.8‰), consistent with formation through interaction with high temperature, evolved seawater. These deposits have 100Zn/(Zn+Pb) values mainly between 60 and 75. The presence of asymmetric proto-quartz-chlorite alteration zones formed via interaction with heated seawater and the 100Zn/(Zn+Pb) values are characteristic of VHMS deposits.

Johnnies-type deposits, which include Johnnies Reward and Gumtree in the SMC and the base metal-Au deposits of the Jervois district in the Bonya Schist further to the east, are Cu-Au(Pb-Zn-Ag) deposits characterised by a close association with abundant magnetite, and an asymmetric quartz-biotite-garnet ± feldspar alteration assemblage. These deposits are closely associated with magnetite, either in a magnetite-diopside ± amphibole skarn assemblage (e.g. Johnnies Reward) or in an iron formation (amphibole-quartz-magnetite rocks, e.g. Gumtree). The host rocks are considerably more Fe rich than the Utnalanama-type deposits, with (Mg/Mg+Fe) values usually between 30 and 60. Although base metals are most concentrated in magnetite-rich zones, Au is concentrated in the structural footwall of these deposits. Johnnies-type deposits are characterised by highly variable 100Zn/(Zn+Pb), with Pb concentrations generally greater than Zn abundances. Gold values are typically one or two orders of magnitude higher in the Johnnies-type than the Utnalanama-type. Moreover, at Johnnies Reward, Mn and some high field strength (HFSE) and rare earth elements (REE) are highly enriched in places within the lode. Based on these characteristics, Johnnies-type deposits are more likely to be IOCG deposits rather than VHMS deposits.

Oonagalabi-type deposits, which are represented by the Oonagalabi deposit and two nearby prospects, are hosted by the ~1765 Ma Oonagalabi assemblage of the Ledan package. Like the Utnalanama-type deposits, Oonagalabi-type deposits are not associated with abundant magnetite, are characterised by a Zn-Cu-Pb(Ag-Au) metal assemblage and have high 100Zn/(Zn+Pb) ratios (87 at Oonagalabi). However, unlike the Utnalanama-type deposits, the main alteration assemblage outside of the host marble is a quartz-garnet-feldspar rock: quartz-cordierite gneiss is rare. Moreover, garnetiferous zones are symmetrically developed about the ore host. Carbonate in the ore host is progressive replaced by calc-silicate and then massive anthophyllite rock. All three rock types are mineralised. These characteristics are most consistent with a carbonate replacement origin, although a VHMS origin cannot be ruled out. If Oonagalabi-type deposits are carbonate replacement deposits, the 1760-1740 Ma Inkamulla igneous suite may have been involved in their formation.

The 1132 ± 5 Ma (Hoatson et al., 2002) Mordor Igneous Complex hosts orthomagmatic PGE-Au-Cu-Ni deposits associated with ultramafic rocks in this potassic alkaline igneous suite. This is the only known deposit of this type in the Arunta region. The Mud Tank carbonatite, which has been dated at 732 ± 5 Ma, hosts gem quality zircon. However, vermiculite deposits, which formed from the weathering of biotite, are economically the most important deposits in the eastern Arunta, with 69,693 tonnes of vermiculite products sold between 1995 and December 2003, with an estimated value of A$18-25M depending on the actual percentage of each size fraction. Another 30,000 tonnes or more of refined vermiculite product can be extracted from the current stock pile and open cut. In addition, two more open cuts of comparable size planned within the current mine lease.

The garnet-rich para-amphibolites of the ISA are the source of the other major industrial mineral deposit in the eastern Arunta Region. Rivers draining the Harts Range and wind have concentrated garnet and hornblende into potentially economic deposits along the northern margin of the ranges. Although the dunes were last stabilised about 20,000 years ago, alluvial processes are currently concentrating garnet and hornblende in sands of the various creeks draining the ranges.

Table 1. Characteristics of Palaeoproterozoic base metal deposits in the eastern Arunta.

Type	Metal assemblage	Other elements	Host	Alteration assemblages	Interpreted age (Ma)
Utnalanama	Mineralised marble: Zn-Pb-Cu(Ag-Au) Calc-silicate: Pb-Zn	Mineralised marble: Bi-Cd Calc-silicate: Sn, HFSEs, REEs	Marble and calc-silicate after marble.	Quartz-cordierite± orthopyroxene rock > massive amphibole±spinel± clinopyroxene rock. Both are concentrated in the footwall to mineralised marble lens.	1810-1800 (age of host); calc-silicate may be younger
Johnnie's	Lode rock: Cu-Pb(Zn-Ag-Au) Footwall garnetiferous zone: Au(Cu)	Lode rock: Mn-Ca-HFSE-REE Footwall garnetiferous zone: Bi±Mo	Lode rock: magnetite-diopside-amphibole± quartz rock (after marble). Footwall garnetiferous zone: Quartz-biotite-garnet±magnetite gneiss.	Quartz-biotite-garnet gneiss in structural footwall to lode rock.	1795-1770 (Pb isotope model age)
Oonagalabi	Zn-Cu-Pb(Ag-Au)	Bi	Marble → calc-silicate → massive anthophyllite schist.	Quartz-garnet rock symmetrically developed about host marble lens.	1760 (?) (age of host)

4. EXCURSION STOPS

Over the three day period of this excursion, a total of 19 excursion stops are planned. Most should take between 30 minutes and one hour, although the stop at the Edwards Creek prospect will take 3-4 hours. Although most stops are designed to minimise the amount of walking, walks of 2 km at the Johnnie's Reward (Stops 2.1 and 2.2) and 1 km at the Edwards Creek prospect (Stop 3.3) are required. Consequently, good quality boots, a hat and drinks are required. To minimise the impact on the rocks we ask that hammers be used sparingly, particularly as some exposures visited may have significance to traditional land-owners. We are visiting the stops on this excursion with permission from leaseholders and, in some cases, Northern Territory Parks and Wildlife.

4A. STOP 1.1. JOINT GEOLOGICAL AND GEOPHYSICAL RESEARCH STATION (JGGRS)

This facility, which is jointly operated by Geoscience Australia and the United States Atomic Energy Detection Service, operates a 20 instrument seismic array designed to detect seismic events associated with the testing of nuclear devices.

4B. STOP 1.2. PALAEOPROTERZOIC-NEOPROTEROZOIC UNCONFORMITY AT HEAVITEE GAP

The Heavitree Gap is the type-section for the Neoproterozoic Heavitree Quartzite. At this location, the unconformity between the Palaeoproterozoic Sadadeen Gneiss, which forms part of the Hayes Metamorphic Complex, and the Neoproterozoic Heavitree Quartzite, which is the basal unit of the Amadeus Basin, is exposed. The unconformity is marked by the contact between coarsely feldspar-phyric, foliated biotite granite (Sadadeen Gneiss) and a 16 m thick, buff to red mudstone/siltstone with minor fine-grained sandstone lenses up to 1 m across and 0.3 m thick in the upper part. These sandstone lenses are inferred to be sand-filled channels (Clarke 1974). This mudstone unit, the Undoolya Siltstone Member of the Heavitree Quartzite, is only locally developed at the unconformity (Clarke 1974). Elsewhere the unconformity is marked by conglomeratic and locally arkosic units of the upward fining Temple Bar Sandstone Member. Clarke (1974) divided the fluvial to shallow marine Heavitree Quartzite into the Undoolya Siltstone, Temple Bar Sandstone, Fenn Gap Conglomerate and Blatherskite Members and suggested an east or northeast provenance.

The basement Sadadeen Gneiss, although undated, is intruded by or has gradational contacts with the Alice Springs Granite, which has been dated at 1752 ± 11 Ma (Zhao and Bennett, 1995). This suggests that the Sadadeen Gneiss and the Alice Springs Granite were both intruded during the Inkamulla Igneous Event. These two units make up many of the hills within the town of Alice Springs. The fabric in the Sadadeen Gneiss, which is defined by biotite, is parallel to bedding within the Heavitree Quartzite, suggesting that it was flat lying as sedimentation in the Amadeus Basin initiated.

The age of the Heavitree Quartzite is poorly constrained. Correlations with other units of the Centralian Superbasin suggest that the Heavitree Quartzite was deposited about ~840 Ma (e.g. Walter et al., 1995). The Heavitree Quartzite unconformably overlies 1080 Ma Stuart Pass Dolerite (Zhao and McCulloch, 1993), and is conformably overlain by the Bitter Springs Formation which contains Late Riphean (950-680? Ma) aged fossils (Walter, 1972; Shergold et al., 1991). Recent detrital zircon studies indicate a maximum depositional age of ~1050 Ma (D. Maidment, pers. comm.., 2004) and suggests this unit may be significantly older than 840 Ma.

4C. STOP 1.3. ARUMBERA SANDSTONE

The Ross River has cut an excellent section that exposes many of the units that make up the Ooraminna Sub-basin in the northeastern part of the Amadeus Basin (Fig. 2). At this and the next stop we examine units that are the approximate temporal equivalents of high grade metamorphic rocks of the Riddock Amphibolite that we will see at stop 2.4. At this stop, we examine the Arumbera Sandstone, a cyclical red-brown mudstone and sandstone unit consisting of four upward coarsening members spanning the Neoproterozoic-Cambrian boundary. The lower two members of the

Arumbera Sandstone contain a variety of non-skeletal metazoan fossils that have been deposited in the Neoproterozoic, contemporaneous with the Ediacara fauna in the Adelaide Geosyncline (Walter et al., 1989). The upper two members of the Arumbera Sandstone contain a wealth of trace fossils and were deposited in the Early Cambrian. At this stop, the upper sequence of the lower Cambrian Arumbera Sandstone passes upwards from massive, fine- to medium-grained, dirty sandstone into laminated shales, siltstone and rare carbonates. Trace fossils are visible in several loose boulders. Additional information about this unit can be found in Freeman et al. (1987), Walter et al. (1989), Shergold et al. (1991), and Kennard and Lindsay (1991).

4D. STOP 1.4. TODD RIVER DOLOMITE

The lower Cambrian Todd River Dolomite conformably overlies the Arumbera Sandstone (Fig. 2). Four of the six lithofacies developed within the Todd River Dolomite are apparent at this stop (Kennard, 1991). The basal unit (lithofacies 1), which crops out relatively poorly, consists mainly of dolostone with stromatolitic bioherms, and is interpreted as a very shallow subtidal and intertidal mixed siliciclastic-carbonate flat. The second unit (lithofacies 3) consists mainly of fine-grained sandstone with lesser dolostone, which are interpreted as a series of barrier bars that have transgressed the underlying carbonate flat. The third unit (lithofacies 4) consists mainly of dolostone with archaeocythans and possible stromatolites. Two horizons with large bioherms are well exposed at the southern edge of the water pool. This lithofacies is interpreted to have formed in a high energy, intermittently emergent, shallow marine environment. The uppermost unit (lithofacies 6) consists of microbial boundstone (stromatolites) and massive dolo-mudstones, and is interpreted to have formed within a cyanobacterial mud flat. Additional information about this unit and the Ross River section can be found in Freeman et al. (1987), Kennard (1991), and Kennard and Lindsay (1991).

4E. STOP 1.5. ARLTUNGA POLICE STATION

Restored stone ruins at this site are the remains of the old Arltunga police station and gaol, which were constructed in 1912. Additional ruins, which can be reached by following a walking track about 1 km to the north-northwest, are present at the government battery and cyanide works, which were operational between 1898 and 1934 (Mackie, 1986). Alluvial gold was first discovered in 1887 at Paddy Rockhole, with reef mining beginning prior to 1890. The opening of the government battery coincided with discovery of the White Range veins (Fig. 3), which produced 81% of the 15,396 ounces (0.479 tonnes) produced in the Arltunga goldfield prior to 1984 (Mackie, 1986). After 1989 an additional 2.098 tonnes of Au were produced from the White Range veins (to December 2003: Ahmad et al., 1999; P. Lamuri, pers. comm., 2004). Historical mining around Arltunga was most active between 1896 and 1913, with peak production in 1903 corresponding to the peak in population (Mackie, 1986).

The Arltunga goldfield occurs within the Alice Springs Arltunga Nappe Complex (~430-300 Ma: Stewart, 1971; Dunlap et al., 1995). The Arltunga Nappe Complex was formed when a south-directed thrusting event resulted in the current structural duplex arrangement of the Amadeus Basin and the Palaeoproterozoic basement. The deposits are hosted both by the Palaeoproterozoic basement and by the Neoproterozoic Heavitree Quartzite (Fig. 3), and are inferred to have an age of ~300-290 Ma (late Alice Springs) based on structural relationships of Au-bearing veins and ^{39}Ar-^{40}Ar ages of white micas associated with the Alice Springs Orogeny (J. Dunlap, pers. comm.., 2002). Palaeoproterozoic rocks that host the deposits (Fig. 3) include the Cadney Metamorphics (marble and calc-silicates), the Hillsoak Bore Metamorphics (predominantly metasediments, including calcareous units and rare marbles, and amphibolites), the Cavenagh Metamorphics (mainly metasediments, including calcareous units, and quartzofeldspathic gneiss with minor iron formation) and the Atnarpa Igneous Complex (retrogressed tonalitic gneiss: Mackie, 1986). Of these units, only the Atnarpa Igneous Complex has been reliably dated at ~1770 Ma (Zhao and Bennett, 1995).

4F. STOP 1.6. MACDONNELL RANGE REEF

The Macdonnell Range reef, which can be traced along strike for about 300 m, was mined from several small shafts and diggings along its easternmost extent. In addition, alluvial diggings worked a small creek that drained the eastern end of the reef. The reef has a sinuous outcrop pattern with a broadly east-west strike and a shallow (15°) northerly dip (Mackie, 1986). The vein orientation is subparallel to that of the foliation developed in the enclosing metasedimentary rocks, which are calcareous in vicinity of the workings (Mackie, 1986). The vein varies in thickness from 0.2 to 0.5 m and consists of white quartz that is variably iron stained and locally contains malachite. A thin, phyllosilicate-rich alteration zone is locally developed on the hanging wall, and Mackie (1986) reported a sheared, graphitic alteration zone ("black plumbaginous slate") along the footwall of the vein. This reef produced a total of 248 ounces of gold from 353 tons of ore between 1896 and 1908 with an average grade of 0.70 oz/ton or 21.8 g/t (Mackie, 1986).

Fluid inclusions from the White Range veins, to which this reef is probably related, homogenise to both the liquid and vapour phase or show critical behaviour. Homogenisation temperatures vary between 280 and 325°C, with most between 315 and 325°C. The inclusions are of low salinity (0-3.5 eq wt % NaCl) and contain significant CO_2, but no other gases (A. Wygralak, pers. comm., 2004). The fluid inclusion data are consistent with phase separation, and the compositions are typical of lode gold ore fluids.

4G. STOP 1.7. SYENITE, MORDOR IGNEOUS COMPLEX

The Mordor Igneous Complex is a plug-like alkaline body that forms a 6 by 6 km body inside the Mordor Pound. The complex intrudes Palaeoproterozoic schist, gneiss and amphibolite that form the floor of the pound (Fig. 4). The walls to the pound are capped by Neoproterozoic Heavitree Quartzite (Hoatson and Stewart, 2001). This complex has been dated at 1132 ± 5 Ma using zircons from a phlogopite-plagioclase-clinopyroxene pyroxenite plug (Hoatson et al., 2002).

The stop is located approximately 100 m north of the road. Mordor syenite generally crops out poorly, typically forming sandy plains dominated by feldspar. At this location a number of low bouldery outcrops are present. The syenite is homogeneous and coarse-grained with minor phlogopite and rare plagioclase. Hoatson and Stewart (2001) suggest that the strong alignment of feldspar characteristic of the syenite and other felsic units of the Mordor Igneous Complex is the consequence of flow lamination.

4H. STOP 1.8. MITHRIL PGE-AU PROSPECT

The Mithril PGE-Au prospect is an orthomagmatic deposit hosted by the layered ultramafic phase of the Mordor Igneous Complex (Fig. 5). Three diamond drill holes have intersected mineralisation at this locality, with the best intersection being 2 metres grading 1.1 g/t Pt+Pd+Au within an 8 m interval assaying 0.67 g/t Pt+Pd+Au. The PGE mineralisation is associated with disseminated sulphides (chalcopyrite > pyrrhotite ~ pentlandite) within a pyroxenite immediately underlying olivine-bearing unit (Tanami Gold Ltd. Announcement to Australian Stock Exchange, 20 December 2002). These ultramafic rocks typically contain phlogopite, with some of the olivine-bearing rocks containing up to 40% phlogopite. Tanami Gold Ltd (announcement to Australian Stock Exchange, 20 December 2002) suggest that the PGE mineralisation formed by the injection of a primitive (i.e. olivine-bearing) magma into the differentiating magma chamber.

4I. STOP 2.1. UPPER CADNEY METAMORPHICS

This stop is within the marbles and calc-silicate rocks typical of the upper part of the Cadney Metamorphics, which we interpret as being near the base of the uppermost unit within the SMC. Although this unit has not been dated, we infer that it has an age of ~1800 Ma based on its (conformable?) relationship with the underlying units of the SMC which have been dated at ~1805 Ma at several locations (see stop 3.3 below). The stop is dominated by clinopyroxene-bearing and scapolite-bearing marble, with the clinopyroxene and scapolite forming in separate layers (probable beds). Minor sillimanite-garnet-biotite metapelitic schists are interlayered with the marbles, and calc-silicate rocks are commonly found along the contact between marble and metapelitic rocks.

4J. STOP 2.2. JOHNNIES REWARD PROSPECT

We interpret the Johnnies Reward prospect as an IOCG deposit, not a VHMS deposit as interpreted previously (e.g. Warren and Shaw, 1985). Johnnies-type deposits differ from Utnalanama-type VHMS deposits in terms of the host, metal assemblages and zonation, associated alteration assemblages and apparent age (Table 1). Other Johnnies-type deposits include Cu-Au deposits in the Jervois mining field and possibly the Gumtree prospect. This stop involves a traverse across the Johnnies Reward prospect from hanging wall into the footwall (Fig. 6) to illustrate characteristics of Johnnies-type deposits. The hanging wall to this deposit (site A) comprises migmatitic biotite quartzo-feldspathic gneiss (probable metasediments) with local bodies of mafic granulite that are interpreted as mafic sills.

The lode unit (site B) consists of an apparently stratiform body of diopside-tremolite-magnetite rock that extends about 200 m along strike and is up to 50 m wide (Chuck, 1984a,b). The presence of isolated, small bodies of forsterite marble at surface and in drill core suggests that the lode rock replaced a carbonate lens. At surface, tremolite is the main mineral other than magnetite, and quartz and malachite staining are locally present. The lode rock is characterised at depth by a Cu-Pb(Zn-Ag-Au) assemblage, with pyrite, chalcopyrite, galena and sphalerite being the main minerals. Unweathered lode rock is characterised by highly variable 100Zn/(Zn+Pb) ratios with an average of 30. The lode rock is characterised by an overall enrichment in Fe and Mg. From structural bottom to top the metal zonation appears to be: Au(Cu-Bi-S±Mo) → Cu-Pb-S(Zn-Ag-Au) → Pb-Mn(Cu-S±Ca) → REEs-HFSEs → Ca. The basal Au enrichment is present in the footwall rocks which can be seen at site C.

The footwall to the lode rock at Johnnies Reward (location C) is characterised by quartz-garnet-biotite-feldspar gneiss with minor magnetite, spinel and orthopyroxene. Chalcopyrite and pyrite are present at depth (Chuck, 1984a,b). The most significant Au grades (to 10 g/t) are present at depth within this zone, with one drill hole (E058-002) having a 50 m intersection grading 1.83 g/t that ended in grade. At surface these garnet-rich rocks have also returned significant Au grades. Further into the footwall (location D), the amounts of garnet decreases and feldspar increases.

4K. STOP 2.3. PINNACLES CU DISTRICT

The Pinnacles Cu district, which is located 2.3 km east of the Johnnies Reward prospect, was discovered in 1889 and produced a total of 248 tonnes of ore averaging 12.4% Cu when mining ceased in 1968 (Mackie, 2002). The district is hosted by marble of the upper Cadney Metamorphics. The visited prospect is hosted by interlayered phlogopite-diopside marble and scapolite marble. The mineralisation occurs in a shallowly dipping, brittle-style vein comprised of quartz and siderite(?) that is oriented sub-parallel to bedding within the host marbles. At depth the main Cu mineral is chalcopyrite, but most ore was extracted from the oxidised zone where malachite, chalcocite and bornite are the main ore minerals. In addition to Cu, these deposits also contain significant Au, Ag and Bi (Warren et al., 1974). We interpret these veins to have formed during the Alice Springs Event (380-300 Ma) based on the brittle character of the veins.

4L. STOP 2.4. RIDDOCK AMPHIBOLITE AT ATURGA CREEK

This washed outcrop is one of the best exposures of the Riddock Amphibolite, which consists of garnetiferous para-amphibolite interlayered with garnet quartzo-feldspathic gneiss, biotite gneiss, garnet-biotite gneiss, sillimanite gneiss and plagioclase-rich gneiss (Hoatson and Stewart, 2001). Hoatson et al. (2002) report a maximum depositional age for this unit of 734 ± 44 Ma based on the analysis of zircon cores. Zircon rims have an age of 461 ± 6 Ma, which are interpreted to record high grade metamorphism associated with the Larapinta Event. Hence, the age of this unit is bracketed between ~735 and ~460 Ma. Based on detrital zircon spectra, D. Maidment (pers. comm., 2004) suggests that the most likely chronostratigraphic correlatives to this unit are the Arumbera Sandstone and Todd River Dolomite, which were visited at stops 1.3 and 1.4. Recognition that the ISA, of which the Riddock Amphibolite is part, has a Neoproterozoic to early Palaeozoic age has revolutionised the geological understanding of central Australia and will have ramifications to the geological evolution of Australia as a whole. This new understanding has only been possible because of the application of modern geochronological techniques. Alluvial processes in Aturga Creek drainage catchment have produced a sand highly enriched in garnet and hornblende. North of the ranges these alluvial sands form part of a potentially world-class, economic, heavy minerals sand deposit (see below).

4M. STOP 2.5. GARNETIFEROUS SAND DUNES

Low stabilised sand dunes at this location form part of a reserve (proven and probable) containing 2.3 Mt of garnet and 12 Mt of alumino-magnesio-hornblende as defined by Olympia Resources Ltd. Following a Defensible Feasibility Study in September 2003, Olympia plans to undertake water exploration, an environmental assessment and pilot plant test work in preparation for possible development of the resource. In addition to the stabilised sand dunes present at this site, the reserves also include buried alluvial sands in the Plenty River floodplain and in channels of Aturga Creek, Plenty River and Ongeva Creek. Additional information regarding this project can be found at http://olympiaresources.com.au.

4N. STOP 3.1. MUD TANK VERMICULITE OPEN CUT

This open cut mines one lens of vermiculite developed of biotite-rich alteration assemblages associated with the 732 ± 5 Ma (Black and Gulson, 1978) Mud Tank carbonatite. The vermiculite forms by weathering of biotite. Other minerals present within the ore lens include very coarse-grained apatite, magnetite, carbonate and some zircon.

4O. STOP 3.2. MUD TANK PROCESSING PLANT

The processing plant is operated by a limited number of staff (usually 3-5) and treats the ore by gently drying it in a gas powered furnace to drive of excess moisture. The dry ore is then passed through a series of specially designed sieves to separate the vermiculite into different size fractions ranging from <1 mm to >4 mm. All fine material less the 0.7 mm (?) is excluded and is stored in a stock pile west of the plant. The various size fraction are bagged into one tonne bags ready for shipment. The vermiculite is not exfoliated on site as this significantly increases the volume for transport. Vermiculite from Mud Tank is transported to South Australia, from where most is shipped overseas for treatment. The discarded fines contain abundant vermiculite, but this material is considered uneconomic given transport costs. The fines also include considerable resources of high-quality iron ore (magnetite) and phosphate (apatite) which are yet to be exploited.

4P. STOP 3.3. EDWARDS CREEK PROSPECT

The Edwards Creek prospect (Fig. 7) is probably the best exposed VHMS (Utnalanama-type) deposit in the SMC. The mineralised zone is hosted by a marble that occurs within a sequence that contains metamorphosed volcaniclastic rocks. This marble lens is up to 8 m thick and can be trace along strike for about 700 m. The main unit in this lens is forsterite marble with up to 5% disseminated pyrite, sphalerite, galena and chalcopyrite.

The marble is underlain by quartz-cordierite ± orthopyroxene ± phlogopite ± orthoamphibole ± sillimanite gneiss which we interpret to be metamorphosed quartz-chlorite altered volcaniclastic rocks. Other, less common, altered rocks include amphibole-pyroxene, massive cordierite and amphibole-spinel rocks. Whole rock $\delta^{18}O$ compositions of this and related altered rocks range between 1.8 and 5.8‰, which is most consistent with alteration by heated seawater.

A sample of quartz-cordierite-orthopyroxene-biotite rock yielded a simple zircon population with an age of 1802 ± 5 Ma, which is most consistent with a volcaniclastic origin for the rock. Analyses of host rocks for the Harry Creek (1801 ± 3 Ma) and the Utnalanama (1810 ± 4 Ma) prospects are similar, suggesting that the rock packages that host Utnalanama-type deposits are correlative and have a probable volcaniclastic origin (J. Claoué-Long, pers. comm., 2003).

The hanging wall is dominated by migmatitic metapelites, and granite gneiss that locally has an intrusive contact with the marble lens. We interpret this granitic rock to be an accumulation of partial melt that formed during peak metamorphism. Remnant lenses of biotite-rich, well-banded quartzo-feldspathic gneiss probably reflect the original rock that overlaid the marble lens. The protolith to this rock probably was sedimentary or volcaniclastic in origin. These remnant lenses have not been altered, indicating an asymmetric alteration pattern consistent with VHMS deposits. A series of mafic granulite lenses, which we interpret as mafic sills, are also present in the hanging wall. The distribution of the mafic sills and the marble lens suggests that the Edwards Creek deposit is located within a syncline. Figure 7 shows the locations of sites visited at this stop.

Site A. The variability in the quartz-cordierite gneiss that characterises the footwall alteration zone is apparent at this site. A sample from this site yielded a SHRIMP U-Pb zircon age of 1802 ± 5 Ma with a single igneous zircon population. As the single population and igneous character of the zircons imply a probable volcaniclastic origin for the population (J. Claoué-Long, pers. comm., 2003), and this age is taken as the true age of the host sequence to the deposit. This age was used to pin the Pb isotope evolution model for the SMC. Zircon overgrowths from this sample returned an age of 1716 ± 3 Ma (J. Claoué-Long, pers. comm., 2003), implying that these rocks have been overprinted by high-grade, Strangways-aged metamorphism.

Site B. This site contains a variety of rock types, the most unusual being a quartz-cordierite-orthoamphibole rock with a relic coarse clastic texture. Gedrite-hercynite-magnetite-phlogopite rock nearby is inferred to be metamorphosed chloritite that either replaced the host or formed as veins.

Site C. Calc-silicates (quartz-diopside-anorthite rock) at this and other locations have replaced marble. In addition to being weakly mineralised in Pb (200-1000 ppm) and Zn (100-1900 ppm), these rocks are also enriched in Bi (to 18 ppm), Sn (to 100 ppm), U (to 100 ppm), Th (to 70 ppm), Y (to 420 ppm) and REEs (totals to 1100 ppm). We interpret this mineralising event to be a separate event from the VHMS event based on this elemental assemblage, which contrasts with that associated with mineralised marble (see below). This event may relate to the Yambah Igneous Event (~1780 Ma).

Site D. The banded, biotite-rich quartzo-feldspathic gneiss at this site is interpreted to be the unit that overlies the mineralised zone. The protolith to this rock was most likely a psammopelitic or volcaniclastic rock. The more massive granitic gneiss is interpreted as a melt generated during high grade metamorphism. Mafic granulite bodies are interpreted as mafic sills.

Site E. Malachite staining is present at the base of the siliceous cap exposed at this site. This siliceous cap is interpreted as a Tertiary weathering feature. Drilling of an induced polarisation anomaly to the north of this site yielded highly gossanous, vuggy material that assayed up to 7.1% Cu and 3.3% Zn. Surface samples of the siliceous rock all contain significant mineralisation, with maximum grades of 0.6% Pb, 1.3% Zn and 0.6% Cu. Along the base of the siliceous ridge to the south, coarse-grained amphibole±spinel rock is present.

Site F. The banded, forsterite marble at this site is typical of the mineralised zone at Edwards Creek. The marble contains up to several percent disseminated and vein galena, sphalerite, pyrite and chalcopyrite. Our analyses of the marble indicate grades up to 0.67% Pb, 3.29% Zn and 0.80% Cu, and analyses of marble in diamond drill core indicate grades up to 0.57% Pb, 1.00% Zn and 0.55% Cu. Other anomalous elements include Cd (to 137 ppm) and Bi (to 20 ppm). The Sn, HFSE and REE anomalies characteristic of mineralised calc-silicate rocks are not present in mineralised marble, which is consistent with two separate mineralising pulses.

Site G. At this site the replacement of marble by siliceous rock is well illustrated. The fabric in the marble is a granulite facies Strangways fabric and silicification clearly truncates the fabric.

Site H. The poorly outcropping black amphibolite between the marble lens and the footwall quartz-cordierite gneiss at this site assayed 11.68% Zn (much to the surprise and consternation of GA's geochemistry lab). Subsequent investigation of this rock indicated that it is comprised almost entirely of hornblende and gahnite. This rock can be traced for about 150 m along the contact between the mineralised marble lens and the quartz-cordierite gneiss, and it varies in width between 0.5 and 5 m. In addition to Zn this rock is enriched in Bi (to 0.48%), Cu (to 0.26%), Pb (to 0.21%), Sn (to 70 ppm), Th (to 40 ppm) and total REEs (~500 ppm). The sulphur values are exceptionally low, with a maximum of only 400 ppm. The origin of this rock is problematic; it may represent original VHMS-related mineralisation that was subsequently metasomatised during the later Yambah or Strangways events.

Site I. At this site an Alice Springs-aged (385 Ma age from monazite intergrown with biotite-chlorite: Ballèvre et al., 1999) shear has retrogressed the quartz-cordierite rock to a chlorite-biotite-staurolite-kyanite schist.

Site J. The massive, coarse-grained gedrite-clinoproxene rock at this site occurs mainly in the southern part of the Edwards Creek deposit. Locally the rock has been retrogressed to a talc-chlorite assemblage. We interpret that it occurs in the footwall to the mineralised marble lens and represents a metamorphosed quartz-talc alteration assemblage.

4Q. STOP 3.4. YAMBAH-AGED GRANITOID

This biotite quartzofeldspathic orthogneiss has a granodioritic composition. The fabric in the rock is interpreted to be Strangways in age. Rock collected from this site has been dated using SHRIMP techniques at 1776 ± 7 Ma (age interpreted by J. Claoué-Long from data collected by S.-S. Sun). Mineral systems associated with the ~1780-1770 Ma Yambah Event may have been responsible for the unusual Sn-HFSE-REE-Zn-Pb metal assemblage in the calc-silicates at Edwards Creek. The IOCG mineral systems that form the Johnnies-type deposits may also have been related to Yambah-aged granitic activity. Most felsic orthogneiss units mapped in the northern part of the SMC are suspected Yambah-aged granitic activity.

4R. STOP 3.5. CHARLES RIVER RAILROAD CUTTING

The Charles River railroad cutting exposes the Charles River fault. Units in this railroad cutting include, from south to north: greenschist facies granitic gneiss (cream coloured rock) → 50 m wide mylonitic zone (Charles River Fault; greenish white in colour) → amphibolite facies rocks (including amphibolite, biotite quartzo-feldspathic gneiss and pegmatite) with intermittent mylonite zones. Rare pseudotachylyte is found along the Charles River Fault. The fabric in the rock and the mylonitic zones both dip to the north at about 45°. Movement on the Charles River Fault is north-side up at this site, making it a reverse fault. At a regional scale this fault has a sinuous pattern. Ten kilometres to the west, the Charles River Fault juxtaposes Palaeoproterozoic rocks against the Neoproterozoic Heavitree Quartzite. Although undated, the Charles River Fault is inferred to be Alice Springs in age.

4S. STOP 3.6. ANZAC HILL

The Anzac Hill overlooks panoramic views of the town of Alice Springs. The main ridge to the south is comprised of Heavitree Quartzite, with the townsite built on an alluvial plain up to 50m thick of recent fill. The hills in the town area are made up of Palaeoproterozoic rocks of the Hayes Metamorphic Complex. The northern end of Anzac Hill is comprised of 1751 Ma Alice Springs Granite, whereas the southern side is made up of Sadadeen Gneiss. Palaeoproterozoic(?) pegmatites are common in the region and truncate low grade Strangways(?) fabrics. The Hayes Metamorphic Complex is unconformably overlain by the Iwapataka Metamorphic Complex, containing an assemblage of metasediments and suspected felsic volcanics dated at 1615 Ma (Zhao and Bennett, 1995). Figure 8 schematically shows the relationship of the Arunta basement rocks with the Heavitree Quartzite in the Alice Springs area. The town site is located in the core of a (late) Alice Springs-aged anticline, which has folded the Palaeo-Neoproterozoic unconformities and the Charles River (and related) Faults. The Charles River Fault appears to be an (early) Alice Springs low angle reverse fault (thrust) that was subsequently folded about the anticline. Clarke (1974) calculated a throw of about 14 km on the Charles River Fault.

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7. FIGURES

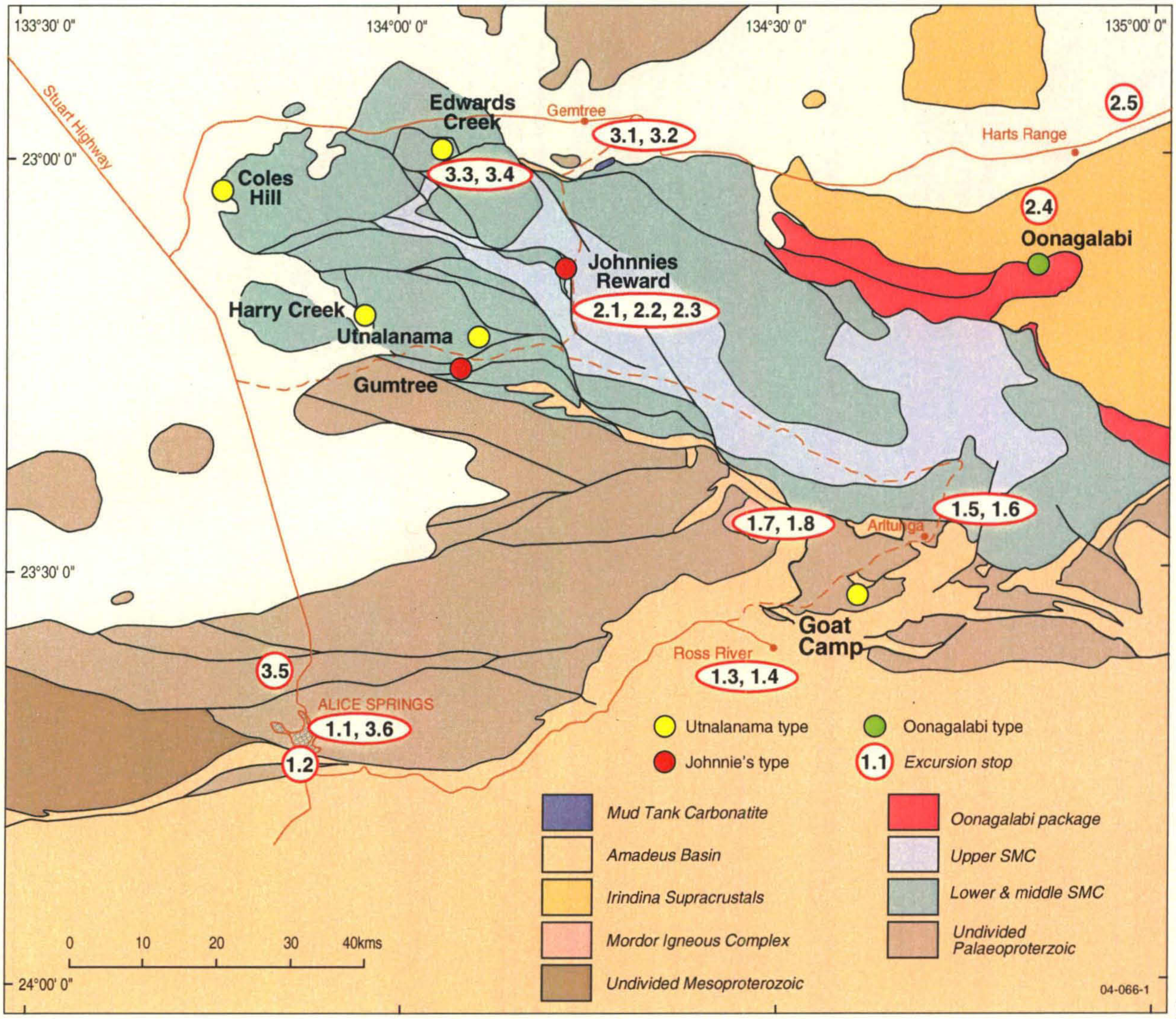

Figure 1. Generalised geology of the Alice Springs and parts of the Alcoota 1:250 000 map sheets showing the location of excursion stops.

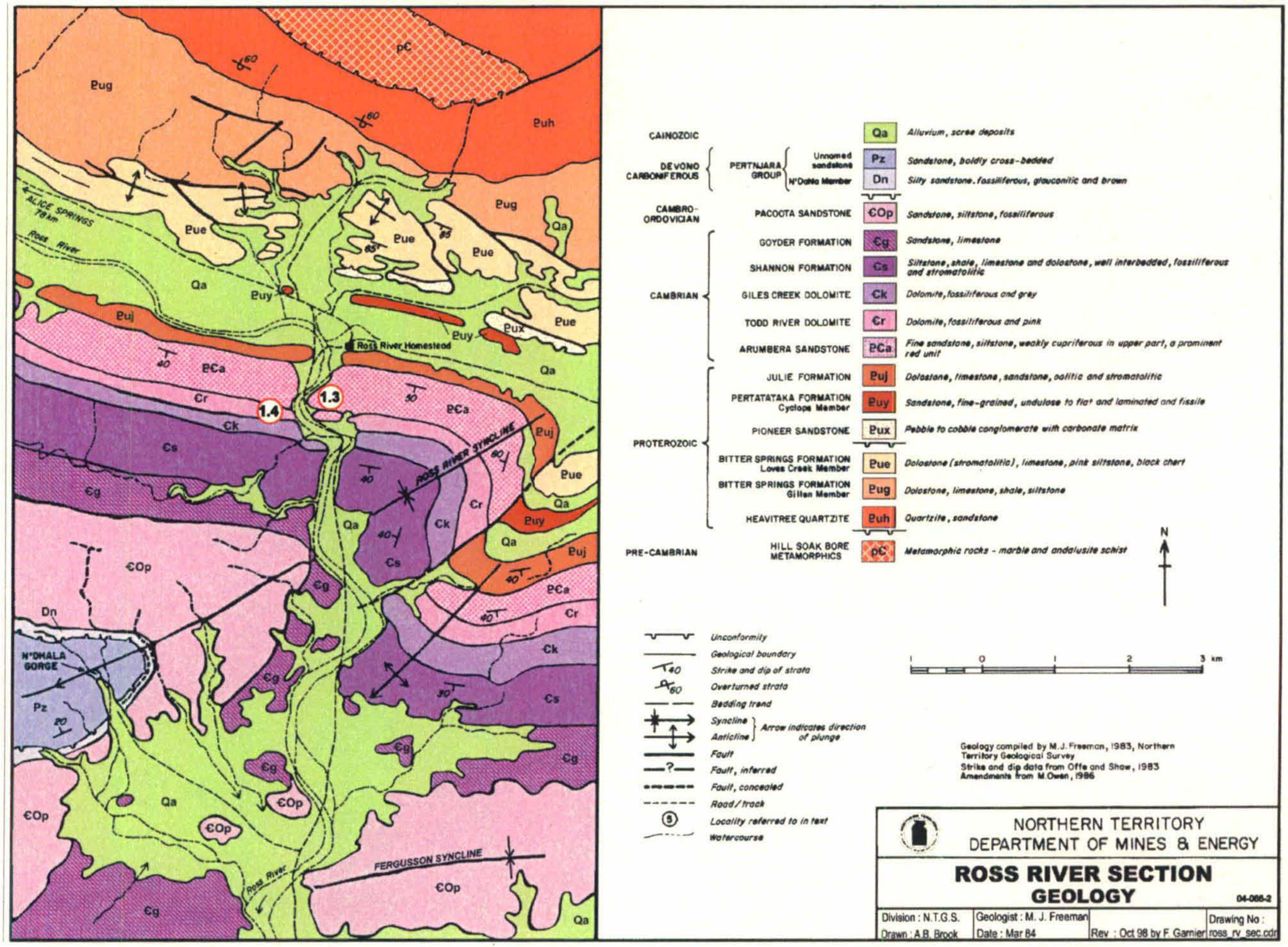

Figure 2. Geology of the Ross River Gorge showing the location of excursion stops 1.3 and 1.4 (modified after Freeman et al. [1987]).

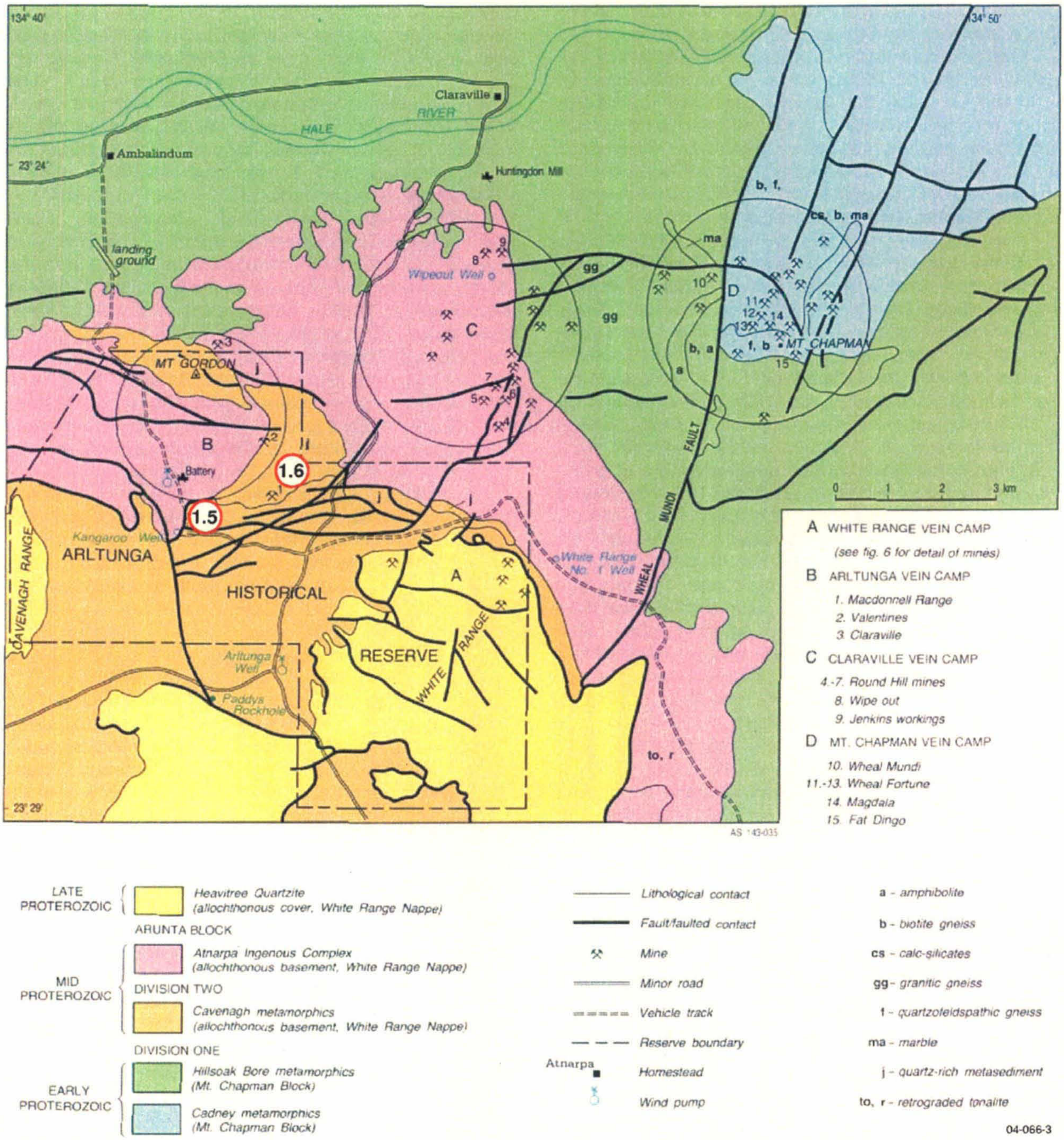

Figure 3. Geology of the Arltunga area showing the locations of excursion stops 1.5 and 1.6 (modified after Mackie [1986]).

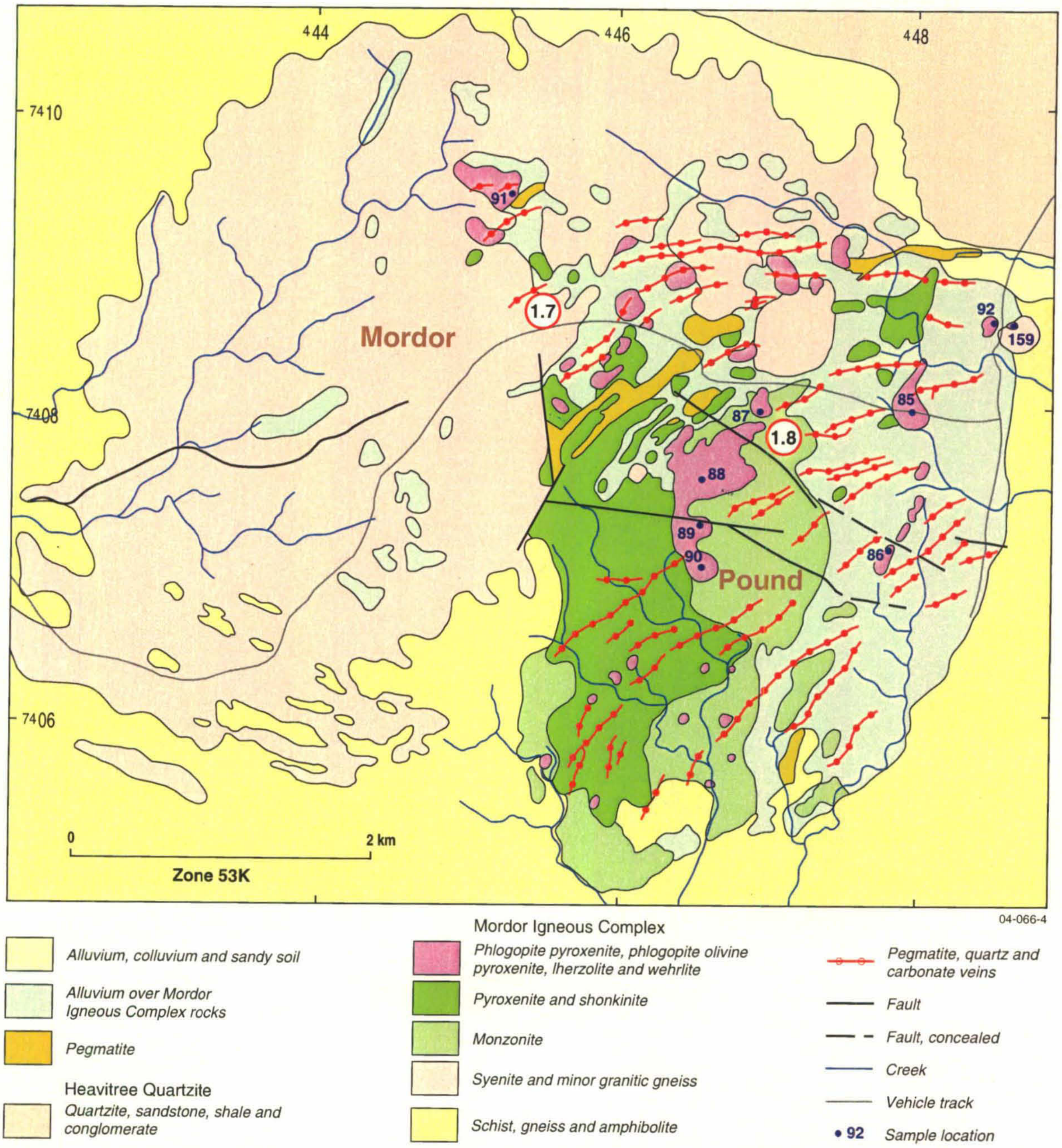

Figure 4. Geology of the Mordor Igneous Complex showing the locations of excursion stops 1.7 and 1.8 (modified after Hoatson and Stewart [2001]).

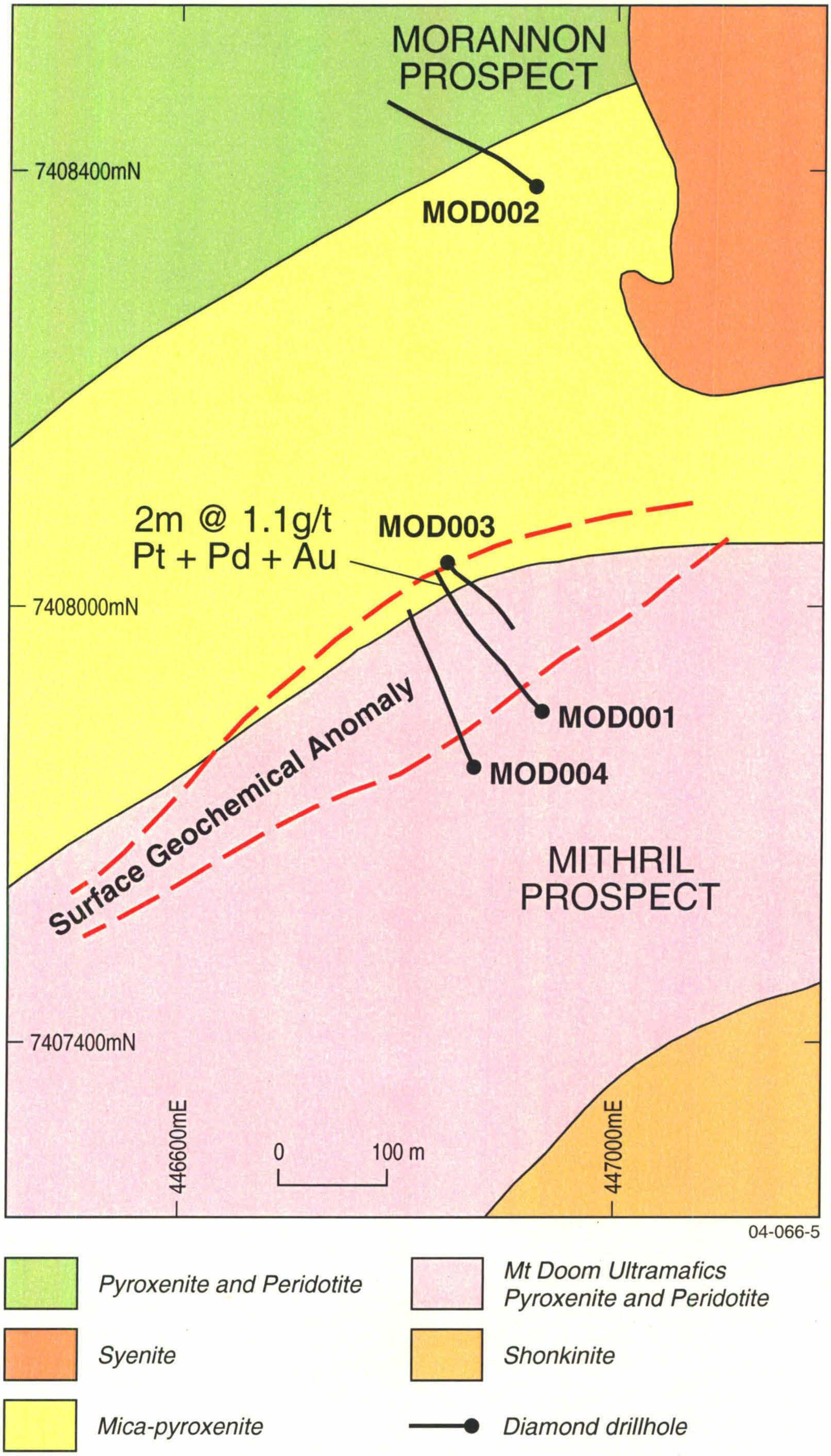

Figure 5. Surface geology of the Mithril prospect (stop 1.8: modified after Tanami Gold Ltd announcement to the Australian Stock Exchange, 20 December 2002).

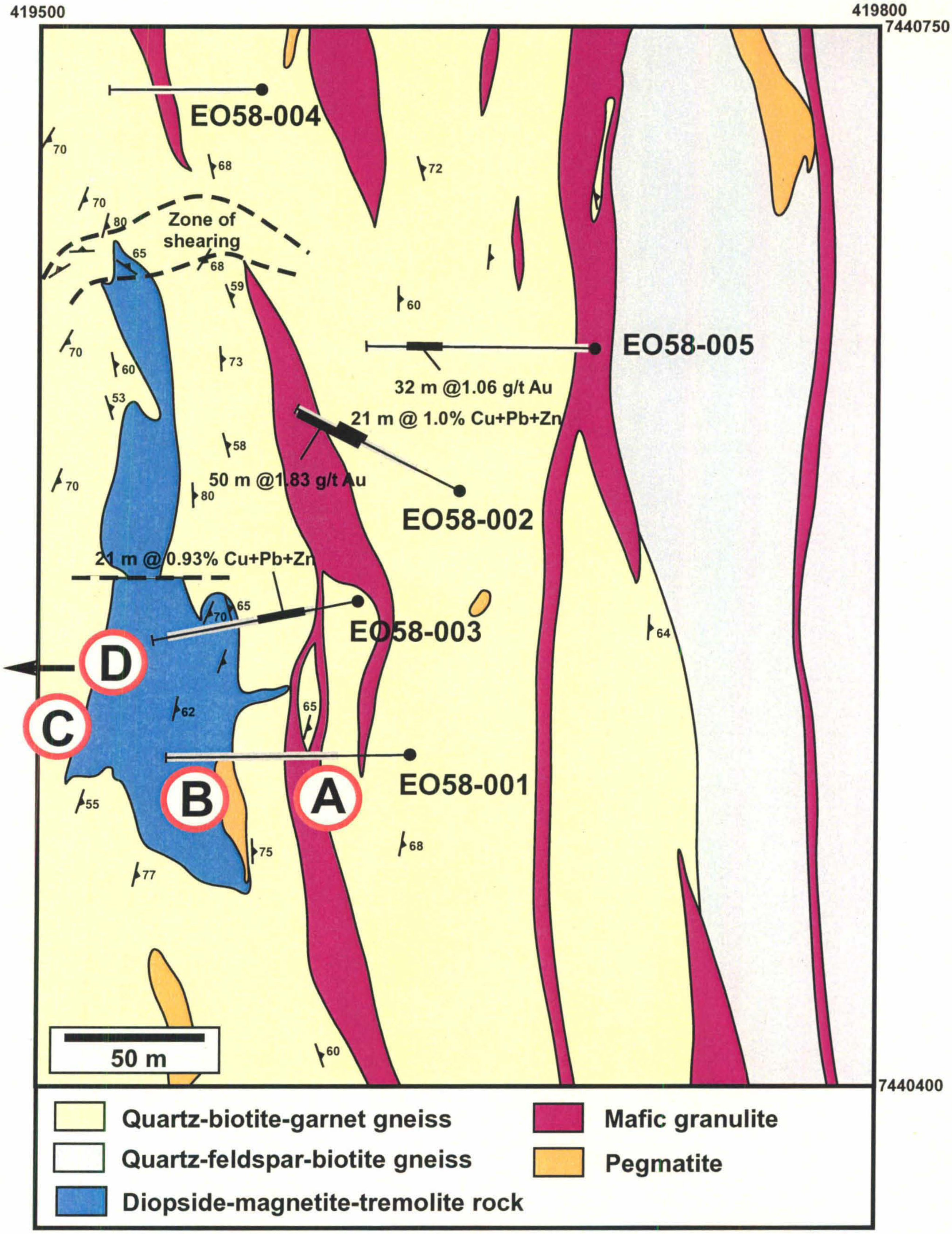

Figure 6. Geology of the Johnnie's Reward prospect showing sites from the traverse for stop 2.2 (modified after Chuck [1984b]).

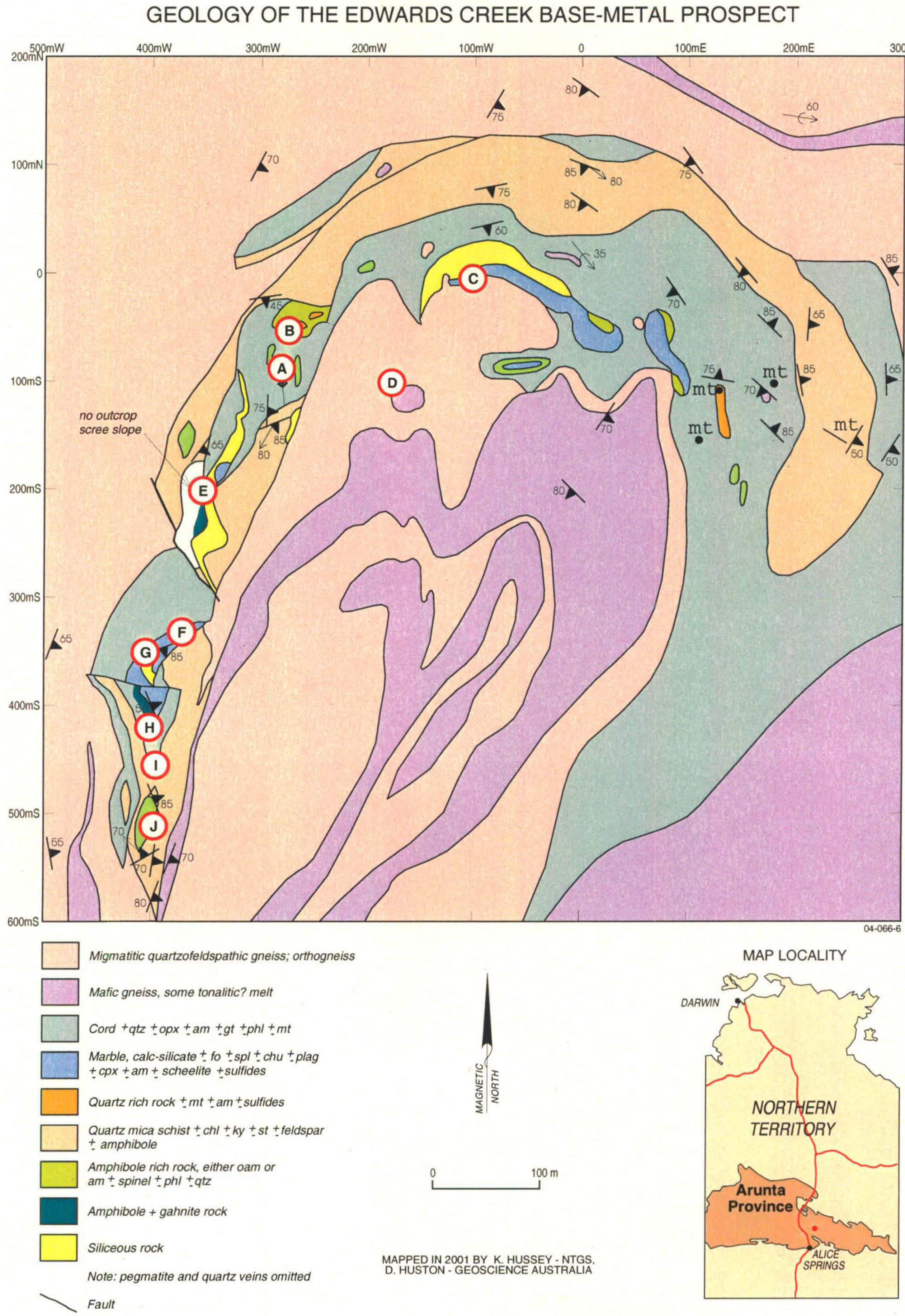

Figure 7. Geology of the Edwards Creek deposit, showing sites from the traverse for stop 3.3.

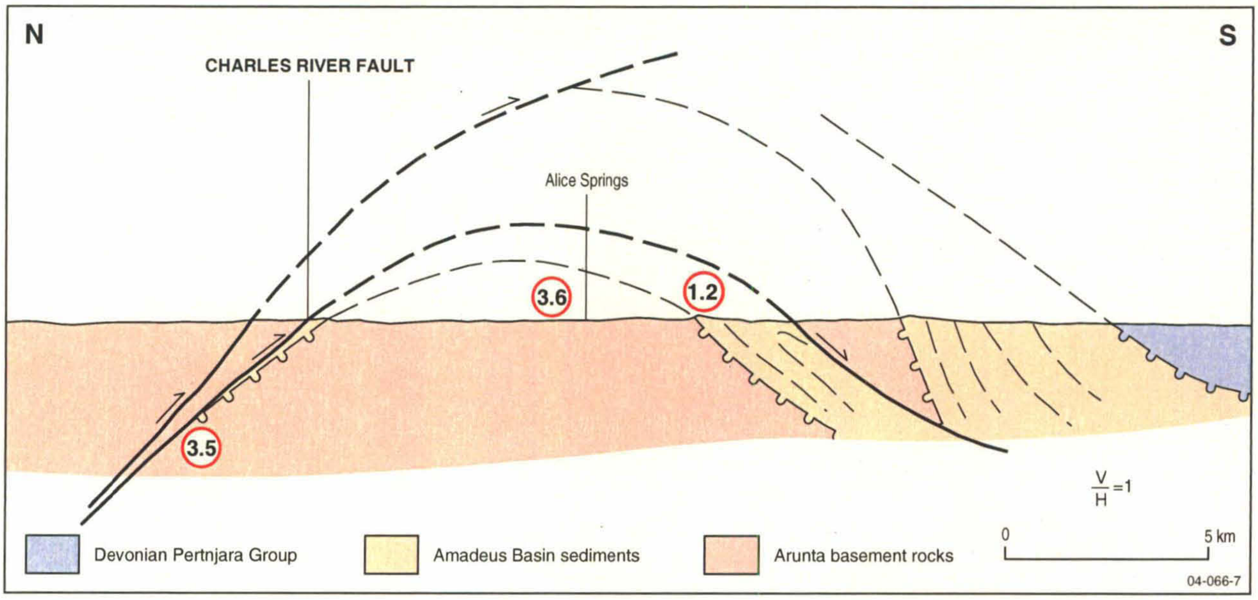

Figure 8. Schematic north-south section showing the Blatherskite Nappe in the vicinity of Alice Springs (modified after Clarke [1974], and Offe and Pillinger [1983]). The relative positions of stops 1.2, 3.5 and 3.6 are also shown on the diagram.