

NORTHERN TERRITORY DEPARTMENT OF BUSINESS, INDUSTRY AND RESOURCE DEVELOPMENT

# GEOLOGICAL SURVEY RECORD 2002-0003

## Annual Geoscience Exploration Seminar (AGES) 2002 Record of abstracts

NORTHERN TERRITORY DEPARTMENT OF BUSINESS, INDUSTRY AND RESOURCE DEVELOPMENT MINISTER: Hon Paul Henderson, MLA CHIEF EXECUTIVE OFFICER: Peter Blake

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Annual Geoscience Exploration Seminar (AGES) 2002. Record of abstracts. (Record / Northern Territory Geological Survey ISSN 1443-1149) Bibliography ISBN 0 7245 7040 3

BIBLIOGRAPHIC REFERENCE: Northern Territory Geological Survey, 2002. Annual Geoscience Exploration Seminar (AGES) 2002. Record of abstracts. *Northern Territory Geological Survey, Record* 2002-004.

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#### MINERAL DEPOSIT MODELS FOR RUM JUNGLE

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The Rum Jungle area represents a region of extremely high mineral prospectivity and contains a variety of commodities including Pb, Zn, Ag, Ni, Co, Cu, U, Au, magnesite and phosphate. The historic Rum Jungle Uranium Field produced some 3530 t of  $U_3O_8$  from 1954-1971 and the Woodcutters deposit produced 4.65 Mt ore at 12.28% Zn, 5.65% Pb and 82 g/t Ag between 1985-1999. Deposits at the feasibility stage include the Browns polymetallic deposit of Compass Resources (70 Mt @ 2.59% Pb, 0.81% Cu, 0.12% Co, 0.11% Ni and 10g/t Ag) and the Winchester Magnesite deposit of Mount Grace Resources (16.6 Mt @ 45.3% MgO).

The Pine Creek Orogen formed in response to rifting of Archaean basement. Gravity modelling shows two aulacogen like depocentres, a northwest trending depression between South Alligator and Darwin and a narrow belt to the west of Jabiru. Depth to basement (granite and gneisses) in these centres is up to 4 km. Basement is exposed near Batchelor (Rum Jungle and Waterhouse Complexes) and Jabiru (Nanambu Complex).

Rb-Sr and conventional/SHRIMP U-Pb zircon dating of the Archaean granite complexes range from 2675-2400 Ma. Tuffaceous sediments (from the Gerowie Tuff and Mount Bonnie Formation) have been dated at  $1885 \pm 2$  Ma (conventional U-Pb zircon). Peak deformation and metamorphism (Nimbuwah Event of the Barramundi Orogeny) occurred at 1865 Ma. Conventional U-Pb and SHRIMP ages on late-to post-orogenic granites (Cullen Igneous Event) are in the range 1800-1835 Ma. Rb-Sr ages on these granites, as well as on the enclosing sediments were reset at 1780 Ma; this is suggestive of a regionally extensive thermal event, probably an expression of the Early Strangways Orogeny in Central Australia. Another explanation may be that the granites took 20-40 Ma to cool to Rb-Sr closing temperatures.

The geology of the Rum Jungle Region is dominated by two dome shaped Archaean complexes (Rum Jungle and Waterhouse complexes) that form island highs on the Batchelor Shelf. These complexes do not host any known mineralisation. The area surrounding them contains numerous mineral occurrences, which can be classified into two depositional settings: (1) interdomal restricted embayments; and (2) open shoreline. Major uranium deposits and the Browns polymetallic deposit occur in the former setting, whereas the Woodcutters deposit is an example of the latter.

Magnesite deposits of the Rum Jungle Region are stratabound zones of coarse magnesite in the Coomalie/Celia Dolomite and show extensive *in situ* brecciation. Minor minerals include dolomite, talc, tremolite, iron oxides and chlorite. Magnesite occurs as medium to coarse bladed crystals, veined by coarse rhombohedral magnesite. Fluid inclusions in magnesite are indicative of moderately saline to hypersaline CO<sub>2</sub>-CH<sub>4</sub>-bearing aqueous fluids that were trapped at temperatures ranging from 100-400°C (average 153°C). Rhombohedral dolomite crystallised at temperatures below 160°C, whereas the bladed variety crystallised at higher temperatures. Calculated pressure from fluid inclusion data is about 1.5 kbars (hydrostatic). These magnesite deposits have been previously interpreted as recrystallised sedimentary magnesite, but could also represent hydrothermal replacement of dolomite by magnesium-rich brines. The latter hypothesis results in a net volume decrease and this 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-stage coarse rhombic magnesite.

Replacement of dolomite by magnesite releases lead and zinc and this provides a possible source for base metal deposits in the area. Geochemical data from the Winchester deposit, near Batchelor, show that whereas the magnesite contains less than 10 ppm Zn, dolomite carries about 20 ppm. There are no apparent variations in Ni or Cu. The analytical method used for Pb (detection limit 10 ppm) does not enable meaningful statistical evaluation.

The Woodcutters orebodies are within and adjacent to a subvertical, north trending, late  $D_2$  fault system along the crest of an early  $D_2$  anticline. Ore minerals occur as replacements of carbonate-rich

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units or as open space infills. Pyrite was the first sulfide to form and was followed by arsenopyrite, galena, and sphalerite. Chalcopyrite, bournonite, boulangerite, tetrahedrite, tennantite, freibergite, stannite, cassiterite, gersdorffite and cobaltite formed late in the paragenesis. Fluid inclusions in sphalerite contain hypersaline CO<sub>2</sub>-bearing aqueous fluid that homogenised at a temperature of 221-294°C. Those in late-stage quartz are moderately saline to hypersaline and homogenised at a temperature of 120-188°C. Fluid inclusions in magnesite veins homogenised at a temperature of 130-360°C. The calculated pressure is in the range 700-1000 bars.  $\delta S^{34}$  values of sulfide range from +5 ‰ to +20 ‰ and indicate the involvement of seawater sulfate or the leaching of sulfate from the sediments. Lead isotope values are highly radiogenic and fall well above the growth curve established for Pine Creek deposits; this suggests lead derivation from old uranium-enriched crust.

Although uranium occurrences are scattered all along the periphery of the Archaean domes, major uranium deposits are notably situated in interdomal settings. These deposits are located within carbonaceous shale of the Whites Formation, immediately adjacent to the contact with the underlying Coomalie Dolomite. Some deposits show zonation and have uranium at the base followed upward by copper and then lead. Uranium appears to have been the first mineral to form and it was subsequently remobilised and altered during later generations. Base metal sulfides apparently post-date early pitchblende.  $\delta S^{34}$  values on primary pyrite range from +8 ‰ to +19 ‰ and these are suggestive of seawater sulfate reduction. Vein sulfides have distinctively lighter values ( $\delta S^{34}$  range -7 ‰ to +5 ‰, average -2 ‰) and these are suggestive of sulfur derivation from igneous source material although biogenic sulfate reduction is also possible. Chalcopyrite has distinctly heavier values (average -0.44 ‰) than galena (average -4.82 ‰) and these indicate probable equilibrium and a temperature of 150°C. This temperature is similar to that obtained from the fluid inclusions in the vein magnesite within the uranium orebodies.

The Browns polymetallic deposit is located in the interdomal setting next to the major uranium deposits. It is hosted within the Whites Formation, close to the contact with the underlying Coomalie Dolomite. Major ore minerals are pyrite, galena, sphalerite, chalcopyrite and siegenite [(Ni,Co)<sub>3</sub>S<sub>4</sub>], which is the main carrier of Ni and Co. Numerous other Ni, Co minerals are recorded. Two texturally distinct phases of mineralisation are recognised. Fine sulfide mineralisation (Stage I) is mostly along S<sub>2</sub> slaty cleavage planes, but some also occurs in bedding-parallel layers. Later coarse sulfides (Stage II) crosscut this cleavage and may have formed during D<sub>3</sub>-D<sub>7</sub>. Pb isotope data on galena plot on the Pine Creek growth curve and are quite distinct from values from the Woodcutters deposit. Preliminary evaluation of sulfur isotope data shows two distinct modes.  $\delta S^{34}$  values on coarse sulfides range from +8 ‰ to +14 ‰ and are similar to values of the Woodcutters sulfides. Fine sulfides are distinctly lighter (-5.26 ‰ to +0.25 ‰).

Thermochemical evaluation of the mineralogical data suggests that pitchblende would have been the first mineral to form as a result of the reduction of oxidised fluid. This may explain why uranium was deposited at the Coomalie/Whites Formation contact. Further reduction would move solutions into the pyrite stability field causing the precipitation of ore sulfides.

Mineral occurrences situated along the open shoreline setting, including the Woodcutters deposit, might have formed from fluids moving upward along the basement-sediment contact. Basal arenites (eg Crater Formation) possibly acted as the principal aquifer. Fluid movements might have resulted from compression related to syn- and post-D<sub>2</sub> deformation/igneous events. Basemetals could have been leached from arenites or may have resulted from the magnesitisation of dolomite. Such a mechanism would explain the prevalence of radiogenic lead. It would further explain the heavy sulfur isotope values, which may have been sourced from the sediments.

The basemetals  $\pm$  U occurrences of the embayment might represent syngenetic or syndiagenetic mineralisation that was mobilised during deformation with possible additional hydrothermal input. Hydrothermal input is envisaged to have come from the leaching of basement and overlying strata via convection cells that resulted from heat generated by radiogenic basement granites. Alternatively, the heat source might have been some hitherto unknown late orogenic granite. In either case, upwardly mobile fluids would have precipitated uranium at the first contact with carbonaceous sediments followed by the deposition of base metals.

## **OIL POTENTIAL OF THE PEDIRKA/EROMANGA BASINS**

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The Pedirka area encompasses several superimposed sedimentary basins, namely the Palaeozoic Warburton/Amadeus Basins, the Permo-Carboniferous Pedirka Basin, the Triassic Simpson Basin and the Jurassic-Cretaceous Eromanga Basin. This contribution concentrates on the Pedirka/Eromanga Basin petroleum systems with emphasis on a Permian-Mesozoic source-reservoir couplet and the Permian Purni/Tirrawarra petroleum system, both of which are believed to be highly prospective. The recognition of a palaeo oil/gas column in Colson 1 is central to new petroleum models.

The exploration history of the northern Pedirka Basin dates back to the early 1960s when the emphasis was on the Early to Middle Palaeozoic Amadeus Basin sequence (McDills 1, Hale River 1). In 1963, the discovery of Permian gas in the Cooper Basin to the south turned attention to sequences of similar age in the Pedirka Basin (eg Colson 1). The 1977 discovery of Jurassic and Triassic oil in Poolowanna 1 focussed efforts towards younger Mesozoic reservoirs (Thomas 1, Etingimbra 1 and Poeppels Corner 1). There is uncertainty about the veracity of these traps and all wells in the area predate now traditional exploration philosophy associated with the Permian-Mesozoic source-reservoir couplet. As a result, the Northern Territory Department of Mines and Energy (NTDME) undertook a program of seismic interpretation in the northern Pedirka/Eromanga Basins in 1998, with the aim of updating the exploration potential of the area. For the first time, a regional structural synthesis is available for key seismic horizons at Mesozoic and Palaeozoic levels. Alexander *et al* (1996) reviewed the hydrocarbon potential of the westernmost depocentre, the Eringa Trough, and concentrated on maturation history by utilizing fission track analysis. This contribution concentrates on the exploration potential of other important depocentres, the Madigan and northern Poolowanna Troughs, which include oil/gas mature Permian sequences that to date have received little attention.

The northern Pedirka Basin in the Northern Territory is sparsely explored compared with its southern counterpart in South Australia. Only seven wells and 2500 km of seismic data occur over a prospective area of 73 000 km<sup>2</sup>, which includes three stacked sedimentary basins of Palaeozoic to Mesozoic age. In this area, three petroleum systems have potential that is related to important source intervals in the Early Jurassic Eromanga Basin (Poolowanna Formation), the Triassic Simpson Basin (Peera Peera Formation) and the Early Permian Pedirka Basin (Purni Formation). They are variably developed in three prospective depocentres, the Eringa, Madigan and northern Poolowanna Troughs. Basin modelling using modern techniques indicates that oil and gas expulsion responded to increasing early Late Cretaceous temperatures in part due to sediment loading (Winton Formation). Using a composite kinetic model, oil and gas expulsion from coal-rich source rocks were largely coincident at this time, when source rocks entered the wet gas maturation window. Purni Formation coals provide the richest source rocks and equate to the lower Patchawarra Formation in the Cooper Basin. Widespread well intersections indicate that glacial outwash sandstones at the base of the Purni Formation, herein referred to as the Tirrawarra Sandstone equivalent, have regional extent and are an important exploration target. They also provide a direct correlation with the prolific Patchawarra/Tirrawarra petroleum system found in the Cooper Basin.

An integrated investigation into the hydrocarbon charge and migration history of Colson 1 was carried out using CSIRO Petroleum's OMI (Oil Migration Intervals), QGF (Quantitative Grain fluroescence) and GOI (Grains with Oil Inclusions) technologies. In the Early Jurassic Poolowanna Formation, between 1984 and 2054 mRT, elevated QGF intensities, evidence of oil inclusions and abundant fluorescing material trapped in quartz grains, and low displacement pressure measurements collectively indicate the presence of palaeo-oil and -gas accumulation over this 70 m interval. This is consistent with current oil show indications such as staining, cut fluorescence, mud gas and surface solvent extraction within this reservoir interval. Multiple hydrocarbon migration pathways are also

indicated in sandstones of the lower Algebuckina Sandstone, basal Poolowanna Formation and Tirrawarra Sandstone equivalent. This is a significant upgrade in hydrocarbon prospectivity, given previous perceptions of relatively poor quality and largely immature source rocks in the Basin.

Conventional structural targets are numerous, but the timing of hydrocarbon expulsion dictates that those with an older drape and compaction component will be more prospective than those dominated by Tertiary reactivation which may have resulted in remigration or leakage. Preference should also apply to those structures adjacent to generative source kitchens on relatively short migration pathways. Earlier formed stratigraphic traps at the level of the Tirrawarra Sandstone equivalent and Poolowanna Formation are also attractive targets. Cyclic sedimentation in the Poolowanna Formation results in two upward-fining cycles, which compartmentalise the sequence into two reservoir-seal configurations. Basal fluvial sandstone reservoirs grade upward into topset shale/coal lithologies, which form effective semi-regional seals. Onlap of the basal cycle onto the Late Triassic unconformity offers opportunities for stratigraphic entrapment.

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## NTGS GEOPHYSICAL PROGRAMS: THE STATE OF PLAY AT THREE-QUARTER TIME

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## **INTRODUCTION**

Geophysical programs in NTGS are designed to assist in the early exploration protocol of regional assessment and area selection. To this end, the core business functions of NTGS Geophysics Section are to:

- acquire, process and archive semi-regional geophysical data;
- geologically integrate these data into NTGS regional geoscience prospectivity enhancement programs; and
- disseminate data and interpretations to the exploration industry.

## AIRBORNE GEOPHYSICAL PROGRAM

Current annual expenditure on airborne geophysics by NTGS equates to around 22% of the overall budget, or about half of the additional funds available through increased funding arrangements of the NT Government 4-year Exploration Initiative. The aim of the airborne geophysical program is to provide explorers with one of the most extensive, uniformly high quality airborne data sets available anywhere in the world.

NTGS remains highly responsive to exploration trends and the needs of its industry clients in planning its annual airborne program. The choice of "standard" flying specifications (400 m line spacing, 80 m flying height, minimum 33 litre spectrometer crystal volume) provides quality coverage that encourages district-scale structural analysis, the discrimination of permissive rock packages and some level of quantitative interpretation.

During 2001, 550 000-line kilometres of airborne magnetic and radiometric data were acquired by NTGS, increasing the proportion of the NT covered by data of semi-regional specifications ( $\leq$ 500 m line spacing) to over 80%:

- 320 000-line kilometres were flown in four separate surveys (**BARKLY**, **EROMANGA**, **STURT** and **WATERLOO**). All data were collected using "standard" NTGS specifications.
- An additional 225 000-line kilometres were acquired from the private sector as part of **BARKLY**, **STURT** and **WATERLOO**. These surveys were flown between 1983 and 1997, at flight line spacings in the range 250-500 m. All private sector data were re-processed prior to public distribution.

Located (ASEG-GDF2 format) and gridded (ERS format) digital data from the 2001 airborne program were released into the public domain during January–March 2002 under the current NTGS zero pricing policy. To date, about 30 requests have been filled for each survey.

## NTGS IMAGE WEB SERVER

In December 2000, NTGS implemented an Image Web Server (IWS) as a means to examine compressed located imagery from all semi-regional government airborne surveys across the NT. Access to IWS is gained through the NTGS website using standard web browsers. Individual magnetic, radiometric and elevation images (ECW format), in total numbering over 500, have been produced using a compression ratio of between 10:1 and 80:1, in order to optimise speed of delivery over the Internet with only a relatively minor compromise in data quality.

During the latter half of 2001, NTGS introduced a first for the exploration industry; this was the web serving of preliminary located imagery during the conduct of its airborne program. Close cooperation between NTGS and airborne contractors enabled image updates to be posted approximately every 4 weeks, thereby facilitating earlier area selection decisions and complementary airborne surveys by explorers.

An additional feature of the NTGS IWS is that explorers are now able to download ECW files for storage on their local PC. This provides an alternative to accessing NTGS imagery via the Internet.

## **GRAVITY PROGRAM**

NTGS and Geoscience Australia undertook an extensive gravity program over the central portion of the Tennant Inlier during 2001. A total of 1605 new 4 km x 4 km and 2 km x 2 km stations were observed. This added to 2419 existing stations from the National Australian Gravity Database and 20 346 prospect-scale and semi-regional stations supplied by several exploration companies. The program encompassed TENNANT CREEK, and parts of BONNEY WELL, GREEN SWAMP WELL, and LANDER RIVER.

Point located and gridded data are available as downloads from the NTGS web site. The spatial relationship between gravity and magnetic signatures of the region can be examined on the NTGS IWS.

## **OPEN FILE GEOPHYSICAL DATA**

NTGS recognises the importance of less extensive private sector airborne and ground geophysical surveys that exceed the specifications of NTGS airborne surveys. It is a statutory requirement for all explorers to submit located digital data corresponding to geophysical surveys undertaken on tenemented ground. This data remains closed file until such time the tenement is surrendered, or the explorer agrees to its earlier public release. At this point, the survey data becomes open file, and available for use by other explorers.

In September 2000, NTGS released a spatial index of open file company geophysical data. This resource is updated every six months and available as a download from the NTGS web site. The index now comprises full specifications from almost 250 separate airborne and ground geophysical surveys.

Note that only surveys that have digital data lodged with the Department are indicated on the index.

## **PROGRAM FOR 2002**

The following program is on the agenda for 2002:

- Acquisition of 245 000-line kilometres of airborne magnetics, radiometrics and DTM in two surveys. Newly flown data will account for approximately 70% of the total. The **GEORGINA** survey will complete coverage of the Georgina Basin in the NT. The **BUCHANAN** survey will lift the proportion of the Wiso Basin covered by airborne data of semi-regional specifications to 75%. A subsequent edition of the Magnetic Map of the Northern Territory (Clifton 2002), scheduled for release in April 2003, will incorporate data from the 2002 airborne acquisition program.
- Gravity surveying in western Arnhem Land will be undertaken during the latter part of the 2002 field season, pending a satisfactory conclusion to land access consultations. Interest in this region relates to areas of basement inliers of the Pine Creek Orogen that may have potential for base metals (several styles are present in the western part of the Pine Creek Orogen) and precious metals (Coronation Hill-type), as well as to outliers of Kombolgie Subgroup that have U prospectivity. Proposed funding for this program will be in the form of equal contributions from NTGS, Geoscience Australia and the private sector. The new data will be acquired at a nominal station spacing of 2 km and cover portions of ALLIGATOR RIVER and MILINGIMBI.
- Territory-wide geophysical companion compilations to the Magnetic Map of the Northern Territory, in the form of radiometrics and DTM, are scheduled for release in mid 2002.

- In order to help relieve pressure on Geoscience Australia following its recent change in policy on data distribution, NTGS will by mid 2002 be in a position to distribute all Commonwealth airborne magnetic and ground gravity data within the NT. These datasets will also be made available on the NTGS IWS.
- The scope and quality of airborne geophysical coverage of the NT is now approaching a stage where NTGS can begin various "value adding" processes. Along with the acquisition of airborne data, NTGS is also well advanced in producing 2-D interpretation products from this coverage. It has commenced a production of 1:250 000 and 1:100 000 standard series Interpreted Geology maps to accompany its other standard series geological maps.
- A direction currently under consideration is the 3-D analysis of several fundamental Territory-wide spatial data sets (geology, magnetics, gravity, seismic tomography) to better define the edges and internal framework of the North Australian Craton. The ultimate aim is to define broad-scale implications for, and controls on mineralising processes.

## **CONCLUDING REMARKS**

The focus of NTGS geophysical programs is the provision of high-quality data and interpretations to explorers to assist in regional target definition and area selection. The semi-regional airborne acquisition program remains the flagship activity of NTGS. This is now entering its final year under the current Exploration Initiative. Through Image Web Server, explorers now have the capacity to rapidly access airborne data over the Internet from within the GIS environment, both during and subsequent to annual flying campaigns.

The adding of value to our Territory-wide data sets is gathering momentum, with systematic 2-D geological interpretation in full swing, and 3-D spatial data analysis in the pipeline.

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#### **GEOLOGY OF THE TANAMI REGION**

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Recent work in the Tanami region has concentrated on using SHRIMP U-Pb zircon analyses to test the stratigraphy presented in Vandenberg *et al* (2001a) and has resulted in some minor revision. MacFarlane Peak Group sandstone and felsic volcanics were sampled to determine whether they were distinct from the Dead Bullock Formation. Numerous Killi Killi Formation sediments were analysed for geochronology with a view to delineating the extent of the "1815 Ma Killi Killi Formation" in contrast with the (1840 Ma) Killi Killi Formation. "Syn-tectonic" Pargee Sandstone and arkose from the Mount Charles Formation were sampled to provide maximum depositional ages.

## STRATIGRAPHY

A revised tectonostratigraphy of the Tanami Region is illustrated in Figure 1.

Archaean rocks of the Billabong complex lie to the southeast of The Granites mine and consist of banded granitic gneiss that has an interpreted magmatic age of  $2514 \pm 3$  Ma (SHRIMP U-Pb zircon, Page 1995).

The Browns Range Metamorphics outcrop on the southern flank of Browns Range Dome (northwest corner of TANAMI) and define a thin east-west striking, steeply south-dipping shear zone (Vandenberg *et al* 2001b). Granitic orthogneiss (quartz-feldspar-muscovite±biotite), muscovite paragneiss and muscovite schist are intruded by fine-grained Coomarie granitic sills and dykes, aplite and pegmatite (Hendrickx *et al* 2000, Dean 2001). The Browns Range Metamorphics underwent high-grade metamorphism at 1880  $\pm$  14 Ma (OZCHRON database, R Page 1995) and this is within error of detrital ages of the structurally overlying MacFarlane Peak Group.

We interpret the MacFarlane Peak Group (MPG) to have been deposited on rifted Archaean crust. The group consists of mafic and felsic volcanics, turbiditic sandstone, siltstone and minor calc-silicate. Metamorphic grade varies from amphibolite facies in the type area to greenschist or lower facies elsewhere. Detrital zircon ages from the type area indicate a complex inherited and metamorphic history. The youngest zircon population, unaffected by later metamorphic or hydrothermal processes, has yielded an age of  $1877 \pm 21$  Ma. The remaining younger zircons appear to have been isotopically disturbed. Granite located 2 km to the west intruded at  $1809 \pm 3$  Ma and may be responsible for metamorphism and for resetting the zircon. The MacFarlane Peak Group has a distinct high magnetic response facilitating its subsurface interpretation over a wide area.

Tanami Group rocks overly the MacFarlane Peak Group on an inferred disconformity. The sedimentary evolution of the Tanami Group involves rapid transgression and deep marine sediment-starved deposition, consistent with a passive margin setting. This is followed by rapid and widespread turbidite deposition due to uplift during the onset of orogeny. The basal Tanami Group is a thin (100-400m?) metaquartzite consisting of laminated quartz-arenite and vein quartz that is intensely deformed. The presence of deformed pegmatite, granite and abundant vein quartz is consistent with this unit being entirely tectonic in origin.

Structurally overlying this quartzite is the Dead Bullock Formation (DBF), which comprises siltstone, graphitic shale, iron-rich beds, and silicified and nodular chert. Metamorphic grade varies from greenschist to amphibolite facies. The highest metamorphic grade is in the southeast where biotite-sillimanite-garnet pelitic gneiss was partially melted during deformation. The DBF includes a chemically reactive package which readily reduces oxidised fluids and hosts gold mineralisation (Wygralak and Mernagh 2001). Magnetically responsive mafic sills intrude the Dead Bullock Formation. The largest of these, the Coora Dolerite, has peperite margins and is therefore interpreted to be basalt intruded into wet sediment (J Claoué-Long *pers com*). The contact between Dead Bullock Formation and overlying Killi Killi Formation may represent a hiatus.

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The Killi Killi Formation is a thick (2-4 km?) monotonous package of interbedded sandstone and siltstone, deposited in a turbiditic marine environment. Mafic sills intrude the unit in the western part of the Tanami region. Metamorphic grade, as in Dead Bullock Formation, varies from greenschist to amphibolite facies. A number of widespread samples have remarkably consistent detrital ages of 1840 Ma (**Table 1**).

Location	Grid refer	ence (AMG)	Age
Maverick area	507450e	7790645n	$1840 \pm 14 \text{ Ma}$
Southwest of Jims Pit	560827e	7767424n	1844 ± 11 Ma
Titania	600798e	7756267n	$1840 \pm 18$ Ma
Dead Bullock Soak	598000e	7730000n	$1840 \pm 10$ Ma

	Table 1.	Killi Killi	Formation y	oungest det	trital zircon a	ages. Grid o	co-ordinates	GDA94.	Zone 52 K.
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The end of Killi Killi sedimentation is marked by the onset of the Tanami Orogenic Event (TOE) (Vandenberg *et al* 2001). The TOE overlaps temporally with the Halls Creek Orogeny (1835 Ma, Blake *et al* 2000) and with deformation in the Tennant Inlier.

The period immediately following the TOE is characterised by crustal extension. This resulted in felsic volcanism and high-level intrusion of Winnecke Group granite to the north, and deposition of an unnamed sedimentary package to the south. These unnamed sedimentary rocks are non-magnetic in outcrop, but overlie highly magnetic rocks, which suggests they differ from the remaining, widespread non-magnetic Killi Killi Formation. The Winnecke Group and sedimentary rocks of equivalent age experienced two deformation event (one folding and one crenulation) after the Tanami Orogenic Event.

The Mount Charles Formation consists of basalt and turbiditic volcaniclastics, and minor arkose and tuffaceous siltstone. We infer it to have been deposited in a failed rift environment after folding events that affected the Winnecke Group. Deformation in the Mount Charles Formation consists of shallow-level brittle faulting and fault-propagated folding, indicating that it at least overlies Winnecke Group rocks. Contact metamorphism of, and intrusion of aplite dyke into the Mount Charles Formation indicate that it predates some felsic magmatism. The youngest granite intrusion in the region is 1790 Ma and therefore, we could safely consider this to be the minimum age for the Mount Charles Formation. An immature arkose contains predominantly Archaean zircons; some poorly constrained analyses indicate a maximum depositional age of 1860-1900 Ma.

The period 1815-1790 Ma is characterised by widespread intrusion of granite, which locally forms contact metamorphic aureoles. Granites are mostly I-type and are similar in character to Halls Creek Orogen granites (Dean 2001). Trace element tectonic discrimination plots reveal some disparity between the suites (**Figures 2a**, **b**). Most granite suites have volcanic arc/syn-collisional geochemical affinities. The exception is the Winnecke Granodiorite, which has a within-plate character, consistent with our interpretation that it intruded into attenuating continental crust. The volcanic arc/syn-collisional signature of the remaining suites reflects a deeper crustal source, which may have been produced by subduction processes. Alternatively, this signature may reflect melting of the lower crust through overthickening in a post-collisional setting, 10-45 Ma after the TOE, or may be syn-collisional to as yet unrecognised events. The 1844  $\pm$  3 Ma Inspiration Peak Granodiorite (nearest sample to the Dead Bullock Soak goldfield), like the remaining Frederick Suite granites, has a volcanic arc granite affinity. (intraplate?)

The latest granites intruded by 1790 Ma. Structural and geochemical relationships indicate that the granites played no genetic role in the formation of gold deposits.

The Pargee Sandstone unconformably overlies the Killi Killi Formation. It consists of conglomerate and arenite and occupies a sub-basin adjacent to a major structure (Bluebush Fault). The unit was previously considered to be a molasse deposited during the Tanami Orogenic Event. However, detrital zircon has yielded a maximum age of  $1770 \pm 14$  Ma and this association is therefore precluded. The Pargee Sandstone is considered to have been deposited during fault reactivation after the Tanami Event.

The following period represents a time of significant peneplanation before deposition of widespread siliciclastic platform sediments of the Birrindudu Group.

### **EXTENT OF TANAMI REGION**

Although this study has concentrated on the TANAMI and THE GRANITES, the Tanami region is more extensive (**Figure 3**). The northern and western margins are covered by shallow-dipping sandstone of the Neoproterozoic Redcliff Pound Group or the Mesoproterozoic Birrindudu Group. Regional magnetic data allow extrapolation of Tanami rocks under non-magnetic cover to the Eastern Lamboo Complex of the Halls Creek area.

The southern and eastern margins are more ambiguous. Dead Bullock Formation rocks have been mapped to 5 km east of Thomsons Rockhole on MOUNT SOLITAIRE. Greenschist facies interbedded sandstone and siltstone outcrops are interspersed throughout the sand plain further east. Similar schistose rocks are observed on MOUNT PEAKE and BARROW CREEK. Our work indicates that these outcrops are equivalent to the Killi Killi Formation and therefore, the southeastern extent of the Tanami region remains unconstrained. The Surprise Igneous province (informal name) is a northwest trending belt of deformed granitoids to the east of Thomsons Rockhole. These intrude rocks of the Tanami Group and are bounded to the east by the edge of the Wiso Basin.

The southern margin to the Tanami Region can be defined by an increase in metamorphic grade. Amphibolite facies pelite south of Fiddler Lake and high-T, low-P transitional granulite pelite of the Highland Rock Metamorphic Complex (HRMC) indicate a progressive increase in grade to the south (Vandenberg *et al* 2001a). Tanami ages have been found in the HRMC, as it has a protolith age of 1820 Ma. The HRMC is not considered to be part of the Tamani region, which we define as low-grade (amphibolite facies or lower) orogenic rocks.

Detailed mapping of ore bodies indicate that young structures host gold mineralistion (Vandenberg 2001b). This finding is supported by Ar/Ar dating that has yielded a 1670-1720 Ma age for mineralisation at Dead Bullock Soak (Wygralak *et al* 2001). Younger metamorphism to the south (HRMC) is poorly understood, but early indications are that it may have played a significant role in ore genesis, by generating late structures or metalliferous fluids, or both.

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Figure 1. Tectonostratigraphy of the Tanami Region.

Figure 2 Trace element tectonic discrimination plots for 1815-1790 Ma granites.





**Figure 3**. Regional extent of the Tanami Region geology. "North Arunta" has incorporated the HRMC and Billabong Complex purely for illustrative purposes. 1:250 000 mapsheet outlines shown in black.

## 1:500 000-SCALE INTEGRATED MAPPED AND INTERPRETED GEOLOGY OF THE TENNANT INLIER

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One focus of the 1999-2003 NT Government-funded Exploration Initiative is the Tennant-Tanami link project. The Tennant Inlier and the Tanami region are two of the three major (Palaeoproterozoic) goldfields of the Northern Territory, the other being the Pine Creek Orogen. The principal objective of this project is to provide a framework to investigate relationships between the Tennant Inlier and the eastern part of the north Arunta province, where geological mapping and geophysical interpretation are currently underway. This work is complemented by an ongoing investigation of the relationships between the Tanami region and western part of the north Arunta Province. Results of work in the Tanami region were presented at AGES 2000 and 2001, and are further reported here at AGES 2002, together with initial findings of investigations in the western north Arunta province.

Prior to the inception of the Exploration Initiative, geological mapping over the outcropping Tennant Inlier was essentially complete. High quality, semi-regional airborne magnetic (and radiometric) data were collected over TENNANT CREEK by AGSO (now Geoscience Australia) in 1998. Aeromagnetic and radiometric coverage was extended over BONNEY WELL, FREW RIVER and ELKEDRA by NTGS in 1999 as part of the current program. These data have been stitched with those of a 1981 survey over BARROW CREEK and a 1993 survey of HELEN SPRINGS to complete geophysical coverage of the Tennant Inlier.

An interpretation of airborne magnetic data and 11 km-spaced BMR gravity data has been integrated with the mapped geology, and a generalised 1:500 000 scale outcrop geology map has been compiled as an initial step in the synthesis of mapped and interpreted geology.

In the Tennant Inlier, bedrock interpretation commenced in TENNANT CREEK and was presented by Johnstone at AGES 2001. This work has now been extended over four additional 1:250 000 sheets and aspects of the initial TENNANT CREEK interpretation have been revisited in the regional context.

The lithostratigraphy of the Tennant Inlier is presented in the newly compiled outcrop geology map. Uniform or similar colours have been chosen for correlated formalised lithostratigraphic units throughout the map area. This is the first step in a rationalisation of the current plethora of stratigraphic names.

The Flynn Subgroup has been abandoned and its constituent formations combined with those of the former Ooradidgee Subgroup to form the Ooradidgee Group. This reflects the overall lithostratigraphic similarities between these two previous subgroups. It is also consistent with a lithostratigraphic and structural distinction between the former Ooradidgee Subgroup and the Wauchope and Hanlon Subgroups of the Hatches Creek Group. The latter two subgroups constitute the revised Hatches Creek Group. The name Tomkinson Creek Group has similarly been abandoned and its constituent formations assimilated by the Hatches Creek Group.

To the southwest of the Davenport Ranges, there is a wide zone dominated by granite and associated metasedimentary rocks, eg Bullion Schist and Lander Rock beds. Stratigraphic and structural evidence suggests that the Bullion Schist is a lateral, probably more distal, equivalent of the Ooradidgee Group and that it is similarly a correlative of the Lander Rock beds on MOUNT PEAKE. Geophysical data are consistent with this interpretation. However, lateral facies variations, and a progressive change in metamorphic grade from sub-greenschist to lowermost greenschist to upper amphibolite facies complicate a determination of the precise details.

Geological coherence between the Tennant Inlier and north Arunta province during both Ooradidgee and Hatches Creek Group times is highly probable. The Ledan Schist (in BARROW CREEK and ALCOOTA) has been correlated with the Lower Wauchope Subgroup; and the Utopia Quartzite (in ALCOOTA) and Coulters Sandstone of the Upper Wauchope Subgroup are similarly correlated. It is anticipated that these relationships will be more precisely demonstrated in the magnetic data as interpretation continues. The solid geology map shows that the gold-mineralised Warramunga Formation is associated with a localised west-northwest trending dome. The unconformably overlying volcanisedimentary Ooradidgee Group surrounds this dome and extends throughout a broad northwest trending zone. In the north of TENNANT CREEK, the unconformably overlying Hatches Creek Group conceals the Ooradidgee Group. To the south, the Ooradidgee Group is widespread in outcrop to the northeast of the Davenport Ranges. It is also exposed in the cores of domes throughout the Davenport Fold Belt.

The Hatches Creek Group is well preserved and classically deformed in northwest trending domes and basins of the Davenport Fold Belt. Isolated remnants of unequivocal Hatches Creek Group rocks in the Crawford and Taylor Ranges indicate that this unit extends to the southwest. A correlation with the Reynolds Range Group (in NAPPERBY) is geologically plausible although it is currently hard to trace direct continuity in the magnetic data.

The magnetic Kudinga Basalt provides a good marker horizon within the Hatches Creek Group. This indicates that the group extends under the Georgina Basin to the southeast of the Tennant Inlier. The Kudinga Basalt is also well expressed in magnetic images to the northwest of the Davenport Fold Belt and under the Wiso Basin on SOUTH LAKE WOODS, well beyond the limits of the present map. Magnetic data will probably ultimately demonstrate direct continuity between the Kudinga Basalt and the Whittington Range Volcanic Member, a correlation originally proposed by Blake (1984).

Conformable strongly magnetic horizons within the Hayward Creek Formation do not appear to have any direct parallels in the correlative Unimbra and Yeeradgi Sandstones. It is probable that these represent intrusive sills localised around a feeder system for the Whittington Range Volcanic Member. It is noted that they are spatially associated with a strong magnetic and gravity feature in the northwest of TENNANT CREEK.

Intense magnetic character is evident in Ooradidgee Group rocks in the Kurinelli area to the northeast of the Davenport Ranges. This is associated with the mafic Edmirringee Volcanics and intrusive dolerites. The magnetic expression of the latter suggests that they consist of folded, stratiform sheets. There is a close spatial association with a strong magnetic and gravity feature and this might represent the locus of mafic magmatism during Ooradidgee times. Blake et al (1987, figure 16) showed five mafic eruptive centres in this area of the Davenport province that are associated with Ooradidgee Group rocks. Although relatively localised in outcrop extent, mafic magmatism was probably widespread at this time. Intrusive dolerites in the Crawford Ranges, amphibolites in the Bullion Schist and Lander Rock beds, and possibly also mafic rocks in the Waldron's Hill area on LANDER RIVER might all relate to this episode of mafic magmatism.

Blake et al (1987, figure 16) showed a large number of felsic eruptive centres in the Davenport province that were associated with both dacitic and rhyolitic lava and ignimbrite during both Ooradidgee and Hatches Creek Group times. Of those associated with the Ooradidgee Group, Blake et al recognised that the Treasure Volcanics include mafic lava, and that possible mafic lava also erupted contemporaneously with the Epenarra Volcanics.

The intense magnetic and gravity features mentioned above are proximal to a northwest trending fault which can be traced for 350 km across the map. The distribution of mafic and felsic volcanic centres identified by Blake et al (1987) indicate that northeast trending faults may also play a role in their distribution.

Comparison between outcropping geology and airborne magnetic data shows that in addition to the mafic volcanics many of the predominantly felsic volcanic units are magnetic. Furthermore, there is good contrast between magnetic volcanic units and interlayered magnetically quiet sandstones. Consequently, it is possible to extrapolate mapped, outcropping stratigraphy beneath covering rocks. It is noteworthy that at depth, under Palaeozoic Georgina Basin sedimentary rocks in central southern ELKEDRA, prominent folds in the Hatches Creek Group trend to the northeast. This is at right angles to the predominantly northwesterly trend in outcrop in the Davenport and Murchison Ranges. A similar northeasterly trend occurs in southwestern TENNANT CREEK, southeastern BONNEY WELL and southwestern FREW RIVER.

Three major phases of granite magmatism have been recognised in the Tennant Inlier by Wyborn et al (1998). These are the 1850 Ma Tennant Creek Supersuite, the 1820 Ma Treasure Suite, and the

1710 Ma Devils Suite. Geophysical data appear to readily distinguish between Tennant Creek Supersuite and Treasure Suite granites on the one hand, and Devils Suite granites on the other. The former has significant magnetic character, apparently due to rafts of non-assimilated country rock. In some instances, the folded character of the country rock can be inferred as ghosts in the granite. In contrast, Devils Suite granites form discrete, sub-circular non-magnetic features associated with marked gravity lows.

Non-outcropping and/or undated granites are more difficult to assign to either the Tennant Creek Supersuite or the Treasure Suite. However, the relationship between the granites and the surrounding magnetic stratigraphy can help. Tennant Creek Supersuite granites appear to be localised in the vicinity of TENNANT CREEK, northeastern BONNEY WELL and northwestern FREW RIVER. Thus, the oldest granites are approximately confined to the regional outcrop extent of the Warramunga Formation and the similarly aged Junalki Formation. Wyborn et al (1998) pointed out that there is a significant density contrast between granites of the Treasure Suite and Tennant Creek Supersuite. Modelling may therefore help refine interpretation of the granites and the distribution of individual suites.

Granites that are penecontemporaneous with those of the Treasure Suite have previously been mapped as the Barrow Creek and Ali Curung complexes in BARROW CREEK. These granites may be compared with a texturally variable spectrum of megacrystic and equigranular, undated but syn-tectonic granites in MOUNT PEAKE. Some of these granites are associated with sub-circular, non-magnetic, gravity lows in western BARROW CREEK. They therefore appear to be comparable with Devils Suite granites, but have 1805 Ma ages. Stratigraphic relationships interpreted from magnetic data indicate that other granite plutons showing similar geophysical character in both BARROW CREEK and MOUNT PEAKE can be satisfactorily interpreted as having probable Devils Suite affinities.

Blake and Page (1988) interpreted the Hatches Creek Group (including what is here referred to as Ooradidgee Group) to have been deposited in an intra-continental rift-sag basin. It is hypothesised that the Warramunga Formation may be associated with a localised pull-apart basin that marks the inception of rifting. The age equivalent volcanisedimentary Junalki Formation accumulated in a contiguous extensional basin that reached from northwestern FREW RIVER across northeastern BONNEY WELL to southwestern TENNANT CREEK. The Warramunga Formation basin or sub-basin deformed contemporaneously with ongoing extension in the surrounding rift, where the volcanisedimentary Ooradidgee Group accumulated. Localisation of gold mineralisation, predominantly in the Warramunga Formation, may in part be a consequence of strain partitioning. Thus, Tennant Creek Supersuite granites may have influenced the response of the Warramunga Formation to the 1805 Ma Murchison Orogeny, which folded the Ooradidgee Group.

In conclusion, the mapped outcropping geology of the Tennant Inlier can be extrapolated under cover using airborne magnetic data. These data indicate that there is continuity between the Ooradidgee and Hatches Creek Groups and rocks of the north Arunta province on BARROW CREEK, LANDER RIVER, MOUNT PEAKE and probably both ALCOOTA and NAPPERBY. Furthermore, the Tennant Creek goldfield emerges as the locus of the oldest, but nonetheless integral, exposed geology in the area.

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## A NEW GEOLOGICAL FRAMEWORK FOR THE SOUTHERN ARUNTA PROVINCE

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A second year of NTGS mapping in the western southern Arunta province (SAP) has built on and further developed ideas presented at AGES 2001 that were based on fieldwork on MOUNT LIEBIG in 2000. In 2001, mapping at varying levels of detail was extended across the entire region (MOUNT LIEBIG, MOUNT RENNIE, LAKE MACKAY). In conjunction with geophysical interpretation, targeted geochronology and geochemistry of igneous rocks, this work forms the basis of the new framework presented below.

A major development has been the recognition that the western SAP consists of two terrains with contrasting protolith ages. These two terrains extend east-west across the northern half of MOUNT LIEBIG and MOUNT RENNIE, with a strong regional gravity contrast marking their boundary. LAKE MACKAY forms the southwestern part of the northern Arunta province and is described by Scrimgeour *et al* (this volume). The 'Haasts Bluff Terrain' (HBT) forms the more southerly and older terrain of the SAP. To its north is the 'Yaya Terrain' (YT), which forms the boundary with the northern Arunta province (North Australian Craton). Both terrains consist of metamorphic complexes that represent discrete cycles of deposition and subsequent metamorphism and deformation. The distribution of the terrains and their constituent elements is shown in **Figure 1**. **Table 1** provides a summary of the stratigraphy and chronology of the region.

The eastern HBT forms the westerly extension of the Madderns Yard and Iwuputaka Metamorphic Complexes, which characterise the SAP in the east (HERMANNSBURG and ALICE SPRINGS). These complexes extend into MOUNT LIEBIG and together form the *Glen Helen domain*. The remaining central and western parts of the HBT comprise the *Kuta Kuta domain*. This domain subdivision is largely based on a sharp contrast in metamorphic grade and on the absence of the Iwupataka Metamorphic Complex in the Kuta Kuta Domain.

In the *Glen Helen domain*, the upper amphibolite facies Glen Helen Metamorphics (Madderns Yard Metamorphic Complex) comprises the oldest suite of rocks and consists of dominantly migmatitic orthogneiss, and minor amphibolite and metapelite-psammite successions. The orthogneiss has yielded SHRIMP U-Pb zircon ages of 1690-1660 Ma. On HERMANNSBURG, a small calc-silicate-hosted base metal prospect at Stokes Yard occurs in this unit. These rocks are overlain by the 1640-1600 Ma Ikuntji Metamorphics (Iwupataka Metamorphic Complex). The *Kuta Kuta domain* consists of 1690-1660 Ma granites, the 1679 Ma Peculiar Volcanic Complex, and biotite-muscovite schist, psammite and calc-silicate of the Lizard schist and Rennie schist.

The Yaya Terrain (YT) is newly recognised and comprises the 1660-1640 Ma Yaya Metamorphic Complex (YMC). The YMC consists of granulite facies metasedimentary packages, dominated by pelites and psammites, that locally grade into more heterogeneous successions of calc-silicates, cordierite pelites, quartzite and mafic granulite. Detrital zircon populations from metasediments indicate a maximum depositional age of  $1661 \pm 10$  Ma. The spread of detrital zircon ages in the range 1700-1660 Ma for the YMC suggest that the predominant source is the HBT. A small Cu prospect is associated with garnet-bearing pegmatite within granulite facies pelite of the YMC at Mt Larrie. Voluminous granite, charnockite and gabbro intruded the YMC at 1640–1630 Ma. The *Dufaur domain* forms the northwest sector of the YT and is composed of greenschist facies interbedded pelite and psammite that are intruded by mafic rocks of the 1635 Ma Andrew Young Complex and by undated biotite granite. The relationship between the low-grade *Dufaur domain* and the YMC remains unclear.

In the far west of the region and underlying the Heavitree Quartzite of the Amadeus Basin are the bimodal Walungurru volcanics. These are of undetermined age, but are interpreted to be either equivalents of the 1640 Ma Pollock Hills Volcanics in WA, or equivalents of 1080 Ma bimodal volcanics of the Tjauwata Group on the northern edge of the Musgrave Block in the NT and WA.

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A major newly recognised tectonothermal event, the Liebig Event, affected the SAP at 1640-1630 Ma. This event effected both the YT and HBT to varying extents. The Yaya Metamorphic Complex was metamorphosed to pervasive high T - high P granulite facies. In the HBT, the *Glen Helen domain* was metamorphosed to upper amphibolite facies, whilst the *Kuta Kuta domain* showed a sharp drop to greenschist facies. The contrast between the HBT and the Yaya Metamorphic Complex indicates that the two terrains resided at significantly different crustal levels at this time, the younger Yaya Metamorphic Complex being considerably more deeply buried. The short time interval between deposition (1660 Ma) and deep burial (1640 Ma) of the Yaya Metamorphic Complex suggests an active tectonic setting for the Liebig Event.

Immediately after the Liebig Event, the *Glen Helen domain* was exhumed and psammite, pelite and an upper quartzite (Chewings Quartzite) of the Ikuntji Metamorphics were deposited on amphibolite facies Glen Helen Metamorphics. The Ikuntji metamorphics have a maximum depositional age of 1638 Ma. An extensive quartzite unit in the *Kuta Kuta domain*, the Putardi Quartzite, may be equivalent to the Chewings Quartzite. Several small Pb-Zn-Cu deposits are hosted in massive tremolite schist and marble of the Ikuntji metamorphics near Haasts Bluff.

This study has provided the first well constrained age of  $1589 \pm 4$  Ma for the Chewings Orogeny, which was recognised by earlier workers in the eastern SAP (see review in Collins and Shaw 1995). In the western SAP, this event resulted in amphibolite facies reworking of all terrains, with a pervasive non-coaxial strain fabric. To date, it has not been recognised in the *Dufaur domain*.

Rare kinematic indicators in the *Kuta Kuta domain* point to south-directed deformation during the Chewings Orogeny, in contrast to north-directed movement as documented by Tessyier *et al* (1988) in the eastern SAP. The ubiquitous amphibolite facies grade and tectonic style of the Chewings Orogeny suggests that it represents the assembly of terrains of the western SAP to the same crustal level and into their current configuration.

Evidence for including greenschist facies pelites and psammites of the *Dufaur domain* within the SAP is equivocal and it is possible that this area forms part of the older NAC. In the eastern SAP on HERMANNSBURG, the Redbank Thrust Zone forms a well defined boundary between the SAP and NAC. However, this boundary is not exposed and is poorly defined by geophysics in the western SAP. There are two possibilities for the age and significance of the *Dufaur domain*. It may be a lower grade equivalent of the Yaya Metamorphic Complex, in which case the NAC/SAP boundary is defined by a geophysical discontinuity that extends across southern MOUNT DOREEN and LAKE MACKAY. Recent geochronology from LAKE MACKAY (Scrimgeour *et al* this volume) confirms that the region immediately to the north of this discontinuity belongs to the NAC. Alternatively, the *Dufaur domain* represents older sediments of the >1820 Ma Lander package of Pietsch (2001) that were intruded by the 1635 Ma Andrew Young Igneous Complex during the Liebig Event. Geochronology of sediments of the Dufaur domain is pending and should resolve its relationship to the YT.

Geophysical interpretation of MOUNT LIEBIG and MOUNT RENNIE shows that the SAP in this area is strongly dissected by predominantly east-west trending structures. These are mostly attributed to the 400-300 Ma Alice Springs Orogeny. Geophysical interpretation, in conjunction with mapping of the basal units of the Amadeus Basin, show this intraplate event to involve only minor shortening at lower greenschist facies conditions in this part of the SAP. A collaborative Ar-Ar study of the Alice Springs Orogeny in the western SAP is currently underway with Jim Dunlap (ANU) and Sandra MacLaren (University of Melbourne).

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<b>Figure 1.</b> Ocological ciclicities of the Southern Afunda Flowing	<b>Figure</b>	1.	Geo	logical	elements	of the	Southern	Arunta	Province
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Event Age Interval	YAYA	FERRAIN	HAASTS BLUFF TERRAIN		
	Yaya Metamorphic Complex	?Dufaur domain	Glen Helen domain	Kuta Kuta domain	
Alice Springs Orogeny 400-300 Ma	Greenschist facies shear zones, south-directed	Greenschist facies shear zones, south-directed	Greenschist facies shear zones, south-directed	Greenschist facies shear zones, south-directed	
Chewings Orogeny 1590 Ma	Upper Amphibolite facies non-coaxial strain	?	Upper Amphibolite facies non-coaxial strain	Upper Amphibolite facies non- coaxial strain	
1640–1600 Ma			Iwupataka Metamorphic Complex Deposition of Ikuntji metamorphics: muscovite- biotite schists, calc-silicate, quartzite (Chewings)	Deposition of Putardi Quartzite?	
Liebig Event 640-1630 Ma	High T high P granulite facies. Intrusion of gabbro, charnockite, granite	? Greenschist facies, localised contact metm. to granulite facies. Intrusion of Andrew Young Igneous Complex.	upper Amphibolite facies migmatisation	Greenschist facies	
1660-1640 Ma	Yaya Metamorphic Complex Deposition of pelite, psammite, mafics, calc- silicate	? Deposition of interlayered psammite and pelite.			
1690-1660 Ma			Madderns Yard Metamorphic Complex Deposition of Glen Helen Metamorphics-granite intrusion, minor psammite and pelite, minor mafic intrusion. Possible felsic volcanism.	Granite intrusion. Deposition of Peculiar Volcanic Complex: flow-banded felsic volcanics, minor tuffs and chemical sediments, subvolcanic intrusives. Deposition of Lizard and Rennie schist: biotite schist, minor psammite, quartzite, calc-silicate	

**Table 1.** Tectonostratigraphic events of the western Southern Arunta Province

## TIMING OF REGIONAL TECTONISM AND Au-MINERALISATION IN THE TANAMI REGION: <sup>40</sup>Ar/<sup>39</sup>Ar GEOCHRONOLOGICAL CONSTRAINTS

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Existing age constraints for geological events in the Tanami Region come predominantly from U-Pb geochronology of i) detrital zircons in sediments, and ii) magmatic zircons in granitoids. These dates have been used, together with observed and inferred geological relationships, to help constrain the timing of stratigraphy, magmatism, deformation, metamorphism and Au-mineralisation (Vandenberg *et al* 2001). Ongoing GA/NTGS zircon geochronology is continuing to refine our understanding of the stratigraphy and magmatic history of the Tanami, with attendant implications for tectonic evolution. In this regard, it is noteworthy that detrital zircon ages of 1815 Ma from the Killi Killi formation require a revision of the existing stratigraphy and/or that the so-called Tanami Orogenic Event significantly post-dates 1815 Ma, in contrast to previous estimates of 1845–1830 Ma. However, detrital and magmatic zircons can provide no direct constraints on the timing of deformation, metamorphism and Aumineralisation, and consequently our current understanding of these processes in the Tanami region is relatively poor, despite being critical to predictive exploration models.

New ages from <sup>40</sup>Ar/<sup>39</sup>Ar geochronology are presented here. These results complement existing U-Pb zircon isotopic constraints from intrusive rocks and detrital zircons in sediments. In general, argon retention is more sensitive to thermal disturbance than Pb in zircons; consequently the <sup>40</sup>Ar/<sup>39</sup>Ar results provide timing information regarding regional cooling and the final hydrothermal activity in mineralised zones.

The samples fall broadly into two categories:

- 1) Micas from Au-bearing veins at the Callie mine.
- 2) Micas and feldspars from regional Tanami granitoids.

## **RESULTS FROM CALLIE**

Gold mineralisation at Callie is hosted in east-northeasterly striking dilational quartz veins, and is concentrated where these veins intersect  $F_1$  fold hinges (Vandenberg *et al* 2001). Gold-bearing quartz veins contain clots and trails of randomly oriented, relatively coarse biotite. Four examples of vein-hosted biotite have been separated from surrounding biotite-bearing foliated metasediments, and analysed by the <sup>40</sup>Ar/<sup>39</sup>Ar step-heating method. Two of these yield "plateau" ages of 1710 Ma and the other two give "plateau" ages of 1735 Ma. At this stage, the significance of the difference in ages between these two pairs of samples is unclear. However, the important first order observation is that vein biotites yield <sup>40</sup>Ar/<sup>39</sup>Ar ages demonstrably younger than both U-Pb zircon and <sup>40</sup>Ar/<sup>39</sup>Ar mica ages from any known Tanami granites (see below). These data therefore strongly suggest that at least some of the hydrothermal activity responsible for vein generation postdates intrusion of the youngest known Tanami granites (1795 Ma, Dean 2001) by several tens of million years. These results are also consistent with structural relationships suggesting that Au-mineralisation occurred late in the deformation history of the region (Vandenberg *et al* 2001).

The host metasedimentary sequence at Callie is crosscut by biotite-rich lamprophyric dykes, which are cut by quartz veins that have a similar orientation and character to auriferous quartz veins. Biotite from one of these dykes yields an  $^{40}$ Ar/ $^{39}$ Ar age of 1760 Ma. If this age is the time of dyke intrusion, as would be consistent with generally older regional cooling ages (reported below), the age of quartz veins must postdate 1760 Ma, consistent with vein-biotite ages of 1710 Ma and 1735 Ma.

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### **RESULTS FROM REGIONAL GRANITOIDS**

Biotite and/or K-feldspar was separated from five drillcore samples of Tanami granitoids, including the Coomarie and Frankenia granitic domes, as well as other smaller intrusive bodies not spatially associated with any known gold mineralisation. Argon geochronological results from these samples provide new constraints on the regional thermal history of the Tanami Block, as well as aiding in the interpretation of the results from Callie discussed above. Biotite ages from these regional granitoids are in the range 1755-1820 Ma. These ages are best interpreted as representing the time of final cooling through a temperature of between 300°C and 350°C - the "closure temperature" for Ar diffusion in biotite. As expected, these ages are slightly younger than U-Pb zircon ages from Tanami granitoids, but are significantly older than the ages reported above for biotite from Au-bearing veins at Callie. It would therefore appear that ambient temperatures in the Tanami Block dropped below 300°C prior to 1750 Ma, strengthening the interpretation that ages from Callie vein-biotite approximate the time of subsequent hydrothermal activity.

K-feldspars from regional granites yield stair-shaped age spectra preserving age gradients from 1700 Ma to as young as 1350 Ma. The younger ages preserved in K-feldspar reflect the lower Ar closure temperature relative to biotite. The large age gradients can be interpreted either as very slow cooling (<1°C/Ma) through the temperature interval 280–130°C, or as a product of partial thermal resetting and/or recrystallisation of feldspar during the Mesoproterozoic. Any such subsequent thermal events were clearly not sufficiently intense to pervasively reset biotite or the more retentive parts of K-feldspar crystals and must therefore have been of relatively low temperature (<250°C).

In contrast to biotite ages from granites distal to known hydrothermal systems, muscovite from the Bunkers Granite, which was collected within a few metres of the fault-related ore-zone at The Granites gold deposit, preserves an  $^{40}$ Ar/ $^{39}$ Ar age of 1710 Ma. The age is indistinguishable from vein-biotite ages from Callie, and may represent further evidence of localised hydrothermal activity at 1710 Ma that is unrelated to any known local magmatism.

## SUMMARY

Argon geochronology from a range of samples reveals significant new details regarding the thermal history and likely timing of hydrothermal activity in the Tanami region. Of most potential interest to the mineral exploration industry, the data appear to require that at least some of the hydrothermal activity found in Au-deposits is as young as 1710 Ma and is therefore unrelated to any known magmatic activity, which ceased at 1795 Ma. In addition, the results from K-feldspars provide initial indications of the Mesoproterozoic thermal history of the region, hitherto essentially unknown.

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## **BYNOE TANTALITE**

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## **INTRODUCTION**

This ongoing project is part of a wider review of the rare element potential of the Northern Territory. Its specific aim is to better understand the mineralogy, chemistry and structure of rare-element pegmatites hosting Sn-Ta mineralisation in the Bynoe region on the Cox Peninsular to the south of Darwin with the ultimate objectives of determining their economic potential and assisting in their exploration.

## **REGIONAL GEOLOGY**

Tantalite in the Bynoe region occurs in granitic pegmatites of the rare-element class. Pegmatites occur in swarms within a 15 km wide belt that extends NNE-SSW from Kings Table on Darwin Harbour to Bamboo Creek and Labelle in the south, a distance of 60 km. They are found in weakly defined clusters centred on Observation Hill, Leviathan, Annie River and Walkers Creek. Pegmatites at Mount Finniss and Labelle are the exception and appear to be almost solitary bodies. The pegmatites occur in the Burrell Creek Formation, a suite of fine to medium quartz-lithic sandstone, siltstone and interbedded carbonaceous shale. This flysch-like package was regionally metamorphosed to biotite-andalusite grade during the Barramundi Orogeny (1870-1855 Ma). The S-type Two Sisters Granite (1850-1800 Ma), which intrudes the Burrell Creek metasediments, is generally considered to be the likely parent granitoid for the pegmatites (Ahmad 1995).

Tertiary processes have leached and intensely weathered the pegmatites to depths in excess of 20 m. The decomposed nature of the pegmatites provided easy exploitation by tin miners at the turn of last century but has hindered an understanding of their petrology, chemistry and morphology.

## MINING AND EXPLORATION HISTORY

Tin mining commenced in the belt in 1886 following the discovery of tin at Leviathan Creek (Summers 1957). Between 1886 and 1910, numerous small diggings, worked by European and Chinese miners, were centred on Leviathan, Annie, Observation Hill, Bamboo Creek and Bells Mona. This early phase of mining was abondoned in 1910. Between 1925 and 1957, mining occurred at Mount Finniss and Walkers Creek. Mount Finniss continued with interrupted production to about 1988. The Hang Gong pegmatite was reworked for a short period between 1981 and 1982. Between 1980 and 1989, several attempts were made to sustain small mining operations in the Annie River district and plants were established on the Saffums 1 and Bilatos pegmatites. A crushing circuit was not included in the operation and recovered grades were below expectation. J Walton discovered the Labelle pegmatite in the far southwest of the belt in 1984.

In 1968, Goldrim Mining carried out the first regional exploration program for tin. The potential for a sizeable Sn-Ta resource was recognised, but no further exploration was undertaken. In 1979, Greenbushes Tin Ltd began assessing the alluvial and soft rock Sn-Ta potential of the belt. In 1982, they formed the Bynoe Joint Venture (BJV) with Barbara Mining Corporation of Germany. The BJV was active in the Observation Hill and Leviathan areas between 1982 and 1994, mapping individual pegmatites, costeaning and auger drilling. A permanent base camp with a trial concentration plant was established in 1983 at Observation Hill. In 1988, they concluded a feasibility study and announced a combined alluvial-pegmatite resource to 20 m depth of approximately 3 Mt at a recovered grade of 159 g/t SnO<sub>2</sub> and 49 g/t Ta<sub>2</sub>O<sub>5</sub>. A crusher was not incorporated in the plant and the BJV operators estimated that approximately 50% of the heavy minerals were lost in processing. At the then Sn-Ta price, mining of the pegmatites was considered to be uneconomic.

In 2001, Julia Corporation Ltd (JCL) entered into an agreement with Corporate Development Pty Ltd to explore the Leviathan and Labelle prospects. Extensive costeaning and RC drilling to a depth of 50 m of these prospects has increased their prospectivity.

## **PEGMATITE MORPHOLOGY**

Pegmatites in the belt vary in size from a few tens of metres long and a few metres wide to hundreds of metres long and tens of metres wide. They typically pinch and swell, and diverge and coalesce so that their dimensions are irregular. Overall, their shape is tabular or pod-like and their orientation is steeply dipping to sub-horizontal.

Mount Finniss and Hang Gong are the two largest mined pegmatites. Mount Finniss was reported to have dimensions of  $300 \times 50$  m, and Hang Gong  $390 \times 60$  m. Surface measurements have proved to be deceptive. Closely spaced costeaning during the recent JCL phase of exploration has indicated that three pegmatites in the Leviathan group that were previously considered to be separate (Northern Reward, Mackas Reward and Welcome Surprise) are a single body. Separately, each was reported to be <300 m long and <18 m wide but as a single body, the pegmatite has dimensions of 850 x 50 m.

## **RELATION TO REGIONAL STRUCTURE**

At Bynoe the regional bedding  $(S_0)$  trends NNE-SSW and dips sub-vertically to the east or west. A penetrative foliation in fine metasediments is axial planar to very tight, moderately steeply dipping mesoscopic folds in  $S_0$ . Both  $S_0$  and  $S_1$  are folded in moderately tight, steeply dipping  $F_2$  folds that have an associated, spaced fracture cleavage or crenulation cleavage  $(S_2)$ .

The pegmatites have previously been reported as being dykes and sills that are broadly conformable to foliation (Pietsch and Clayton 1990). Mapping of larger pits in the Observation Hill area does not support this. Although their regional strike is generally NNE-SSW, in the same trend as the enveloping boundaries of the belt, and approximates the local  $S_1$  foliation, their dips are rarely conformable to  $S_1$ . Careful examination indicates that pegmatites at Observation Hill transgress bedding,  $S_1$  and  $S_2$ .

## PETROLOGY OF PEGMATITES AND BORDERING COUNTRY ROCK

A fluid inclusion and oxygen isotope study of pegmatite by Ahmad (1995) suggested an emplacement temperature of about 300°C from a post-orogenic magmatic source. Chilled borders and cockscomb mineral textures, which are oriented perpendicular to pegmatite walls and grade internally to granular textures, are evidence of inward cooling from pegmatite margins. Although quartz core zones have been reported, they are rare and are confined to wider swollen sections of pegmatites. Field investigations indicate that a number of reported quartz "cores" are post-pegmatite quartz veins.

The bulk mineralogy of unweathered pegmatite consists of microcline, perthite, K-feldspar, albite, muscovite and quartz. Minor components include cassiterite, tantalite-columbite, amblygonite, magnetite, zircon, ilmenite, garnet and tourmaline (Pietsch and Clayton 1990, Ahmad 1995). In outcrop, primary mineralogy is preserved only in quartz-rich samples that either consist solely of quartz and muscovite, or consist of feldspar that is protected from decomposition by quartz-mica shielding. Feldspar is otherwise reduced to kaolin.

Although the pegmatites are zoned in their mineralogy, intense weathering hinders examination. While the Mount Finniss mine was operating, Summers (1957) had the opportunity to examine and report on zoning within that body. He described five zones, although zones 1 and 2 are distinguished on textural grounds. Adapting Summer's description to a mineral-based classification, four mineral zones can be recognised:

1. A wall zone of quartz and muscovite. This consists of a narrow (typically 1-3 mm wide), fine granular border that passes inward to increasingly large laths of muscovite and long prisms of quartz arranged perpendicular to the wall in cockscomb habit. The contact with the inner cockscomb-

textured assemblage is sharp, initially with small (<1 mm), preferentially-oriented crystals that increase in size to grains over 6 cm within 20 mm of the border;

- 2. An outer intermediate zone of fine quartz, mica and feldspar (replaced by kaolin), which has a typically granitic texture;
- 3. An inner intermediate zone of dominant feldspar (kaolinised) and only minor quartz; and
- 4. A core zone of massive quartz.

Summers could not be precise as to the dominant site of cassiterite-tantalite mineralisation in the Mount Finniss pegmatite and it was concluded to be sporadic throughout all zones.

There is the likely possibility that mineral and chemical zoning is overprinted and disrupted by postmagmatic gas-charged fluids enriched in alkali elements,  $SiO_2$  and rare lithophile metals. A preliminary study of thin and polished sections of mineralised pegmatite indicate the presence of two cassiterite populations, a coarse-grained and fractured phase and a finer-grained phase that occurs in recrystallised stringers of fine quartz and muscovite.

The most obvious alteration in the adjacent country rock is tourmalinisation. This grades from pervasive tourmaline replacement of country rock selvage to tourmaline and muscovite that forms in veins and joints as far as several metres from the pegmatite. Tourmaline and tabular grains of diaspore to 4 mm in length that occur perpendicular to the contact are considered to be evidence of escape of volatiles fluids from the pegmatite at the time of emplacement. Andalusite porphyroblasts, the product of earlier regional metamorphism in the belt, are replaced by sericite marginal to the pegmatites (Ahmad, 1995).

## **PEGMATITE INTERNAL CHEMISTRY**

Recent RC drilling of the Labelle pegmatite by JCL has provided an opportunity to investigate majorand trace-element distribution within a pegmatite body. The Labelle pegmatite is approximately 15 m wide in the discovery pit and exposes a lenticular quartz core and a quartz-muscovite wall zone. The intermediate zone is totally kaolinised. One RC drillhole that was sited approximately 150 m south of the discovery site was examined in detail. Drilling exposed a muscovite-quartz border that graded into a narrow quartz-muscovite wall zone. Although a quartz-rich core was not intersected, a narrow, coarse muscovite-rich zone was encountered in the centre of the pegmatite and probably represented the lateral extremity of the quartz core exposed in the discovery pit. The chemistry of the intermediate zone was unexpected, for whereas the outer section returned high K<sub>2</sub>O levels that indicate a dominant K-feldspar or microcline mineralogy, the inner intermediate zone is Na<sub>2</sub>O dominant and reveals an albiteprominant mineralogy.

Furthermore, in contrast to the normal zoning exhibited by rare-element pegmatites, in which the lithophile trace elements (Ta, Sn, Nb, Y, Hf, La, Cs) and  $P_2O_5$  are concentrated towards the inner intermediate zone (Cerny 1989, 1993), in the Labelle pegmatite, these elements are concentrated in the wall zone. This same phenomenon, as indicated in Sn-Ta abundance, is commonly repeated in other pegmatites in the belt.

The concentration of Sn-Ta at the margin of the Bynoe pegmatites tends to be the rule rather than the exception. A minority of pegmatites display an irregular distribution of metals, whereas some have been described as having uniformly low or high levels across their entire width. There is a suggestion that uniformly high levels are more sustainable in east-west trending pegmatite segments.

## **REGIONAL TRENDS IN PEGMATITE CHEMISTRY**

Over 200 samples have been collected from 42 pegmatites in the Observation Hill, Annie River and Leviathan districts. A relatively high correlation exists between Ta and the elements Sn, Nb, Cs, and Rb but there is a surprisingly poor correlation for Ta and Sn with other lithophile elements such as Be, Li, Ga La, Y, Zr and Hf. The mineralogy and trace element chemistry of the Bynoe pegmatites places them in the Complex Pegmatite Type. However, on the edges of the sampled belt, there is an indication of variance towards the Albite-Spodumene Type (high Nb/Ta ratio) and in the Bells Mona district, they are of Beryl Type (low Sn and Cs, high Nb/Ta and high K/Cs).

A spatial plot of data indicates significant enrichment of tungsten in the south relative to its abundance in the north of the belt. Other refractory elements display local concentrations that appear to indicate a north-south variance (boundaries trend east-west) that may reflect the proximity of possible underlying granite cupolas, or the intensity of late east-west structures in the belt, or both. Post-F<sub>3</sub> faults have recently been recognised in the Rum Jungle area (J Lally, NTGS, pers com).

#### **RESOURCE POTENTIAL**

Recent RC drilling to 50 m depth at Leviathan by JCL has upgraded that resource and assisted in estimating a potential total resource for the Bynoe district. It is currently estimated that the Observation Hill, Leviathan and Annie River districts (65 pegmatites) have a pegmatite resource to 50 m depth of approximately 7.1 Mt grading 113 g/t Ta<sub>2</sub>O<sub>5</sub> and 320 g/t Sn<sub>2</sub>O. A further 300 000 tonnes grading approximately 70 g/t Ta<sub>2</sub>O<sub>5</sub> and 320 g/t Sn<sub>2</sub>O is thought to be present at Mount Finniss and a similar tonnage at 130 g/t Ta<sub>2</sub>O<sub>5</sub> and 160 g/t Sn<sub>2</sub>O at Labelle. BJV in 1988 estimated that the Observation Hill area contained a conservative 1.3 Mt of alluvial ore of 40 g/t Ta<sub>2</sub>O<sub>5</sub> and 200 g/t Sn<sub>2</sub>O recovered grade (Observation Hill trial concentration plant).

### CONCLUSIONS

Tantalum in the Bynoe area is associated with granitic pegmatites of the Complex Lithium-Caesium-Tantalum (LCT) Type. Unlike classic pegmatites of this type, they display variable zoning in their chemistry and mineralogy. The unusual alkali-element zoning of the Labelle pegmatite and an accompanying enrichment of lithophile elements at the margins requires further investigation. Ideally, the complex pegmatite grades from Na-feldspar + quartz at the margins through increasingly Kfeldspar-enriched, feldspar + quartz assemblages into massive K-feldspar and eventually into a quartzmica-feldspar, lithium-enriched mineral assemblage, the product of a gas-charged residual melt. The final phase should be saturated in SiO<sub>2</sub> and residual alkali elements should enter a final, fine albitemica-quartz assemblage. The underlying process is controlled by supersaturation of feldspars and quartz, caused by increasing concentrations of H<sub>2</sub>O, Li, B, F and P in the melt.

The mineralogy of the pegmatite/wall rock contact zone of the Bynoe pegmatites is unusual and may hold a clue to explaining the unusual internal mineral zoning. Whereas tourmaline is a common accessory mineral of rare-element pegmatites, it is uncommon in the Bynoe pegmatites. Tourmaline is confined almost totally to the contact zone of the country rock either as pervasive replacement or as veins up to several metres from the pegmatite. A possible explanation for the unusual zoning is that the melt degassed into country rock soon after emplacement, producing premature supersaturation at the margins and causing incompatible lithophile elements to be dumped in the wall zone of the pegmatite. It has been shown experimentally that the presence of B and F depresses albite activity and expands the liquidus field of K-feldspar in pegmatitic melts (Cerny 1993). A high activity of B and F at the time of emplacement may have subdued Na-feldspar crystallisation (absence of Na<sub>2</sub>O in the wall zone of the Labelle pegmatite) in favour of K-feldspar and this may have been sustained while P<sub>B</sub> and P<sub>F</sub> remained high. With the premature release of internal over-pressures caused by the escape of a gas-charged phase, the activity of Na-feldspar in the melt would be increased leaving residual K<sup>+</sup> to be taken up in the final hydrous mica-quartz phase of crystallisation. Mineral textures of the intermediate zone are obviously critical in helping to explain the chemical and mineral zonation, but suitable unweathered samples are not available at present.

The regional north-south zoning is interesting. M Ahmad (NTGS, pers com) suggested that the gradation from high to low tungsten from south to north might indicate a more proximal granite source in the south, possibly where it is more deeply exhumed. The suggestion of regional rare-element clusters requires further investigation and is somewhat hindered by element mobility in the weathered profile.

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## DIAMOND EXPLORATION IN THE NORTHERN TERRITORY

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The Northern Territory is presently receiving intense interest from three major global diamond players (Rio Tinto, BHP Billiton, De Beers) and four active juniors (Elkedra, Tawana, Astro, Flinders). Together, these diamond explorers account for nearly half of the Exploration Licence applications and grants in the Territory (about 390 000 km<sup>2</sup>).

Diamond exploration in the Northern Territory goes back to the mid 1970s when Stockdale (De Beers), ADEJV (Ashton) and CRAE (now Rio Tinto) first undertook reconnaissance stream-sediment sampling across much of northern Australia. These early surveys were based on conventional stream sampling programs for diamond and selected indicator minerals, using reconnaissance sample densities of one sample per  $>100 \text{ km}^2$ , and follow up densities of no more than 30 per 100 km<sup>2</sup>. The approach was mostly empirical, and based on southern African models, and on the newly discovered Argyle deposit in the Halls Creek Orogen. Such exploration techniques focussed on the coarse fraction (>0.5 mm) in well defined drainage trails and used classical indicators with little regard to tectonic setting. However, the 1179 Ma age for the Argyle lamproite and its location within the Halls Creek Orogen (Boxer and Jaques 1990) may well have influenced some exploration strategies to focus on Proterozoic mobile belts.

These early programs found the Timber Creek and Packsaddle dykes (Stockdale), Emu pipes (CRAE) and the Coanjula 'bodies' (Ashton). Kimberlite occurrences seem to define a broad arc along the southern exposed margin of the McArthur Basin, where it is onlapped by intracratonic Palaeozoic and Mesozoic basins. The kimberlites demonstrate a high-level fracture control, generally have signatures of Cr-spinel and pyrope indicators, and have ample microdiamonds. However, all occurrences are small in size and macrodiamonds are sparse.

Perhaps the most astonishing thing to come out of these early surveys and the follow-up work, is the emergence of a great swathe of microdiamonds that extends right across the heart of the cratonic Northern Territory. This swathe envelopes known kimberlite occurrences, but extends well beyond them. There are literally thousands of microdiamond occurrences within this region. Individual grain shapes are mainly octahedra and dodecahedra, but there are some twins and irregular grains, and some curious frosted spongy cubes. There has been some discussion within the industry on the significance of this swathe, including suggestions that microdiamonds were recycled through the Cretaceous and have been redistributed more widely by fluvial and aeolian processes.

The only published synopsis of the distribution of microdiamonds is that of Smith *et al* (1990) which is heavily influence by the strange Coanjula occurrence. It should be possible to more precisely define the swathe and even contour the density and tenor of microdiamond occurrences. NTGS will shortly commence this task. At present, it seems that it has a regional geological control, and that it extends equally over well-drained and non-drained regions. It is therefore geologically controlled and not an artifact of Cenozoic geological history. Moreover, there does appear to be a strong correlation between microdiamonds and macrodiamonds in the known kimberlite occurrences. It therefore represents a prime exploration area.

Although some major companies seemed disillusioned by the small size of known kimberlites and the dearth of macrodiamonds, Australian Diamond Exploration NL (an associate of Ashton) pursued leads provided by microdiamond and chromite indicators into areas of poorly defined drainage. This resulted in the discovery of the Merlin crater-phase pipe field, only 10 km to the south of the Emu pipes.

The Merlin discovery was due to the persistent follow-up of reported occurrences of just 16 chromite grains and one microdiamond (pulled from NTGS open-file databases) by using high-density loam and stream sampling (Reddicliffe 1999). This led to the first macrodiamond. After repeated RAB drilling of thin but geochemically opaque lateritised Cretaceous cover, the first of 14 diamondiferous kimberlite pipes was found. Merlin has produced over 270 000 carats since commencement of mining operations in December 1999. Its gem-quality resource is around 2.9 Mt at 0.23 ct/t.

The lessons of the Merlin field are salutary and numerous:

- there is a correlation between microdiamond and macrodiamond tenor;
- the deposit lies on a tableland with ill-defined drainage;
- the pipes are small at the surface, but occur in clusters that merge at depth;
- the kimberlite is 340 My old (Lee 1997), and is therefore younger than the host Cambrian sandstone and older than the Cretaceous cover;
- the Cambrian host acts to preserve the crater facies;
- Cretaceous strata cap the kimberlite pipes, even when it is largely exhumed and this inhibits the ability of the pipes to shed indicators;
- the kimberlite has no anomalous magnetic or gravity signature (but does have an EM expression); and
- the pipe field relates to fractures in a cratonic environment, not to a mobile belt.

These features have drawn todays diamond explorers away from mobile belts and into the heart of the North Australian Craton (NAC) with its challenges of ill-defined drainages, and lateritic weathering. In the vanguard are the junior explorers. This new wave of explorers is chasing subtle indicator minerals including the microdiamond swathe, but is also employing geologically-based area-selection concepts. The recent availability of high-resolution aeromagnetic, gravity, crustal temperature and teleseismic geophysical datasets allows favourable tectonic areas to be identified over much of the North Australian Craton. Deep lithospheric roots below 'old and cold' crustal nuclei may extend into the elevated diamond stability field, which may be tapped by much younger kimberlite and related diatremes (Taylor *et al* 2000).

There is geophysical and geochronological evidence that much of the NAC is underlain by Archaean basement, or by basement reworked prior to the Barramundi Orogeny. Cratonic nuclei may be quite prevalent in the craton, but are obscured by the effusive Antrim Basalt.

The recently listed **Elkedra Diamonds NL** has 49 000 km<sup>2</sup> under EL grant or application in the southern Georgina Basin, covering the Altjawarra nucleus within the cratonic basement (Myers *et al* 1996). This may be a classic Archaean nucleus that contains a deep cold sub-lithospheric root, and as such is considered to be highly prospective for diamond-bearing kimberlite. Previous sampling by CRAE and Stockdale recovered many microdiamonds and at least one macrodiamond from this area.

High-resolution aeromagnetics flown for NTGS under the NT Government's Exploration Initiative show great details of the internal and marginal features of identifiable basement blocks. They also identify a number of pinpoint dipolar anomalies, which may be kimberlites. At least one of these pinpoint anomalies has a coincident microdiamond occurrence in the soil. These techniques, together with high-density loam and termite-mound sampling, are new tools in defining drilling targets for diamond exploration in these areas

**Tawana Resources NL** have an entitlement to earn 60% interest in Timber Creek kimberlites, held by De Beers. These small, diamond-bearing dykes were discovered by Stockdale (De Beers) in 1991. One dyke (TC-01) contains small coloured diamonds at a grade of around 1 ct/t. They were emplaced at the surprisingly young time of 179 Ma into the Bullita Group (Belousova *et al* 2001), which forms a McArthur Basin-style Proterozoic platform cover, of age 1600–1200 Ma, on the NAC. During the 2002 dry season, Tawana plans to test a 10 000 tonne bulk sample from the TC-01 diamondiferous kimberlite and also intends to undertake additional tests on alluvial diamond deposits in the nearby Whirlwind Plains. The presence of these deposits has been known for some time, but their source is unknown. In addition, Tawana has secured an area-of-influence agreement with BHP Minerals in the surrounding area, with the hope of utilising a Falcon airborne gradiometer to assist in exploration.

Flinders Diamonds NL has successfully floated on prospects that include the Strangways project to the north of Alice Springs. This is located on the intersection of the G2 and G3 gravity corridors and is

within the reworked southern margin of the NAC. Indicator minerals (including a microdiamond) have been recorded in this area.

Astro Mining has made EL applications over 18 000 km<sup>2</sup> in the eastern part of the microdiamond belt in the Calvert Hills east of Merlin, in the extension of the Halls Creek Orogen into the NT and in the center of the NAC around Barrow Creek.

Of the major explorers, **Rio Tinto** has extensive applications and grants over the McArthur, Wiso and Georgina Basins that include exploration areas and a database acquired from Ashton. The company has commenced a program of tenement reduction, so as to focus on the region around Merlin and the Yambarra project in the Fitzmaurice Shear Zone, which is the extension of a tectonic zone that hosts the Argyle deposit in Western Australia. Due to long-standing Native Title access problems (now slowly being resolved), this prime area, which has excellent drainage traps, has never been sampled for diamonds.

**BHP Minerals** has made 79 EL applications that cover 50 000 km<sup>2</sup> in the Wiso Basin, in advance of the release of high-resolution aeromagnetic data by NTGS. The Wiso Basin must be regarded as one of the least explored sedimentary basins in Australia and has a basement that can be interpreted in detail using aeromagnetics.

In addition to substantial holdings in the Victoria Basin, **De Beers** has extensive applications along the suture zone on the northern margin of the Arunta province against the intact NAC basement, where it is buried by the southern part of the Wiso Basin.

Altogether, there is nearly 400 000 km<sup>2</sup> of the Northern Territory under EL grant or application. As much of this area is not yet granted, only low-levels of grass-roots activity are presently taking place. In 1996, the Northern Territory Government ceased granting ELs over Pastoral Leases due to Native Title issues. However, as a result of the new expedited process under the Native Title Act 1996, ministerial grants are now beginning to flow and serious exploration activity is about to commence.

Since 1980, some \$108 M has been spent on diamond exploration in the Northern Territory, but the current levels are low - about \$4.2 M in 2001. These levels are expected to rise dramatically in 2002. Redicliffe (1999) recorded that ADEJV spent \$25 M in 15 years prior to the Merlin discovery. Globally, the odds are stacked against a significant discovery. Of 7000 known world kimberlites, 700 are significantly diamondiferous, and only 70 are economically viable.

However, the prognosis for the Northern Territory must be considered high by world standards, because:

- the microdiamond swathe must have prospectivity significance;
- Archaean basement under the NAC must be extensive;
- the NAC deep lithosphere is demonstrably fertile for diamonds;
- Palaeozoic cover offers protection and preservation for kimberlite pipes;
- Cr-spinels and microdiamonds are robust in the weathering environment; and
- there is extensive coverage of high-resolution airborne geophysical surveys.

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### **GRANITE PETROGENESIS IN THE NORTHERN ARUNTA PROVINCE**

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The northern Arunta province<sup>1</sup> is the confluence of three well understood regions in the Proterozoic North Australian Craton: the Tanami region to the northwest, the Tennant Inlier to the southeast and the central Arunta province to the south. A relatively comprehensive geological understanding of these three surrounding regions has been driven by the presence of economic gold mineralisation and relatively good basement exposure. On the other hand, the northern Arunta has average basement outcrop of <10% and economic mineralisation has *yet* to be discovered. Hence, geological interpretation and mineral exploration in this region has relied heavily on regional datasets, particularly aeromagnetics, gravity and published geological maps. Due to the large extent of the northern Arunta province, its proximity to known mineral deposits and its limited coverage by modern exploration methods there is a significant possibility that economic mineral deposits are hidden beneath the veneer of recent cover. With this in mind, the Tennant-Tanami Link project was initiated by NTGS to assist mineral exploration by providing a better geological framework of the northern Arunta. The project involves generation and interpretation of geological, geophysical, geochemical and geochronological data in order to unravel the basement configuration and reconcile stratigraphic differences with surrounding areas.

Granite constitutes a significant portion of the North Australian Craton and has been interpreted from aeromagnetic and gravity data to form much of the basement in the northern Arunta (Ahmad 2002). Thus, an understanding of northern Arunta granites is fundamental to resolving the local geological framework. In particular, it is critical to determine: 1) whether northern Arunta granites represent discrete igneous events; 2) if they are similar to granites in adjacent regions; and 3) whether certain granite compositions are related to mineralising systems. Moreover, an understanding of local granite petrogenesis will help constrain the regional geological history and tectonic setting of the northern Arunta and its surroundings. Whole-rock elemental abundances of 93 northern Arunta granite samples are presented and discussed here. Fifteen granite samples have also been submitted for SHRIMP zircon U-Pb age determination and some preliminary results are presented.

Northern Arunta granites typically outcrop as low whalebacks or clusters of very large boulders. They have broad textural variation and are variably deformed. In general, the exposed granites are strongly foliated, coarse-grained and have large euhedral feldspar megacrysts. Most of the exposed northern Arunta granites contain enclaves, xenoliths and biotite schlieren; these indicate that they incorporated crustal material during crustal fusion, or by assimilation of countryrock during magma migration, or both. Geological relationships with adjacent volcanosedimentary successions are rarely exposed, although some regional relationships can be inferred using geophysical data. Two examples should be noted. First, 17 km to the north of Mount Solitaire (AMG 727000, 7747100), well foliated coarse porphyritic granite intrudes strongly folded psammopelites of the Lander Rock beds. In pelites adjacent to this granite, a thin (<50 m) thermal aureole has formed, which contains andalusite developed parallel to S<sub>2</sub> fold axes. This suggests that the granite intruded during deformation. Second, in the DeBavay Hills area (AMG 707200, 7717700), geophysical interpretation indicates that the magnetic Dead Bullock Formation is cut by a low density, nonmagnetic body which can be equated with nearby massive coarse granite. Thus, the granite probably intrudes the Dead Bullock Formation, although the contact is not exposed.

Preliminary results from the earliest magmatic phase of the Figtree granite (40 km east of Mount Solitaire) indicate a crystallisation age of  $1812 \pm 7$  Ma. This granite is similar to that which clearly intrudes the Lander Rock beds (see above), and thus 1812 Ma may be an approximate age for many of the syntectonic northern Arunta granites. This age is within error of the Bean Tree granite (1803 ± 6 Ma) and Ooralingie granite (1809 ± 5 Ma), which are 250 km to the southeast of the Figtree

<sup>&</sup>lt;sup>1</sup> 1:250 000-scale map sheets: MOUNT SOLITAIRE, LANDER RIVER, HIGHLAND ROCKS, MOUNT THEO, MOUNT PEAKE.

granite, but in the same broad granite-dominated structural domain immediately to the south of the Wiso Basin (Ahmad 2002). Furthermore, felsic volcaniclastic units to the north of the Bean Tree granite may correlate with extensive, but poorly exposed, weakly deformed felsic lithologies 15 km to the northeast of Mount Solitaire. This correlation fits the preliminary geological data and suggests that there is extensive lateral continuity of Davenport stratigraphy. There are also 1812 Ma granites in the Tanami region, including the Inningarra granite, which is adjacent to The Granites goldmines, and the goldbearing Winnecke granophyre. Similarly aged granites have also been reported in the central Arunta province (Haverson suite; Zhao and McCulloch 1995). Importantly, granites from the Arunta province, Tennant Inlier and Tanami region have abundant inherited zircons, some with Archaean ages, although exposed Archaean basement is limited to quartzofeldspathic orthogneisses in the Billabong Complex and Browns Range Dome.

Northern Arunta granites have quite restricted major element abundances (eg  $SiO_2 = 65-75\%$ ,  $Na_2O = 2-3\%$ ,  $K_2O = 3.5-6\%$ ) and define typical partial melt-fractional crystallisation trends on Harker diagrams. The granites are slightly to moderately peraluminous I-types (ASI = 1.0-1.3; normative corundum), and are generally classified as monzogranite to granodiorite on quartz-alkali feldsparplagioclase diagrams, and as granite to granodiorite on normative feldspar ternary diagrams. Interpretation of trace element compositions is complicated due to the affects of accessory mineral fractionation. However, trends can be discerned for some critical trace elements. Primitive-mantlenormalised diagrams fail to distinguish between individual plutons among the northern Arunta granites, because the composition of the primitive mantle is far removed from that of granite and subtle compositional variations are readily masked. Such normalisation fails to discriminate between many northern Australian Proterozoic granites, with most having a "Barramundi signature"; that is, an overall negative slope and large negative Ba, Nb, Sr-P and Ti anomalies (Wyborn et al 1987). Nevertheless, the widespread presence of granite with Barramundi signatures does indicate remarkable gross compositional uniformity of the North Australian granites and perhaps reflects their formation by a single petrogenetic processes. Normalisation using an average composition of the upper crust provides a more relevant reference from which to discriminate between granites (see Sylvester, 1994). A number of distinct types are revealed within the northern Arunta granites using this method, although the significance of such divisions has yet to be determined. It is anticipated that by applying this approach to granites in adjacent areas, subtle regional variations may be revealed. Such an outcome would have important implications for defining tectonic models and understanding mineralising systems in the North Australian Craton.

Fusion of quartzofeldspathic basement, perhaps analogous to Billabong orthogneiss, appears to adequately explain the genesis of northern Arunta granites. The widespread presence of enclaves, biotite schlieren and inherited zircons clearly indicates significant involvement of pre-existing crust during granite formation. Restricted silica contents of the granites probably reflect near minimum melt compositions and less evolved compositions were probably formed by greater degrees of partial melting or incorporation of restitic material. The relatively low aluminium saturation of the granites indicates that source rocks were never weathered. Fractionation trends for Ba, Zr, P<sub>2</sub>O<sub>5</sub>, Ce and Y are similar to those defined for low-temperature I-type granites, which are interpreted to form by crustal fusion (Chappell *et al* 1998). Sm-Nd isotopic compositions of granites from the Tennant Inlier (unpublished data) and the central Arunta province (Zhao and McCulloch 1995) also indicate significant involvement of older crustal material. If this model is correct, then inferred tectonic processes which resulted in crustal melting need to be evaluated within a North Australian context.

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## EVENT CHRONOLOGY AND PROSPECTIVITY OF THE MAFIC MAGMATIC SYSTEMS IN THE ARUNTA PROVINCE

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As part of the National Geoscience Agreement with the Northern Territory Geological Survey (NTGS), Geoscience Australia is evaluating mafic-ultramafic intrusions in the Arunta province of central Australia. The major aims of this regional study are to constrain the various mafic-ultramafic magmatic systems within the event chronology of the Arunta, and to provide a geoscientific framework for assessing the resource potential of the intrusions. Sixteen bodies were sampled from a 90 000 km<sup>2</sup> area (**Figure 1**). SHRIMP U-Pb zircon ages were obtained for thirteen bodies by targeting fractionated mafic rocks with relatively high abundances of Zr (80-220 ppm). Our 100% success rate in finding large quantities of zircon in samples targeted by field and chemical criteria opens the way to dating mafic magmatism more routinely elsewhere.

The Arunta province is a geologist's dream for examining mafic-ultramafic intrusions, for they are generally well exposed, and differential movements along province-wide fault systems have exposed representatives from different crustal depths. The Arunta intrusions have historically been regarded as having low potential for mineralisation because of their high metamorphic grades and protracted tectonothermal histories spanning more than 1500 million years. Intermittent phases of company exploration during the last three decades have been restricted to a few intrusions (eg Mordor) and university studies (Bonnay *et al* 2000) have generally focussed on structural-metamorphic aspects of granulite bodies (Mount Hay Granulite). This is in contrast to other Proterozoic provinces (Musgrave Block, Halls Creek Orogen, Albany-Fraser Orogen), where more extensive investigations have defined a range of orthomagmatic and hydrothermal PGE, Cr, Ni, Cu, Co, Ti, V and Au deposits that are associated with mafic-ultramafic intrusions (Hoatson and Blake 2000). The recent resurgence in exploration in these provinces has generated new interest in the economic potential of the Arunta intrusions.



Figure 1. Mafic-ultramafic intrusions investigated in the Arunta Province

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## MAFIC EVENT CHRONOLOGY AND PRELIMINARY GEOCHEMICAL CHARACTERISTICS

The new U-Pb geochronology highlights distinctly episodic emplacement of Proterozoic maficultramafic systems in the Arunta. Ages summarised in **Table 1** draw on the following major constraints:

## North Arunta intrusions (north of Redbank Thrust Zone)

- 1. Valuable crosscutting relations between different intrusions are exposed where the Johannsen Metagabbro is intruded by the Harry Anorthositic Gabbro, which locally interfingers with an unnamed tonalite body (Hoatson and Stewart 2001); these are in turn cut by a NNE-trending dolerite dyke. The igneous units record a progression of crystallisation ages at 1805 Ma, 1785 Ma, and 1690 Ma and zircons within the older bodies record metamorphism synchronous with the younger intrusions; all are consistent with the relative timing evident in outcrop.
- 2. The Mount Hay and Enbra Hills mafic granulite bodies lack relative timing constraints in the field, but their zircons have complex internal zoning patterns that record 1805-1810 Ma primary ages and subsequent event histories similar to the Johannsen Metagabbro.
- 3. The 1780 Ma primary ages of the geographically dispersed Mount Chapple Metamorphics, Attutra Metagabbro and tonalite bodies (see point 1) are broadly synchronous with the first metamorphic event recorded in older mafic granulites (Enbra Granulite, Johannsen Metagabbro, Mount Hay Granulite).
- 4. Of particular significance is the youngest event in the granulite rocks which records previously unrecognised metamorphism in the central Arunta at 1690 Ma, together with intrusion of the dolerite dyke (see point 1), indicating an extensional regime at that time. This age correlates within the established Proterozoic event chronologies of the Mt Isa and Broken Hill regions.

## South Arunta intrusions (south of the Redbank Thrust Zone)

5. Zircons from the Andrew Young Hills, Papunya gabbro, and Papunya ultramafic bodies in the southern Arunta indicate a single magmatic event at 1635 Ma and no evidence of zircon inheritance or metamorphic recrystallisation. The South Papunya gabbro has an interpreted primary age at 1635 Ma and inherited zircons in the range 1670-1700 Ma. The distinctive age chronology of all these units is clearly different to older magmatic systems of the north Arunta and indicates that the northern boundary of the south Arunta probably passes north of the Andrew Young Hills intrusion.

## Mordor Igneous Complex

6. Zircons from a plagioclase pyroxenite plug in the Mordor Igneous Complex have a simple crystallisation age of  $1131.8 \pm 4.5$  Ma, which is consistent with, but more precise than published Rb-Sr and Sm-Nd isochron ages (Nelson *et al* 1989).

## Riddock Amphibolite

7. A garnet-bearing para-amphibolite from within the Riddock Amphibolite contains metamorphic zircons formed at  $461 \pm 6$  Ma that preserve zircon cores with a range of Neoproterozoic ages as young as  $734 \pm 44$  Ma. It is interpreted that the sample is a metasediment deposited with orthoamphibolite units at or after  $734 \pm 44$  Ma that was subsequently metamorphosed at  $461 \pm 6$  Ma, during the Larapinta Event.

Table 1. Event chronology of Arunta mafic-ultramafic magmatic systems

<b>MAGMATIC</b> <b>EVENTS</b> (Ma) <sup>1</sup>	I (1810)	II (1780)	III (1690)	IV (1635)	V (1130)	VI (735-460)
Riddock Amphibolite						$734 \pm 44$ to $461 \pm 6$
Mordor Igneous Complex					$1131.8 \pm 4$	.5
SOUTH ARUNTA INTRUSIONS	5					
Andrew Young Hills				$1632.9 \pm 2.0$	.8	
South Papunya gabbro				$1634.6 \pm 4.6$	.8	
Papunya gabbro				$1636.5 \pm 2.$	.4	
Papunya ultramafic				$1639.2 \pm 2.$	.0	
MUTUALLY CROSS-CUTTING	INTRUSION	s				
Dolerite dyke (cutting Johannsen M	. and Tonalite)	~	1686 ± 8			
Tonalite (cutting Johannsen M.)	,	$1785.6\pm3.5$	$1683 \pm 20$	)		
NORTH ARUNTA INTRUSIONS	5					
Mount Chapple Met.		$1774.0 \pm 1.9$	complex	history		
Attutra Metagabbro		$1786.4\pm4.2$	1	5		
Mount Hay Granulite	$1805.4 \pm 3.4$	$1777.5 \pm 3.1$	$1693 \pm 20$	)		
Johannsen M.	$1805.6 \pm 3.2$	$1783.8\pm1.9$	$1697\pm7$			
Enbra Granulite	$1812.4 \pm 2.4$	$1786.6 \pm 3.9$	$1685 \pm 11$	1		

<sup>1</sup>Events I to VI do not represent a sequential sequence that operated for *all parts* of the Arunta Province. Zircons were dated by SHRIMP II in Canberra using cathodoluminescence imaging to target probe sites within the complex internal zoning patterns that were often found. Ages are quoted at 95% confidence; most have precision better than  $\pm$  5 Ma. Primary crystallisation ages are in bold type; 'metamorphic' ages are in normal type. M. = Metagabbro; Met. = Metamorphics.

Chondrite-normalised multi-element patterns of rocks with melt-like compositions assist in refining the correlations of mafic magmatic systems indicated by the geochronological framework. The 1810 Ma Mount Hay and Enbra Hills bodies are compositionally the same, but are distinct from the coeval Johannsen Metagabbro, which at comparable degrees of fractionation (8% MgO content), has lower abundances of TiO2 (0.8%), Zr (42 ppm) and Y (22 ppm). This suggests that magma generation for the Johannsen Metagabbro was by larger degrees of mantle melting, if the low Zr/Sm values (~18) are not related to clinopyroxene accumulation. The estimated parent magma composition of the 1785 Ma Mount Chapple Metamorphics has chemical affinity with the Attutra Metagabbro, except for higher (La/Sm)N values (2.5 versus 1.8) and lower Zr/Sm values (23 versus 30). Together, they have considerably lower Nb/Th and Nb/Ba values than those of the Mount Stafford dolerite and Kanandra Granulite. The south Arunta intrusions have a large range of (La/Sm)N values (1.8-3.5), requiring progressive crustal contamination and crystal accumulation to explain the different ratios of La/Sm, Nb/La and Zr/Sm. The Andrew Young Hills intrusion is one of the most contaminated mafic bodies investigated in the Arunta.

## **ECONOMIC POTENTIAL**

Hoatson (2001) has used incompatible-element discrimination diagrams (**Figure 2**) to show that the Arunta intrusions fall into two major geochemical groups that highlight geographical differences in mineral prospectivity:

(1) A S-rich group (300-1200 ppm S) in the geographical western and central Arunta has some potential for orthomagmatic Ni-Cu-Co sulfide associations. The identification of favourable mineralised environments, such as feeder conduits or depressions within the basal contacts of large prospective contaminated bodies, such as Andrew Young Hills, Mount Chapple, and Mount Hay, will be achieved through airborne electromagnetic/gravity and remote-sensing techniques in association with diamond drilling and petrological information.
(2) A relatively S-poor (<300 ppm S), slightly more primitive group in the eastern Arunta has greater potential for orthomagmatic PGE-sulfide associations. Of this group, the Riddock Amphibolite (igneous units) and Attutra Metagabbro appear to have the most favourable low S concentrations for PGE mineralisation.

Both groups have potential for hydrothermal polymetallic deposits of Cu-Au±PGEs±Ag±Pb, spatially associated with the intrusions. The absence of thick sequences of primitive ultramafic rocks throughout the Arunta downgrades the potential for PGE-chromite associations. The absence of these economically important rocks is a feature of the Arunta that contrasts with other mineralised Proterozoic provinces (Musgrave Block, East Kimberleys).



**Figure 2.** Logarithmic plot of whole-rock S and Zr concentrations for Arunta mafic and ultramafic rocks. Fields for mineralised west Pilbara layered intrusions are also shown.

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## **OONAGALABI-TYPE BASE METAL MINERALISATION IN THE ARUNTA PROVINCE**

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The Arunta Province hosts several enigmatic small- to medium-sized base metal prospects, located mainly in the Strangways Metamorphic Complex (SMC). Although these deposits have been known since the 1950s, no economically viable deposit has been defined, with the largest, Oonagalabi, having an inferred resource of 25 Mt grading 0.5% Cu and 1% Zn (Close 1979). Although these deposits typically grade less than 3% combined Cu, Zn and Pb, higher grade intersections to 10% combined are known. The origin of these deposits, which were termed Oonagalabi-type by Warren *et al* (1974), is not clear and different models, including volcanic-hosted massive sulfide and Broken Hill-type, have been proposed by previous workers. This enigma is principally due to the influence of high-grade regional metamorphism and intense deformation. The aims of this joint NTGS-GA project are to better understand the nature and genesis of Oonagalabi-type prospects. Key aspects include detailed mapping and sampling of selected prospects to understand the stratigraphic/structural framework of the prospects and their host rocks, as well as documenting the geochemistry and petrology of the alteration zones. This project will also concentrate on determining the timing of mineralisation as well as the age of the host rocks.

Oonagalabi-type deposits predominantly occur in granulite facies rocks of the SMC or its reworked equivalents and are complicated by overprinting structures and a complex polymetamorphic history. Several small prospects with similar characteristics occur in rocks that are interpreted to be lower grade lithostratigraphic correlatives of the SMC. The SMC is interpreted to be a package of sedimentary and probable bimodal volcanic (or intrusive?) rocks that is overlain by a more carbonate-dominated siliciclastic/carbonate package. Possible correlation of the latter with the Reynolds Range Group in the north Arunta province suggests that an unconformity may be present within the SMC. Most Oonagalabi-type prospects occur in the older package. The majority of the SMC was probably deposited between 1820 Ma and 1780 Ma, although some parts may be older (1850-1835 Ma?). These rocks were then metamorphosed to granulite facies conditions during the 1780-1720 Ma Strangways Orogeny.

Detailed mapping and sampling of selected prospects (Edwards Creek, Harry Creek, Johannsens Phlogopite mine and Oonagalabi) commenced in 2001 and work on other prospects and regional alteration zones will commence this field season. Warren *et al* (1974) and Stewart and Warren (1977) recognised that the Oonagalabi-type was characterised by an assemblage of three mineralised rock types: (1) forsterite marble, accompanied by calcium minerals such as diopside; (2) Mg- and Al-rich rocks, usually characterised by anthophyllite, gedrite, cummingtonite, Mg-Al spinel, enstatite, and sapphirine; and (3) quartz-magnetite rock, which occurs everywhere except for Oonagalabi itself. The most extensive development of these assemblages is at Oonagalabi.

The unusual mineralogy and chemistry of these rocks clearly indicates that they are almost certainly metamorphosed hydrothermally altered rocks with protolith compositions such as quartz-chlorite. Phlogopite is also present in these rocks and indicates that not all are depleted in K. The type and amount of amphibole varies between, and within individual prospects, probably indicating variations in the initial protolith composition or metamorphic conditions or both. The amphibole occurs: (1) as essentially monomineralic zones of gedrite? (Edwards Creek), anthophyllite (Oonagalabi) or cummingtonite-grunerite series (Harry Creek); (2) in layers within orthopyroxene-cordierite-quartz granulites (Edwards Creek and Harry Creek); and (3) with the quartz-magnetite association (Harry Creek and Edwards Creek).

Mg-rich cordierite is also a common mineral within Mg-Al-rich rocks. In some instances (Harry Creek and Johannsens Phlogopite mine), it can be the dominant mineral, so as to form virtually monomineralic zones or pods. Orthopyroxene-cordierite-quartz granulites, referred to as cordierite 'quartzites' by some workers, commonly display lithological layering and are present as apparently

<sup>&</sup>lt;sup>1</sup> Geoscience Australia (GA)

strataform, regional zones through parts of the SMC. These rocks may represent regionally metamorphosed chloritic alteration zones in sedimentary protoliths, particularly where the modal abundance of cordierite is high.

Evidence from deposits we have examined and from the regional distribution of hydrothermally altered rocks suggest that relatively extensive hydrothermal systems operated in the SMC prior to metamorphism. This project will determine what type of hydrothermal system operated and assess its potential for economically significant mineral deposits.

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## AN OVERVIEW OF GEOSCIENCE AUSTRALIA WORK AS PART OF THE NORTH AUSTRALIA NGA PROJECT

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In July 2000, Geoscience Australia (then the Australian Geological Survey Organisation) joined with the Northern Territory Geological Survey (NTGS) in the North Australia NGA (National Geoscience Agreement) Project (NAP), a three year program to assist NTGS in their regional mapping and metallogenic programs in the southern Northern Territory. We are presently about halfway through this project, which is due to be completed in June 2003. Geoscience Australia has worked closely with NTGS on a number of aspects of this project, most of which are being reported separately at this conference (Wygralak and Mernagh 2002, Fraser 2002, Hoatson *et al* 2002, Hussey and Huston 2002, Korsch *et al* 2002, Meixner *et al* 2002). Other topics include the results of a gravity survey in the Tennant Creek area, certain aspects of the mineral potential of the region, and the diamond potential. This contribution summarises these other topics, reports new developments on the NAP web page, and presents proposed work for the remainder of the project.

In July 2001, Scintrex Pty Ltd conducted a gravity survey on behalf of GA and NTGS covering the Tennant Creek and parts of the Green Swamp Well and Bonney Well 1:250 000 sheets. The survey was conducted on a 4 km × 4 km grid, or better, and the data were combined with existing detailed gravity data for a complete coverage of the survey area. These data are available online at www.dme.nt.gov.au/downloads/ or as part of the complete Australia gravity data set (available on CD from the Sales Centre, Geoscience Australia, GPO Box 378, Canberra, ACT, 2601 for \$99 plus postage and handling). As part of the work program for this coming year, these data, in combination with aeromagnetic data, will be modelled to establish the 3-D geological architecture of the Tennant Creek region.

Weight of evidence analysis has been used in a preliminary mineral potential assessment for lode gold in the Tanami Region. This technique assesses the influence of factors such as proximity to faults, or granitoids, and host rocks on known deposits, and uses these data to determine mineral potential, as measured for the entire region. Analysis of known deposits indicates that they are closely related to faults, but no statistically significant relationship was noted with respect to granitoids. The most common host unit is the Mount Charles Formation, but significant deposits are hosted by the Killi Killi and Dead Bullock Soak Formations. Future work in mineral assessment will be to refine the Tanami lode gold assessment using open file geochemical data and fault classification, and to assess the potential for sediment-hosted Zn-Pb-Ag deposits in the Victoria and Ashburton Basins.

The North Australian Craton (NAC) has considerable potential for diamonds. Diamondiferous kimberlites are known to have been emplaced during three separate events: 1200 Ma (Argyle); 360 Ma (Merlin); and 180 Ma. Parts of the NAC pose significant problems for diamond exploration. For instance, diamond indicator minerals, with the exception of diamond and, to a lesser extent chromite, typically do not survive intense weathering and the Merlin pipe is not magnetic. The purpose of this part of the NAP is to define areas of higher potential at the craton scale to provide better focus for exploration.

In addition to the work program already identified, GA, in close collaboration with NTGS, will concentrate on:

- (1) characterising regional fluids in the Tanami region and their relationship to ore fluids;
- (2) determining the timing, origin, and stratigraphic correlation of eastern Arunta Cu-Zn-Pb deposits;
- (3) assessing links between the Tanami and Arunta in terms of correlation, provenance and thermotectonic history; and
- (4) placing constraints on the internal geologic architecture and geological history of the Arunta.

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## DEEP SEISMIC REFLECTION PROFILING IN THE NORTHERN TERRITORY: PAST WORK AND FUTURE DIRECTIONS

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## **INTRODUCTION**

Current geological mapping by the Northern Territory Geological Survey is leading to a much better understanding of the surface geology of the Territory. Less well understood is the geometry of the Northern Territory in the third dimension (depth), although this has been predicted by the construction of cross-sections (on recent 1:250 000 geological maps). At shallow depths, cross-sections can be constrained by drilling results, if available, but deeper levels can only be examined by geophysical techniques such as seismic reflection or magnetotelluric profiling, or by modelling of potential field data.

Deep seismic reflection profiling has been used for many years by Geoscience Australia (formerly AGSO), often in conjunction with state government, research and industry partners, to provide images of the continental crust of parts of Australia in the third dimension. Here, we discuss aspects of previous deep seismic surveys that have been conducted in the Northern Territory, briefly examine the results and interpretation of recent reprocessing of some of the deep seismic reflection data from the Arunta province and present proposals for future deep seismic transects in the Northern Territory.

## PREVIOUS DEEP SEISMIC SURVEYS IN THE NORTHERN TERRITORY

A very limited amount of deep seismic reflection profiling has been conducted in the Northern Territory to date; this included one extensive survey in 1985 to examine the geometry of the Amadeus Basin and part of the Arunta province (Goleby *et al* 1988, Wright *et al* 1990). This survey collected 486 km of 20 s two-way travel time (TWT) data (to approximately 60 km depth) along four traverses, using explosive sources. At the same time, an additional wide-angle refraction survey was conducted in the Arunta province. A second wide-angle survey was conducted in the Amadeus Basin in 1988.

Reflection profiling indicated that the dominant feature of Arunta province crust is a series of planar structures that dip about  $40^{\circ}$  to the north. These penetrate to depths of greater than 20 km (Goleby *et al* 1989, Shaw *et al* 1992).

## **REPROCESSING OF 1985 DATA**

As part of the NGA North Australia Project Mineral Promotion, Geoscience Australia has reprocessed the northern part of the 1985 regional traverse that was completely within the Arunta province (line BMR85-1A) to investigate if it was possible to improve the quality of the section and hence improve on the original interpretation of this line.

Improvements in processing algorithms, particularly signal enhancement and pre-stack migration techniques, have greatly enhanced the final quality of the seismic section. Recent reprocessing concentrated on three main areas: static corrections, signal enhancement and migration. First breaks were picked for all shots and an improved refraction statics model was calculated, resulting in better definition of the near surface. Signal enhancement methods focused on increasing signal to noise levels within recorded data and improving continuity of reflecting events. The main improvement to the quality of the section came from the application of time-based pre-stack migration. Pre-stack migration resolves details in many of the smaller structures and sharpens up the final section. The results of this reprocessing are an improvement in the quality of the final section through improved clarity, leading to

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a better understanding of the geodynamic history of the region. The remainder of the 1985 seismic data will now be scheduled for reprocessing.

# INTERPRETATION OF REPROCESSED DATA

Reprocessing of the reflection data, and in particular the migration of the upper 10 s TWT (approximately 30 km) of the data, has enabled us to refine published interpretations (see references above). The new sections confirm the existence of north-dipping faults. In addition, the increased clarity shows the presence of several large hanging wall anticlines, indicating that the faults are thrusts. Hence, massive crustal shortening has occurred in this part of central Australia.

Some of the planar faults have a stronger seismic response than others. For example, an unnamed fault about 8 km to the north of the Desert Bore Fault has a much stronger seismic response than the Desert Bore and Harry Creek Faults.

Based on crustal reflectivity patterns, we are able to partition the crust into several fault-bounded packages. Key faults that form boundaries to the packages are the Ormiston Thrust Zone, Redbank Thrust Zone, Desert Bore Thrust, the unnamed fault about 8 km to the north of the Desert Bore Fault and the Patty Hill Thrust.

## PROPOSALS FOR FUTURE SEISMIC WORK IN THE NT

In terms of enhancing the mineral potential, we present four proposals for deep seismic reflection profiling within the Northern Territory. An accompanying program that would undertake a wide-angle refraction experiment and/or a lithospheric tomography experiment, such as has been conducted by the SKIPPY Australia-wide experiments, would strengthen the surveys.

#### 1. Batten Trough, McArthur Basin

Key geological problems that could be addressed here include:

- 1. the geometry of the McArthur Basin and contained sub-basins;
- 2. the stratigraphy and thickness of the basin succession;
- 3. the nature of the main faults (Emu, Tawallah, Mallapunyah, Calvert faults); and
- 4. possible east-west growth faults and sub-basin architecture near HYC.

#### 2. Western Arunta - Tanami

Key geological problems that could be addressed here include:

- 1. the geometry and character of the Trans Tanami Fault Zone;
- 2. the relationship of Proterozoic rocks to Archaean domes;
- 3. the relationship of major gold deposits to major regional structures; and
- 4. the nature of boundaries between the North Australia Craton and Central Australia domains, and between the Tanami region and Arunta province.

#### 3. Northern Arunta – Tennant Inlier

Key geological problems that could be addressed here include:

- 1. a comparison of tectonic style between the northern Arunta and Tennant Inlier;
- 2. the nature of boundaries between the North Australia Craton and Central Australia domains, and between the Tennant Inlier and Arunta province;
- 3. the geometry of the Wiso Basin, including the Lander Trough and its margins; and
- 4. the controls on mineralisation in Tennant Inlier.

# 4. Eastern Arunta province

Key geological problems that could be addressed here include:

- 1. the geometry of the southern Georgina Basin;
- 2. internal sequence stratigraphy, structural geometry, potential petroleum traps;
- 3. the geometry of structures and rock packages associated with Ordovician Larapinta Event;
- 4. crustal architecture across the doubly vergent intraplate Alice Springs Orogen; and
- 5. the nature of the boundary between the North Australia Craton and Central Australia domains.

## CONCLUSIONS

Only a very limited amount of deep seismic reflection data has been collected in the Northern Territory. Reprocessing of part of these 1985 data has improved the section quality. Interpretation of the reprocessed sections confirms that the central Australian crust is dominated by north-dipping faults, and that these faults are thrusts as shown by large hanging wall anticlines. Based on reflectivity patterns, major crustal packages can also be defined. Future seismic programs can address several key geological problems of importance to mineral exploration, with the potential for high impact.

## ACKNOWLEDGEMENTS

This presentation would not have been possible without the input of Dennis Gee, David Rawlings, Barry Pietsch (NTGS), David Huston (GA NAP), Barry Drummond, Tim Barton and David Johnstone (GA and ANSIR). We thank Malcolm Nicoll, Richard Larson and Tony Meixner (GA) for providing visual information and Joe Mifsud (GA) for drafting the figures (Powerpoint).

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## GEOLOGICAL FRAMEWORK OF THE RUM JUNGLE MINERAL FIELD

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## **INTRODUCTION**

The Rum Jungle Mineral Field is located 100 km to the south of Darwin on the western side of the Pine Creek Orogen and comprises Palaeoproterozoic basin fill sediments unconformably overlying domed, late Archaean granite-gneiss basement complexes (**Figure 1**). It contains a wide spectrum of mineral commodities including U, Cu, Co, Ni, Pb, Zn, Magnesite and Phosphate. Despite having been an active mining district since 1950 (Rum Jungle uranium mines), regional controls on the location of ore deposits remain poorly understood and the mineral occurrences have not been the subject of modern geoscientific investigations. The last published geological map was compiled in 1981 by BMR (now Geoscience Australia). Since then, a considerable amount of new geological, drilling, geochemical and exploration data has been collected. These data include a high resolution NTGS airborne geophysical survey flown in 1999. One significant mining operation (Woodcutters Zn-Pb-Ag) has recently closed down, and two new mineral projects (Browns Pb-Cu-Co-Ni-Ag and Winchester magnesite) are in feasibility. A detailed study of the Browns polymetallic deposit is one aspect of the joint NTGS-University of Leoben study into mineralisation processes and ore deposit controls in the Rum Jungle area. A new 1:100 000 solid geology interpretation has recently been released and this represents a synthesis of available geological information aimed at outlining locations of mineral prospectivity.

## STRATIGRAPHY

A summary of stratigraphic relationships in the Rum Jungle Mineral Field is shown in **Figure 2**. The Rum Jungle and Waterhouse basement complexes comprise schist, granite gneiss, banded iron formation and granite exposed in two inliers in the centre of the map area. Both complexes are poorly exposed, but have been subdivided into different units by mapping and their geophysical characteristics. Geochemically, granitic rocks of the basement complexes are heterogenous in both bulk rock and trace element composition, and this reflects the variety of lithologies mapped. Whole zircon dating of the youngest granitic phase (from crosscutting relationships) gives a minimum age of 2500-2600 Ma for the Rum Jungle Complex (Richards *et al* 1966).

The basement complexes are unconformably overlain by the Namoona Group, which consists of fluvial to shallow marine clastic sediments of the Beestons Formation followed by shallow water stromatolitic carbonates of the Celia Dolomite. The contact between the Namoona Group and the overlying Mount Partridge Group is unconformable and indicates a period of minor uplift and erosion. Pebbles of Beestons Formation sandstone are found in BIF conglomerate near the base of the Crater Formation.

Crater Formation arkose, conglomerate, coarse sandstone and minor shale grade upward into stromatolitic carbonate of the Coomalie Dolomite. This unit has a gradational contact with the overlying Whites Formation, which comprises carbonaceous siltstone and mudstone, and interbedded dololutite in places. Thinly bedded, colour-banded siltstone and mudstone of the Wildman Siltstone contains massive orthoquartzite beds of the Acacia Gap Sandstone Member (Ppa in Figure 2) and thin basaltic volcanics of the Mount Deane Volcanic Member (Ppd in Figure 2). The Whites Formation and overlying units of the Mount Partridge Group are missing from the sequence to the west of the Waterhouse Complex and this suggests that basement topography was still exerting an influence on sedimentation at this time.

Another period of minor uplift preceded deposition of the South Alligator Group and is marked by a possible palaeo-regolith breccia, the Ella Creek Member of the Koolpin Formation (Ese in Figure 2). The Koolpin Formation, Gerowie Tuff and Mount Bonnie Formation represent a transition from shallow water cherty and tuffaceous sediments to deeper water siltstone, mudstone and sandstone. They

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grade into turbiditic greywacke of the Burrell Creek Formation. A depositional age of 1885 Ma for the South Alligator Group has been provided by U-Pb dating of zircons in tuffs in the central Pine Creek Orogen (Needham *et al* 1988). Chert-dominated South Alligator Group rocks are absent to the west of the basement complexes and a lateral facies change is interpreted that produced fine-grained non-outcropping quartz-sericite and quartz-chlorite schists stratigraphically below coarser Burrell Creek Formation rocks. Dolerite and gabbro sills of varying thicknesses (Zamu Dolerite) intruded the sedimentary succession prior to deformation and metamorphism.

After deposition of the Burrell Creek Formation, deformation, metamorphism and granite intrusion occurred over a protracted period between 1880 Ma and 1760 Ma. Uplift and erosion preceded the deposition of fluvial platform cover sandstone, represented by the Depot Creek Sandstone in the Rum Jungle area. The base of the Depot Creek Sandstone is marked by siliceous breccia with a fine haematitic matrix that is preferentially developed over the Coomalie Dolomite. This is here termed haematite quartzite breccia (HQB). Differing modes of origin have been proposed for the HQB, either as an *in situ* weathering product, a talus slope deposit or a hydrothermal/tectonic breccia. The Depot Creek Sandstone is correlated with the upper part of the Katherine River Group (Ahmad 2002) and this gives a depositional age of 1720-1700 Ma.

#### **STRUCTURE**

The Rum Jungle area has been affected by nine deformation events that have occurred during three main periods: pre-Beestons formation ( $D_A$ ); 1880-1760 Ma ( $D_1$ - $D_6$ ); post-1700 Ma ( $D_7$ ,  $D_{GRF}$ ). In addition to these, extensional deformation is assumed to have occurred prior to and during deposition of the lower part of the sedimentary succession.

The earliest recognisable deformation event is defined by foliation in granite gneiss and schists of the Rum Jungle Complex, which is crosscut by younger Archaean granite. Younger granite phases are also foliated parallel to the east-west structural 'grain' apparent on geophysical data; this 'grain' is truncated by the unconformity at the base of the Proterozoic sediments. Some faults and shear zones within basement complex rocks are also truncated by the unconformity. Although there is more than one deformation event represented, these events are collectively termed  $D_A$ .

The major phase of deformation affecting the Rum Jungle area was initiated after deposition of the Burrell Creek Formation at 1880 Ma. North to northwest directed movement occurred on low angle thrust faults (D<sub>1</sub>) developed near the basement-sediment contact and in some units higher in the succession. Upright east trending map-scale folds (F<sub>1</sub>) also developed on the south and north margins of the Rum Jungle Complex. North, northeast and northwest trending upright, tight to isoclinal folds (D<sub>2</sub>) and axial planar slaty cleavage (S<sub>2</sub>) developed during a major phase of east-west compression that affected the entire Pine Creek Orogen. Orientations of F<sub>2</sub> folds were strongly influenced by the shape of the basement complex margins, particularly those of the Waterhouse Complex. Garnet and andalusite overgrow and are deformed by S<sub>2</sub> and this indicates a metamorphic event early in D<sub>2</sub>. D<sub>1</sub> and D<sub>2</sub> are correlated with the 1880-1860 Ma Nimbuwah Event that produced high-grade gneiss in the northeastern Pine Creek Orogen.

 $D_3$  produced open, upright east trending folds and a locally developed cleavage in the southern part of the Rum Jungle area. Large scale  $F_3$  folds are related to the intrusion of Cullen age granitoids to the east of Rum Jungle from 1840-1820 Ma.  $D_4$  formed northeast and northwest trending upright map-scale kink folds and locally developed crenulation cleavages. It is unclear whether the two orientations are related to the same event as no crosscutting relationships have been observed.  $D_5$  faults offset earlier folds and generally trend north to northeast. East- and west-side-up reverse movement is indicated by displacement of the stratigraphy across the faults.

 $D_6$  faults trend northeast and are restricted to the eastern part of the Rum Jungle area. On a regional scale, they can be correlated with similarly oriented structures such as the Pine Creek Shear Zone (Figure 1). They are also the locus for late-stage dyke intrusions. In the Pine Creek area, these structures have been correlated with the Shoobridge Event (1780-1760 Ma), which is the age of low-grade regional metamorphism and Rb-Sr resetting throughout the Pine Creek Orogen.

Following deposition of Tolmer Group sediments from 1740-1700 Ma,  $D_7$  reverse faulting occurred along northwest trending structures that might have been reactivated  $D_5$  faults. Mount Partridge Group sediments were overthrusted onto the Depot Creek Sandstone and HQB along moderately to steeply dipping faults that occur along the southwestern Waterhouse Complex and in the Rum Jungle Creek South and Embayment deposits. In both areas  $D_7$  reverse faults are associated with uranium mineralisation.

The final major deformation event  $(D_{GRF})$  to affect the area was dextral strike-slip movement along the Giants Reef Fault. Lateral offset on the fault is about 7 km and there are variable amounts of dip-slip offset. A change in orientation of the Giants Reef Fault at its intersection with the Rum Jungle Complex has caused a complex pattern of overprinting synthetic and antithetic faults and drag folds that crosscut mineralisation in this area. The Giants Reef Fault is part of an extensive fault system that can be traced into the Halls Creek Mobile Zone to the south-southwest.

#### STRUCTURES AND MINERALISATION

In the Woodcutters area, mineralised faults are steeply west dipping and have sinistral reverse (westside-up) movement sense. These faults offset  $F_2$  fold axes and are crosscut by northwest trending faults that are conjugate with the Giants Reef Fault. No other crosscutting relationships with regional structures have been recorded and mineralisation could therefore correlate with any event from  $D_3$  to  $D_7$ .

 $D_7$  reverse faults and breccia zones are associated with U and U-Cu mineralisation in the Kylie, SE Kylie and Riverside prospects on the southwestern Waterhouse complex margin. Beardsmore (1983) interpreted similar age faulting as controlling U mineralisation in the Embayment area. Rum Jungle Creek South is located near a  $D_7$  fault, but the relationship to U mineralisation is unclear.

Base metal mineralisation in the Embayment area occurred in two stages. Early, fine-grained galena, sphalerite, chalcopyrite and siegenite are deformed parallel to the  $S_2$  slaty cleavage and textural evidence indicates a syn-sedimentary or syn-diagenetic origin. Later galena, sphalerite, Cu and Co-Ni mineralisation is contained within brittle structures that crosscut the  $S_2$  cleavage. Mineralisation is offset by a dextral strike-slip fault parallel to the Giants Reef Fault. As at the Woodcutters deposit, structural overprinting relationships indicate that coarse mineralisation correlates with one of the regional deformation events from  $D_3$  to  $D_7$ .

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Figure 1. Generalised geology of the Pine Creek Orogen, showing location of Rum Jungle 1:100 000 map sheet



Figure 2. Schematic stratigraphic column for the Rum Jungle area

# POTENTIAL FIELD MODELLING OF PROPOSED LAND SEISMIC TRANSECTS IN THE NORTHERN TERRITORY

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Four land seismic surveys have been proposed over the Northern Territory: 1) southern McArthur Basin, crossing the Batten Fault Zone; 2) Tanami region and northwestern Arunta province; 3) central Arunta, extending the existing BMR seismic line northeasterly across the Wiso Basin, the Tennant Creek province and the Georgina Basin; and 4) two north trending transects in the eastern Arunta, beginning in the Amadeus Basin and terminating in the Georgina Basin.

Prior to seismic acquisition, 2<sup>1</sup>/<sub>2</sub>-D potential field forward modelling was conducted to refine existing geological models. Analysis of the magnetic and gravity fields helps define a number of variables, including dips, depths, extent, shape and orientation of structures and geological contacts. Inherent non-uniqueness of potential field modelling requires geological input to ensure that results are realistic. The high frequency component of the gravity field is lost in 11 km regional gravity data, which is typical of the level of coverage in the Northern Territory. It is impossible, therefore, to model near surface geology based on regional gravity. However, near-surface geology can be modelled in more detail using semi-regional airborne magnetic data, as the along-line sample interval is typically 7 m along flights lines spaced 400-500 m apart.

The proposed seismic transect in the southern McArthur Basin starts on the Bauhinia Shelf in the west, crosses the Batten Fault Zone and finishes on the Wearyan Shelf in the east. The McArthur Basin consists of a thick platform of unmetamorphosed and relatively undeformed sediments. At the base of the succession is the Tawallah Group, a laterally consistent unit, composed primarily of sandstone and minor volcanics. Overlying rift-related McArthur and Nathan Group carbonates are separated by regional unconformities. These are in turn overlain by clastic sediments of the Roper Group. The Batten Fault Zone coincides with the position of the former Batten Trough. Inversion of the trough has stripped the overlying Nathan and Roper Groups and exposed the McArthur Group.

Forward modelling of the gravity field along the proposed seismic transect yields a geological model that matches observed gravity data. Thick sections of dense McArthur Group carbonates produce a broad gravity high over the Batten Fault Zone. Gravity lows over the Bauhinia Shelf are modelled using thick sections of up to 5 km of low density Roper Group clastic sediments directly overlying the Tawallah Group. The lower gravity field over the Wearyan Shelf is modelled by thinner Roper and McArthur Group rocks overlying the Tawallah Group. The observed magnetic field along the proposed transect consists of two broad positive anomalies. Modelling known volcanics in the McArthur Basin sediments cannot reproduce these anomalies. The source of these anomalies is suggested to occur within McArthur Basin basement at a depth of over 8 km. Due to their high densities and magnetic susceptibilities, the source is probably of mafic composition.

In the Tanami Region, two proposed seismic transects extend in a northwesterly and northerly trend. Four sections were selected for potential field modelling, one located to follow the northwesterly trending seismic transect, whereas the others cross major structures and regions of interest. Results of the modelling indicate that the Coomarie and Frankenia granite domes have large depth extents (approximately 8 km) and form a single pluton at depth. These granitoids do not appear to have vertically dipping contacts; they widen at the base and have dips of up to 45°. A thick succession of dense, magnetic MacFarlane Peak Group sediments occupies a synform with a basal contact at about 5 km depth between the two granitic domes. A fault-bounded wedge of dense, magnetic Mount Charles Formation is located within the synform. The northwest-bounding Black Peak Fault dips subvertically, whereas the other bounding fault dips at 60° to the northwest. On the southern edge of the Browns Range Dome, the Browns Range Shear Zone is modelled with a southerly dip of approximately 70°. The granitic dome extends to approximately 8 km depth and is a composite pluton consisting of granitic bodies with differing densities and magnetic susceptibilities. To the south of the Browns Range Shear

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Zone, thick sections of dense McFarlane Peak Group are modelled beneath approximately 2.5 km of Birrindudu sediments. Late-stage northwesterly trending structures, including the Tanami and Mongrel Faults dip steeply (70°) to the southwest, whereas other northwest trending structures dip steeply to the northeast.

The eastern Arunta seismic transect extends from the Georgina Basin in the north across the Harts Range Metamorphic Complex and into the Amadeus Basin in the south. This line was designed to model the geometry of a proposed Cambrian intraplate rift-fill sequence, the Irindina Supracrustal Assemblage (ISA), that overlies basement of the Strangways Metamorphic Complex (SMC). The transect crosses a regional corridor defined by lower magnetic intensities. This corridor extends west-northwest across central and northern Australia, and may be the geophysical expression of the proposed rift. Modelling suggests that the ISA forms a thin veneer over SMC basement in the Harts Range. This veneer is much thicker to the north, where it is coincident with an area of extremely low magnetisation. Dips of the major block boundaries are consistent with a modified rift, centred to the south of the Delny Shear Zone. The Illogwa Shear Zone that bounds the ISA to the south appears to be a major north-dipping crustal structure.

# GEODYNAMICS OF THE REDBANK PACKAGE, BASAL MCARTHUR BASIN

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The 1815-1705 Ma Redbank package is a 3-6 km thick flat-lying succession of shallow marine to braided fluvial sandstone, lesser conglomerate, mudstone, carbonate, and rhyolitic-basaltic volcanics and high-level intrusions. It constitutes the base of the McArthur Basin and other coincident basins in northern Australia, and covers an area >400 000 km<sup>2</sup>. It is divided into four mesopackages (**Figure 1**).

# LITHOLOGICAL ATTRIBUTES

Coarse siliciclastics and rhyolitic volcanics at the base of the Redbank package (Yirrumanja and Liverpool mesopackages, Figure 1) formed in a braided fluvial environment. These are overlain by widespread sheets of supermature quartzarenite and intervening flood basalt, the former deposited in complex, high-energy shallow marine, fluvial and aeolian settings on an extensive low-gradient shelf. Overlying mudstone and carbonate were deposited on a shallow epeiric shelf. A regional sequence boundary formed during subsequent regional uplift and local synsedimentary deformation, and was followed by deposition of another widespread quartzarenite sheet (Costello mesopackage). The overlying succession of fine clastics and carbonate formed in marginal marine, epeiric shelf and moderately deep water settings.

The overlying Mitchell mesopackage records the complex interaction of siliciclastic sedimentation with mafic and felsic volcanism and high-level plutonism. Notable features of this dynamic high-relief volcano-tectonic landscape were regional-scale dolerite sills and sheet-like rhyolitic lavas with ephemeral alluvial and debris flow aprons. Epiclastic materials were reworked in bordering lakes and low-relief braidplains that prograded radially away from volcanic centres. Periods between magmatic events were characterised by deposition of widespread immature sandstone sheets in extensive high-energy braided fluvial settings and the development of low-relief regional disconformities.

# SPATIAL AND TEMPORAL CONSTRAINTS

The Redbank package evolved synchronously with orogeny and magmatism in the Central Australian Mobile Belt (Strangways Orogeny, **Figure 2**). This belt has been interpreted by Myers *et al* (1996) as a collisional orogen and the site of microcontinent accretion events. Periods between orogenic events record the emplacement of calc-alkaline magmatic suites with a subduction signature (Zhao and Cooper 1992) and this is suggestive of an ambient Cordilleran-style active southern margin to the NAC, the 'Strangways arc' (**Figure 3**). This temporal and spatial coincidence has received little attention in previously proposed models of widespread extension in the McArthur Basin, even though it lies only 1000-1500 km north of the interpreted palaeosuture. The tectonic model presented below is built around a geodynamic scenario where active margin processes in central Australia influenced basin formation in the NAC hinterland.

# **BASEMENT HETEROGENEITY**

Analysis of the AGSO geochronological database shows a near ubiquitous Archaean component in Proterozoic magmatic rocks of the NAC, suggesting the existence of a substantial and widespread Archaean basement that was thermally reworked during the Barramundi Orogeny and subsequent periods of magmatism (Scott *et al* 2000). The heterogeneous nature of the basement has been illustrated in recent interpretations of regional geophysics by Tarlowski and Scott (1999), who identified ten discrete domains of distinctive 'crust type' in the NAC. Boundaries between these basement domains

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are dominated by northwest and northeast structural trends that are thought to be discontinuities. Boundaries appear to have evolved during formation of 1820-1400 Ma basins of the NAC, including the McArthur Basin, as they coincide roughly with basin depocentres. In addition, basement heterogeneity coincides roughly with 500 km-scale lateral variations in basin thickness shown on isopach maps. Tarlowski and Scott (1999) recognised three northwesterly-oriented belts of distinctive geophysical character in the NAC, which are truncated by northeasterly-oriented transverse structures. Scott *et al* (2000) noted that the dimensions of these belts (about 300 km wide) were consistent with long-wavelength folding of the lithosphere.

Isotopic and geophysical data suggest the presence of a widespread lower crustal mafic underplate under the NAC and this indicates that vertical accretion was an important element in cratonisation (Etheridge *et al* 1987). P-wave velocities in the lower 20-30 km of the crust are anomalously high (7-7.6 km/s, Drummond 1988), consistent with a gabbroic or mafic garnet granulite/eclogite underplate or both.

# **BASIN ARCHITECTURE**

Based on overall dimensions, geometry, thickness, facies, palaeocurrent patterns, sedimentation rate and structure, the Redbank package is best 'categorised' as an Intracratonic Basin (ICB), analogous with the Interior Basins of the USA (eg Michigan Basin). Four distinct basin architecture types are recognised (**Figure 4**):

- *Wedge basin architecture* is evident in the overall southward-thickening and northward-progradation of the Redbank package, specifically within sheet sandstone units of the Liverpool, Costello and Mitchell mesopackages (eg Wununmantyala Sandstone);
- *Elongate basin architecture* pertains to the low-relief northwest-oriented depoaxes and epeiric basin characteristics of carbonate-mudstone units (eg Wollogorang Formation);
- *Magmatic basin architecture* is developed in coarse fluvial clastic units of the Yirrumanja and Mitchell mesopackages, where the depositional setting and facies patterns are influenced mostly by associated magmatism; and
- *Growth-fault basin architecture* is implied from localised thickness changes in the lowermost Liverpool mesopackage (eg Yiyintyi Sandstone) that are consistent with large-scale (20?-50 km) northward-tilted 'sub-basins'.

## MAGMATISM AND THERMAL ANOMALY

Felsic igneous units of the Redbank package show variable geochemistry through space and time and probably reflect partial melting of heterogeneous Archaean mafic crust adjacent to large basaltic magma chambers at or near the Moho. Five main Proterozoic mafic igneous events are recognised, spanning a period of 480 my. Mafic units have the geochemical attributes of typical flood basalt provinces and show temporal trends that appear to be the result of partial melting of chemically-stratified mechanical and thermal boundary layers at the base of the lithosphere. Geochemical provinciality suggests that some volcanic phases were the result of partial melting of a heterogeneous (metasomatised?) portion of the lithosphere, whereas others were derived from homogeneous (anhydrous?) lithosphere. There is no evidence of a deep-seated plume component, or a requirement for rifting. Instead, partial melting is thought to have been the result of a persistent thermal anomaly related to insulative heating of the craton and mantle convection associated with far-field subduction and orogenesis ('convective roll', **Figure 5**). Magma extraction probably took place episodically at transtensional sites along regional strike-slip fault systems.

#### **GEODYNAMIC MODEL**

Assessment of these architectural elements and various data from the Redbank package and adjacent tectonic provinces favours a convergent tectonic setting during this timeframe, rather than the extensional setting previously proposed. Any geodynamic model for the Redbank package must involve a variety of subsidence mechanisms operating inboard of the southern active margin of the North Australian Craton (Strangways arc; **Figure 6**). Details of these geodynamic scenarios and subsidence mechanisms are presented in Scott *et al* (2000) and Rawlings (2002), including a bibliography indicating from where ideas were extracted. A chronology of events in the Redbank package is presented in **Figure 7**.

## GEODYNAMICS DURING SUBDUCTION

During times of low-angle subduction in the Strangways arc, the NAC was tilted southward as a result of the dynamic topography associated with subduction of oceanic plate under warm 'insulated' craton (**Figure 6A**). Clastic deposition on a low-angle ramp or platform led to thickening (ie wedging) of the basin toward the arc in the south or southwest ('wedge basin architecture'). Enhanced mantle convection (a 'convective roll') and elevated temperatures, coupled with dynamic topography, promoted phase transformations in the lower crust and upper mantle, and provided substantial additional subsidence by densification of the lithosphere. Extensive magmatic underplating, which preceded and accompanied the Redbank package, provided a large volume of gabbro which subsequently underwent thermally-enhanced transformation to eclogite or garnet granulite. A proportion of the subsidence would also have resulted from thermal contraction of the mafic underplate, eclogite and surrounding lithosphere as the thermal anomaly waned. Differential subsidence of the basin was enhanced by varying viscoelastic behaviour of the heterogeneous crust, in response to the thermal anomaly, and by pulsing of the regional stress field as subduction evolved. These processes may have been enhanced by thermal blanketing of radiogenic basement by the thick clastic cover sequence. Transtension along strike-slip faults also provided local subsidence and pathways for magmatism.

When steep subduction occurred beneath the Strangways arc, the influence of dynamic topography was probably reduced, but the convective roll could maintain a thermal anomaly in the upper mantle (**Figure 6B**). Mantle convection led to mechanical and thermal erosion of the subcontinental mantle lithosphere (SCML), where large magma sources accumulated. Transtensional deformation along lithosphere-scale strike-slip faults facilitated the local migration of melt into magma chambers within the lower crust and upper SCML, where fractionation and melting of crustal wall-rock took place. Mafic and felsic volcanics and high-level intrusions were then emplaced locally, producing an irregular but radial surface topography and sedimentary apron ('magmatic basin architecture'). The load of the volcano-sedimentary pile provided some accommodation space, but differential erosion dominated, producing numerous local unconformities. Phase transformations in the lithosphere and thermal contraction and densification of underplated mafic bodies probably provided the bulk of the subsidence.

Subduction dynamics or mantle convection were periodically conducive to back-arc extension, where a zone of extension and tilt-block 'sub-basins' developed parallel to the arc ('growth-fault basin architecture'; **Figure 6B**). Lithospheric attenuation led to a thermal anomaly that contributed to subsidence in the following depositional phase via thermal relaxation.

## **GEODYNAMICS DURING COLLISION**

Several phases of microcontinent accretion are interpreted to have taken place at the Strangways arc. Assuming the oceanic slab was detached during collision, the convection process and dynamic tilt would have ceased and the associated thermal anomaly would have waned. It is envisaged that plate margin stresses associated with the orogenic collisions were transmitted into the adjacent NAC interior and were responsible for most aspects of the Redbank package architecture, including the following:

## EARLY COLLISION (**Figure 6C**)

- Craton-wide flexural uplift and development of regional unconformities.
- Back-bulge flexure and cratonward progradation of clastic wedges (some 'wedge basin architecture').
- Tectonic escape and the development of local magmatic impactogens (eg 'Mt Isa and Davenport Rifts').

## SYN-COLLISION (Figure 6D)

- Synsedimentary strike-slip faulting.
- Tectonically-induced viscoelastic behaviour of the heterogeneous lithosphere.

### LATE COLLISION (Figure 6D)

• Lithosphere-scale folding and development of mudstone-carbonate epeiric basins ('elongate basin architecture').

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the mesopackage divisions. Excludes 'late' intrusive units. No thicknesses are inferred. Vertical time scale is approximate only.

Sandstone and conglomerate

S



1870-1885 Ma BARRAMUNDI OROGENY

**Figure 2** Timing of basin development in the North Australian Craton and orogeny in central Australia, showing the coincidence of the Redbank package and Strangways Orogeny (modified after Scott et al., 2000).



**Figure 3** Palaeotectonic reconstruction for the NAC during 1830-1700 Ma, showing the orientation of the active margin/collision belt (Strangways arc), tectonic ridges and palaeorifts (modified after Myers et al., 1996). Convergence directions are approximate only. LRFT=Leichhardt River Fault Trough ('Mount Isa Rift'); DR='Davenport Rift'.



Figure 4 Basin architectural elements of the Redbank package.



**Figure 5** Schematic model for the development of a convective roll inboard of a subduction zone that leads to a transient thermal anomaly in the lithosphere (after Froidevaux and Nataf, 1981). Vertical dimension not to scale.



**Figure 6** Palaeotectonic reconstructions for the NAC during 1820-1700 M a, showing proposed subsidence mechanisms and mantle processes, and their relationship with possible subduction and collision geometries in the Strangways arc.



## D) SYN- to LATE COLLISION



Figure 6 (cont)



Figure 7 Time-space diagram illustrating the evolving Strangways orogenic belt and interpreted geodynamic regime in central Australia (Strangways arc) and its relation to basin formation in the Redbank package.

## BROKEN HILL AND MOUNT ISA AGE TERRAINS ON THE SOUTHERN MARGIN OF THE NORTH AUSTRALIAN CRATON

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## INTRODUCTION

Ongoing NTGS studies in collaboration with Geoscience Australia in the western part of the southern Arunta province have resulted in the recognition of two distinct terrains: the 1660-1630 Ma Yaya Terrain in the north and the 1690-1660 Ma Haasts Bluff Terrain in the south (Edgoose *et al*, this volume). The distinct protolith ages and geological evolution of the southern Arunta province raise questions regarding its relationship to the rest of the Arunta and the North Australian Craton. In addition, sedimentation and tectonism in the southern Arunta province occurred within the prospective P7 interval (1700-1600 Ma), and it is therefore worth considering what relationships and correlations may exist between the southern Arunta and highly mineralised terrains of the same age.

# LAKE MACKAY 1:250K SHEET, AND COMPARISONS WITH SOUTHERN ARUNTA PROVINCE

In addition to studies in the southern Arunta province, the current project also includes remapping of LAKE MACKAY<sup>3</sup>. A helicopter survey over this mapsheet followed by SHRIMP U-Pb geochronology suggests that the area is dominated by pelite-psammite associations that form part of the >1820 Ma Lander Package (Pietsch 2001). Much of the central and southern parts of the sheet comprise poorly outcropping greenschist facies pelite and psammite that were intruded by granites at 1760 Ma. SHRIMP U-Pb dating of detrital zircons from this sequence gives a maximum deposition age of  $1866 \pm 5$  Ma. In the northeastern corner of the sheet are granulite facies pelites and psammites that have a very similar distribution of detrital zircon ages to the low-grade sediments and an identical youngest zircon population of  $1864 \pm 5$  Ma. This data suggests that the high- and low-grade rocks belong to the same sedimentary package. Metamorphic zircon rims in the high-grade rocks give an age of  $1804 \pm 7$  Ma. The northwestern part of LAKE MACKAY is dominated by coarse porphyritic garnet granite, which intruded at around 1800 Ma and which shows evidence for isotopic disturbance at 1600 Ma. A younger sequence of felsic volcanics and arenites, the Nicker beds, occurs near the eastern mapsheet boundary and extends into MOUNT DOREEN; it has a SHRIMP U-Pb zircon age of  $1772 \pm 5$  Ma (Young *et al* 1995). Existing data from LAKE MACKAY clearly indicate that this region forms part of the northern Arunta province and has a distinctly different geological history to younger terrains of the southern Arunta.

## **REGIONAL CORRELATIONS OF THE SOUTHERN ARUNTA PROVINCE**

Although the protolith ages of metasediments and volcanics in the southern Arunta province are much younger than in the northern Arunta, they are similar in age to units that host mineralisation at Broken Hill and Mount Isa. The Broken Hill Group, which hosts the Broken Hill orebody, has an age of 1690-1670 Ma (Page and Laing 1992, R Page 2002 pers comm), but supracrustal rocks from this time interval are conspicuously absent from the North Australian and Gawler Cratons. SHRIMP U-Pb zircon dating of volcanics associated with minor Fe-rich chemical sediment, calc-silicate and pelite of the Peculiar Volcanic Complex in the Haasts Bluff Terrain (MOUNT LEIBIG) gives an age of  $1679 \pm 3$  Ma. These are interpreted to be the only known age equivalents of the Broken Hill Group in Australia outside of

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<sup>&</sup>lt;sup>3</sup> Names of 1:250 000 mapsheets are in CAPITALS.

the Curnamona Province. Similarly, the 1660-1640 Ma pelite-dominated sequence of the Yaya Metamorphic Complex of the Yaya Terrain is comparable in age to host units of the Mount Isa (1652 Ma) and Lady Loretta (1647 Ma) orebodies in the Mount Isa Inlier (Southgate *et al* 2000). In comparison, there is no evidence to support the notion that the southern Arunta is a northern extension of the Musgrave Block, which has significantly younger protolith and Nd model ages.

#### 1640-1630 MA LIEBIG EVENT: ACCRETION OF THE SOUTHERN ARUNTA PROVINCE?

A major tectonic, thermal, and magmatic event at 1640-1630 Ma, the Liebig Event, has been identified by NTGS studies in the southern Arunta province. New information on the metamorphism and magmatism associated with this event provides an insight into the tectonic environment at the southern margin of the North Australian Craton (NAC) at this time.

The Liebig Event was most intense in the Yaya Metamorphic Complex, which was metamorphosed at granulite facies conditions ranging from 750-900°C and 9-10 kbar (30-35 km depth). The timing of this high-grade metamorphism is given by SHRIMP U-Pb dating of zircon rims from MOUNT LEIBIG; this gives an age of  $1638 \pm 8$  Ma. The highest grades of metamorphism are found adjacent to gabbro and charnockite bodies that have been dated at  $1638 \pm 2$  Ma and  $1637 \pm 2$  Ma, respectively, and metamorphism is therefore likely to have been the result of the intrusion of mafic and charnockitic bodies into the lower crust. The timing of metamorphism suggests that the Yaya Metamorphic Complex was buried to the deep crust within 10-20 million years of deposition. Mineral reaction textures suggest that the terrain was very rapidly exhumed following metamorphism. Deep crustal metamorphism and rapid burial and exhumation imply the existence of overthickened crust in a very active tectonic environment during the Liebig Event. This contrasts with Palaeoproterozoic tectonothermal events in the rest of the Arunta and NAC, which are typically associated with low-pressure metamorphism and no exhumation of lower crustal rocks. Voluminous felsic and less abundant mafic magmatism occurred in the Yaya Terrain at 1640-1630 Ma and the high-K metaluminous calc-alkaline geochemistry of the granites and granodiorites is consistent with an Andean- or Cordilleran-style continental margin.

The effects of the Liebig Event also extend beyond the Yaya Terrain. To the north, the 1635 Ma Andrew Young Igneous Complex (Young *et al* 1995) intruded into greenschist facies schists of the Dufaur domain, resulting in localised upper crustal contact metamorphism. These mafic rocks extend west-southwestward from southern MOUNT DOREEN into northern MOUNT RENNIE. In the Haasts Bluff Terrain, the Madderns Yard Metamorphic Complex in the east underwent migmatisation at upper amphibolite facies, whereas the Kuta Kuta domain in the west shows no evidence for significant metamorphism during the Liebig Event. In the Mount Webb region immediately across the Western Australian border, the Mount Webb Granite intruded at  $1639 \pm 5$  Ma (Wyborn *et al* 1998) and is interpreted as forming part of the western extension of the Yaya Terrain.

The timing of the Liebig Event corresponds to a major hairpin bend in the apparent polar wander path (APWP) for northern Australia (Idnurm 2000). This implies that it was an event of regional significance that led to a reversal in the direction of plate movement of the North Australian Craton. This evidence, along with the rapid burial and exhumation of sediment and large-scale calc-alkaline magmatism is consistent with the collision and accretion of the southern Arunta onto the NAC at 1640-1635 Ma.

#### Effects of the Liebig Event across the NAC

Scott *et al* (2000) proposed that the basin dynamics of the northern Australian platform cover (Victoria-Birrindudu and McArthur/Isa Basins) were fundamentally affected by accretional events at the southern margin of the NAC. Distal effects of the Liebig Event are evident in platform cover sequences as a period of extensional deformation, tuffaceous sedimentation and Pb-Zn mineralisation. In the McArthur Basin, a tuff within the HYC deposit in the Barney Creek Formation has an age of  $1639 \pm 3$  Ma, whereas in the Limbunya Group of the Victoria-Birrindudu Basin, tuffaceous deposition occurred at  $1636 \pm 5$  Ma and  $1638 \pm 7$  Ma. Major bends in the APWP, such as the hairpin bend at 1640 Ma that is associated with the Liebig Event, are commonly associated with mineralising events, due to changes in intraplate stresses that result in the migration of fluids (Southgate *et al* 2000). We propose that the Liebig Event had a major regional impact that included a distal continental back-arc environment across northern Australia, allowing enhanced flow of mineralising fluids.

## SUMMARY AND IMPLICATIONS FOR PROSPECTIVITY

- The southern Arunta province is interpreted to have accreted onto the NAC during a major event at 1640-1635 Ma and therefore its metallogenic potential should be considered independently from the rest of the Arunta.
- Metasedimentary successions in the southern Arunta fall into the highly prospective P7 (1700-1600 Ma) interval. They are equivalent in age to mineralised successions from Mount Isa and the McArthur Basin (Yaya Complex) and Broken Hill (Haasts Bluff Terrain).
- The Yaya Terrain is a continuation of the same terrain that hosts the 1640 Ma Mount Webb Granite Suite, which contains a major granite-related alteration system with potential for Cu-Au mineralisation (Wyborn *et al* 1998).
- Several small calc-silicate-hosted Pb-Zn deposits occur in the Haasts Bluff terrain and will undergo more detailed study by NTGS in 2002.
- The 1640-1630 Ma Liebig Event had a significant impact across the NAC that included a continental back-arc environment in platform cover sequences of northern Australia, with extensional deformation, tuffaceous sedimentation and Pb-Zn mineralisation (eg HYC deposit,  $1639 \pm 3$  Ma, Page and Sweet 1998).
- The Liebig Event was accompanied by significant mafic magmatism that included intrusion of the Andrew Young Igneous Complex in MOUNT DOREEN and gabbroic and rare ultramafic bodies in the Yaya Terrain. Geophysical evidence for an extension of the Andrew Young Complex west-southwest into northern MOUNT RENNIE has now been confirmed by field observations during 2001 and this upgrades the Ni-Cu potential of the southwestern Arunta.
- In contrast to the southern Arunta, the Lake Mackay region is dominated by low-grade metasediments of similar age to much of the northern Arunta, Tanami region and Tennant Inlier, and has higher prospectivity for Au mineralisation.

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#### **ARUNTA PROJECT: SPATIAL EXPLORATION DATA CAPTURE**

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### **INTRODUCTION**

The principal aim of this project is to facilitate mineral exploration within the Arunta province by making spatial (GIS) historical Exploration Licence data available to the exploration industry. The project is designed to quickly show the exploration history of any area within the province. Previously, exploration work could only be assessed via the NTGS Industry Reports Management System (IRMS) searching of voluminous company reports using map sheet search criteria.

The project area covers 18 250K map sheets in the Alice Springs region, is divided into Western, Central and Eastern modules (**Figures 1**, **2**) and contains 622 surrendered (open-file) Exploration Licences. The map sheets largely cover high-grade metamorphic rocks of the Arunta province, including the Ngalia Basin. Total exploration expenditure in the area since 1972 is estimated to have been well in excess of \$50 M.

## DATA CAPTURE

Much of the work described below was undertaken by Exploremin Pty Ltd under contract to NTGS. The project commenced with the spatial capture of 4677 surrendered (open-file) Northern Territory Exploration Licences as GIS (MapInfo) polygons. Licences relevant to the Arunta province (**Figure 2**) were extracted and attributed with 29 data fields including tenement, commodity, exploration summary, drilling and geochemical sampling fields. Several metadata fields were included to record aspects of the data capture.

Hard copy and scanned (post-1983) company reports were examined and relevant exploration aspects used to populate the EL polygon attribute fields. Scanned company report files (.tiff) were often converted to Adobe Acrobat files (.pdf) and have been hot-linked to the EL polygons. The resulting single MapInfo table is referred to as the Arunta EL Summary table.

Locations of drillholes and stream sediment, rock-chip and soil sampling points were determined using MapInfo and Discover GIS software. Tablet digitising was used to derive digital coordinates from hard copy figures and plans, and on-screen digitising was employed for scanned reports. The datum was assumed to be AGD66 unless otherwise stated, and local grid coordinate data was transformed using the Discover Grid Transformation function. Capture of hard copy tabular coordinate (and geochemical) data was facilitated by Optical Character Recognition software. Derived point locations were routinely checked for location accuracy by spatial comparison to ancillary geological and topographical maps, and Landsat TM imagery. NTGS MODAT (Mineral Occurrence Database) locations were checked and modified if necessary, and any new mineral occurrences were added to MODAT.

Coordinate data was exported from MapInfo into Explorer 3 drilling and geochemical sampling templates (Excel) that contain look-up codes and a data validation file. The templates were then populated with additional data derived from company reports, including geochemical results and tenement/report details. Completed templates were then loaded into the Explorer 3 (Access) geological database via further data validation steps.

All drillhole collar positions have been captured, although capture of down-hole geochemistry, surveying details, coded geology etc was largely restricted to data supplied digitally. However, drillhole summaries and/or significant results information are often included in drillhole collar tables.

All stream sediment samples have been captured, including diamond exploration sampling results. The majority of sample locations are positioned with respect to an Auslig 250K vector drainage table that has been modified in areas of more detailed sampling density. Diamond sampling capture information includes comments on the presence or absence of indicator minerals.

All digitally supplied soil and rock chip samples have been captured, but not all hard copy results were recorded because of time and budget constraints. A soil and rock chip metadata field within the Arunta EL Summary table is used to record those surveys not captured.

# RESULTS

DATA POINTS	Western Arunta module	Central Arunta module	TOTAL
Drillholes	8582	5205	13787
Stream sediment samples	707	11138	11845
Rock chip samples	534	2243	2777
Soil samples	2336	3934	6270
TOTAL	12159	22520	34679

The table below summarises the results of exploration data capture within the Western and Central Arunta modules.

The current status of data capture is shown in **Figure 2**. Data capture on the Western module is complete and work on the Central module should be completed during April this year. Eastern Arunta data capture is scheduled for completion in the second half of this year.

During the course of data capture, several areas were highlighted as having possible exploration potential. These were captured as MapInfo polygons or points and attributed with selection rationale and ancillary information including company report and tenement numbers. Such capture commenced on the Napperby sheet of the Central Arunta Module and currently, the Arunta Exploration Highlights table contains 38 base metal, gold and diamond exploration locations.

The following products covering the Western and Central modules will shortly be released on CD:

- Arunta EL Summary table.
- Arunta Exploration Highlights table.
- Modified 250K Auslig drainage table.
- Explorer 3 database (Access) files for drillholes, and stream sediment, rock chip and soil sampling.



Figure 1. Location of the Arunta project area.



Figure 2. Exploration Licence data capture status.

#### **MOUNT SOLITAIRE: ESTABLISHING TANAMI-TENNANT LINKS**

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Integration of geological and geophysical data and production of a preliminary basement interpretation for MOUNT SOLITAIRE (1:500 000 scale) support earlier reconnaissance work that suggested several major domains across the Tanami-MOUNT SOLITAIRE region (**Figure 1**). These domains include the Archaean Billabong Complex, Tanami Group, Surprise Igneous Province (including the Killi Killi Formation-equivalent Lander Rock Beds), Highland Rocks Metamorphic Complex, and Cambro-Ordivician Wiso Basin sediments (Hendrickx *et al* 2000a, b, Vandenberg *et al* 2001).

Billabong Complex Archaean granitic gneiss  $(2514 \pm 3 \text{ Ma}, \text{SHRIMP U-Pb zircon}, \text{Page 1995})$  displays a penetrative steep northwesterly dipping gneissosity that is overprinted by north-northeasterly dipping shear bands (eg at AMG 694690E-7712190N). The preservation of quartz-dynamic recrystallisation microtextures indicates that crystal-plastic deformation continued past the metamorphic peak.

Structurally overlying the Billabong Complex is the Thompson Quartzite (basal unit of Tanami Group). Contacts are not exposed, although overprinting relationships and the ENE strike of an  $S_2$  crenulation cleavage through the Thompson Quartzite are consistent with structural development in the structurally overlying Dead Bullock Formation (eg at AMG 711537E-7716499N). These relationships support previous suggestions that the Thompson Quartzite is a basal unit of the Tanami Group (Hendrickx *et al* 2000a).

The Surprise Igneous Province is defined as a northwest trending zone of deformed monzogranite, granodiorite and minor metasediment across central and eastern MOUNT SOLITAIRE, immediately to the south of the Wiso Basin. Granitic textures range from fine-grained equigranular to megacrystic and most are tectonically foliated. Porphyritic and megacrystic granites show a syntectonic flow alignment of phenocrysts. Megacrystic granites are similar to the Mount Stafford Granite (1820 Ma). A recent zircon SHRIMP age of  $1813 \pm 6$  Ma for the 'Fig Tree granodiorite' (AMG 778960E-7723516N) is consistent with widespread intrusive activity throughout the Tanami-North Arunta region during this period. Drilling in northeastern and southern MOUNT SOLITAIRE and northern MOUNT THEO is suggestive of extensive granite and granitic gneiss under shallow surficial cover.

Killi Killi Formation interbedded psammite and pelite in the Surprise Igneous Province (AMG 726087E-7747478N) is indistinguishable from the Lander Rock Beds in MOUNT PEAKE to the east (AMG 303850E-7601400N) and MOUNT THEO to the south (AMG 773540E-7594440N). Bedding in upper greenschist facies and alusite-biotite schist and psammite is well preserved. Structure is dominated by mesoscopic easterly plunging  $F_1$  folds with axial planar  $S_1$  schistosity. Two sets of crenulation cleavages ( $S_2/S_{3?}$ ) overprint  $F_1$  structures and are axial planar to northeast striking open folds. Late undeformed pegmatite dykes strike to the northwest.

The Highland Rocks Metamorphic Complex (HRMC) coincides with the Willowra Gravity Ridge, but does not outcrop in MOUNT SOLITAIRE. The HRMC is exposed throughout central-eastern HIGHLAND ROCKS, and consists of garnet-sillimanite gneiss, layered garnet-sillimanite pelite, migmatite and deformed granite (eg at AMG 616160E-7632717N). The HRMC is geophysically inferred to continue to the east through MOUNT SOLITAIRE. Preliminary peak P-T estimates from garnet-biotite-sillimanite-cordierite-quartz-kfeldspar-plagioclase gneiss (sample HR00MH44, AMG 622661E-7637074N) indicate pressures of 4-5 kbar and temperatures of 680-750°C (low pressure transitional upper amphibolite-granulite facies). Geophysical data indicate numerous crustal-scale shear zones through the HRMC. Preliminary geochronological results indicate that much of the deformation, metamorphism and granitoid intrusions through the HRMC may be younger (Late Strangeways events?) than events recognised in the Tanami (Tanami Orogenic Event, probably coeval with the Halls Creek Orogeny). Preliminary zircon SHRIMP U-Pb ages for the Fiddlers Lake granite suggest an intrusive or recrystallisation age of 1720 Ma (AMG 647425E-7681200N). The interpreted zircon SHRIMP age for the foliated biotite-bearing 'Dead Fox Granite' is 1785  $\pm$  4 Ma (AMG 654057E-7672860N).

Across MOUNT SOLITAIRE, late faults are marked by large quartz reefs and topographic lineaments. These structures continue to the east into MOUNT PEAKE, cut the Cambrian Central Mount Stewart Formation and indicate Palaeozoic tectonism and fluid movement. Many of these faults may be reactivated Proterozoic structures.

The southern edge of the Wiso Basin is similarly marked by southeast striking quartz reefs and topographic lineaments, as well as several small high-magnetic anomalies surrounded by lower magnetic and gravity zones. Reconnaissance across MOUNT PEAKE suggests that the magnetic anomalies are amphibolitized dolerite within foliated granite (eg at Waldrons Hill AMG 238300E-7710400N). Whole rock elemental analysis of gabbro from the Waldrons Hill gold prospect returned Au and Pt values of 9 ppb and 5 ppb, respectively (sample NA1AC021).

The subhorizontal Hanson River Beds (quartzose dolomite) and unconformably overlying Lake Surprise Sandstone outcrop in the northeastern corner of MOUNT SOLITAIRE and constitute part of the Wiso Basin Palaeozoic stratigraphy (Kennewell and Offe 1979). Geophysical interpretation suggests that buried Davenport stratigraphy underlies the Wiso Basin (Donellan and Johnstone *pers com*). It remains to be determined whether the structural contact between the Wiso Basin and Proterozoic rocks of the north Arunta province dips steeply south (a thrust) or north (a normal growth fault).



MT SOLITAIRE 1:500 000 BASEMENT INTERP

Figure 1. Simplified MOUNT SOLITAIRE basement interpretation.

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#### TANAMI GOLD - WHAT HAS BEEN ACHIEVED AND WHERE TO FROM NOW?

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The Palaeoproterozoic Tanami Region is one of the most rapidly developing gold provinces in Australia. Its steadily growing gold resource currently stands at 12.5 Moz, including past production of 4.1 Moz. The entire Region contains some 60 gold occurrences. Most of these are concentrated in three goldfields – Tanami, The Granites and Dead Bullock Soak (DBS). Mined deposits usually contain reserves of 0.01-0.1 Moz Au. Unique in size and a notable exception is the Callie deposit (DBS goldfield). Prior to 30 June 2001, this open cut and underground mine produced 1.7 Moz Au and there is a remaining underground resource of 4.3 Moz Au. Other significant deposits include Groundrush (0.5 Moz Au), Titania (0.3 Moz Au) and Minotaur (0.1 Moz Au). The Coyote deposit in Western Australia also appears to contain significant mineralisation, but its resource has not been announced as yet.

In 1999, the Northern Territory Geological Survey commenced a major multidisciplinary project in the Tanami Province. This was designed to facilitate mineral exploration in the region by provision of a new generation of geological maps and the development of mineralisation models. Results of this work to date have been published in Hendrickx *et al* 2000, Dean 2001, Vandenberg *et al* 2001, Wygralak and Mernagh 2001 and Wygralak *et al* 2001.

Earlier reported metallogenic work (Wygralak and Mernagh 2001) concentrated on the delineation of physico-chemical characteristics, and the origin and evolution of hydrothermal fluids in the Tanami, The Granites and DBS goldfields. Pilot work has also been performed on the newly discovered Groundrush deposit.

Mineralising fluids in each of the goldfields have a unique physico-chemical signature. Fluids in the *Tanami goldfield* have a temperature range of 120-220°C and contain almost no gases. Mineralisation occurred at shallow depths of 0.4-1.8 km. Gold was precipitated as a result of decreasing pressure and temperature. In *The Granites goldfield*, fluid temperature was in the range 260-312°C and the fluid contained significant amounts of CO<sub>2</sub> mixed with minor CH<sub>4</sub> and N<sub>2</sub>. Gold precipitated due to reaction of the fluid with host rocks containing magnetite, graphite and, in the case of the Bullakitchie deposit, carbonates. The depth of mineralisation is estimated at 3.8–7.5 km. In the *Callie deposit* (DBS goldfield), mineralising fluid had a temperature of 310-330°C and contained CO<sub>2</sub> and N<sub>2</sub>, but no CH<sub>4</sub>. Gold precipitation occurred at a depth of 3.2–5.8 km as a result of the reaction of fluid with carbonaceous sediments. In the *Groundrush deposit*, fluid temperature was in the range 390-430°C. Fluid was dominated by CH<sub>4</sub> and there was a minor amount of CO<sub>2</sub>. Mineralisation occurred at depths of 5.7-8.3 km and phase separation was the precipitation mechanism.

During the 2001 field season, similar studies were conducted on gold occurrences in the Winnecke area, Falchion prospect and White Range deposit. In the *Winnecke area*, spotty gold mineralisation in quartz veins hosted by the Winnecke Granophyre was previously reported by Otter Gold. Fluid inclusion and Raman spectrometry work on samples from this locality revealed that gold-related fluids had a temperature range of 200-220°C and contained only minor amounts of CO<sub>2</sub> and CH<sub>4</sub>. Fluid inclusion data indicate that gold was precipitated from a boiling fluid at shallow depths of 0.4-0.5 km.

Auriferous fluids in the *Falchion prospect* had a temperature range of  $320-340^{\circ}$ C. Raman analysis indicated the presence of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>. These gases occur in extremely variable proportions. This indicates either the presence of several fluids or one fluid, which has interacted with a variety of rocks so as to generate locally high CH<sub>4</sub> during reaction with graphitic rocks and N<sub>2</sub> during reaction with sedimentary rocks. Another group of inclusions contains graphite, suggesting the presence of an additional strongly reduced fluid. At this stage, there are insufficient data to estimate the depth of mineralisation.

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Fluid inclusion and Raman work performed on Heavitree Quartzite-hosted gold mineralisation in the *White Range deposit* revealed boiling fluids, with temperatures in the range 320-340°C. Gold precipitated at a depth of 2 km as a result of fluid boiling.

An important finding from our work is that granites played no genetic role in gold mineralisation, despite a close spatial relationship between mineralisation and felsic intrusions. This statement is based upon different Pb/Pb isotopic signatures of granites and auriferous sulfides, and on the age difference between the intrusives and mineralisation. The former appear to be about 100 million years younger. Close spatial relationships between felsic intrusives and some gold deposits most likely indicate that the intrusives provided a favourable structural setting for mineralising fluids.

A  $1710 \pm 20$  Ma  $^{40}$ Ar/ $^{39}$ Ar age has been obtained for biotite associated with ore-stage veins in Callie and similar younger ages have been obtained from the Titania and Galifrey prospects (Wygralak *et al* 2001). These are suggestive of a link with the Strangways Event (1720-1730 Ma), which was responsible for widespread deformation and metamorphism in the Arunta province to the southeast of the Tanami Region. This significantly enhances the gold prospectivity of Strangways terranes in the Arunta province.

Except for the Tanami goldfield, where fluids have a strong meteoric water signature, oxygen and hydrogen isotopes of fluids do not distinguish between magmatic and metamorphic origin. The provenance of gold is therefore unclear, but it is likely that gold was scavenged from country rocks by high-pressure fluids circulating along  $D_5$  faults and percolating into surrounding rocks. Subsequent fault failures and a resulting sudden drop in pressure reversed the direction of gold-bearing fluids back into fault systems.

A pilot study has been conducted into the suitability of acoustic decrepitometry as a cheap and rapid exploration tool to detect  $CO_2$  in fluid inclusions hosted by hydrothermal quartz veins. In most cases,  $CO_2$  is a favourable gas component of fluids associated with gold mineralisation and its detection in quartz veins enhances their gold prospectivity. The decrepitometry was conducted on samples with fluid characteristics that were already known from previous microthermometric and Raman work. Based on the samples studied, decrepitometry has proved to be a credible method for detection of  $CO_2$  in inclusion fluids that contain  $CO_2$ -H<sub>2</sub>O±NaCl. However, the method has limitations and is unable to detect  $CO_2$  if it is mixed with significant amounts of other gases such as CH<sub>4</sub>.

Our future work will concentrate on: (i) tracing regional changes in the physico-chemical character of fluids; (ii) establishing the difference between fluids in mineralised and distant areas; and (iii) establishing the chronology of fluid flow. The first stage of this work will be focussed on THE GRANITES, HIGHLAND ROCKS, MOUNT SOLITAIRE and MOUNT THEO and will attempt to establish the differences in fluid characteristics between the Tanami and North Arunta provinces.

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