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AGES PROGRAM

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PREFACE

Abstracts in this volume are arranged in the order of presentation as per the program (reproduced above). Summaries of each talk are given before printouts of the PowerPoint presentations.

Throughout this volume, the names of 1:250 000 and 1:100 000 mapsheets are shown in large and small capital letters respectively, eg MOUNT PEAKE and ANNINGIE.

THE TANAMI IN 3-D

Leon C Vandenberg and Tony Meixner[1]
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The NTGS Tanami project has largely focused on developing a geological framework and mineralisation models for the Tanami Region in TANAMI and THE GRANITES (Hendrickx *et al* 2000, Crispe *et al* 2002, Wygralak and Mernagh 2002). This project is largely winding down, with publication of reports due during 2003. However, NTGS involvement with the Tanami is continuing with: (1) regional geoscientific studies of the Tanami Region in BIRRINDUDU, commencing in 2003; and (2) modelling of the three dimensional geological architecture of the Tanami region, in collaboration with Geoscience Australia. This presentation focusses on the 3-D modelling project, which commenced during 2002.

The New Tanami 3-D model

The web-served 3-D Tanami model integrates serial structural cross-sections and new gravity/magnetic forward modelling with other data (see below) to create 3-D and 2-D views of the geology in 3-D space. The format of the model enables simultaneous viewing and comparison of various datasets, and the model can evolve as new data is included.

To build the model, fifteen structural cross-sections have been integrated with forward modelled gravity and magnetics (**Figure 1**). This process required critical assessments of many of the assumptions previously made for the Tanami.

It is anticipated that the model and data contained therein will be of particular relevance to regional mineral exploration and target generation, and will be available as a free download from GA and NTGS.

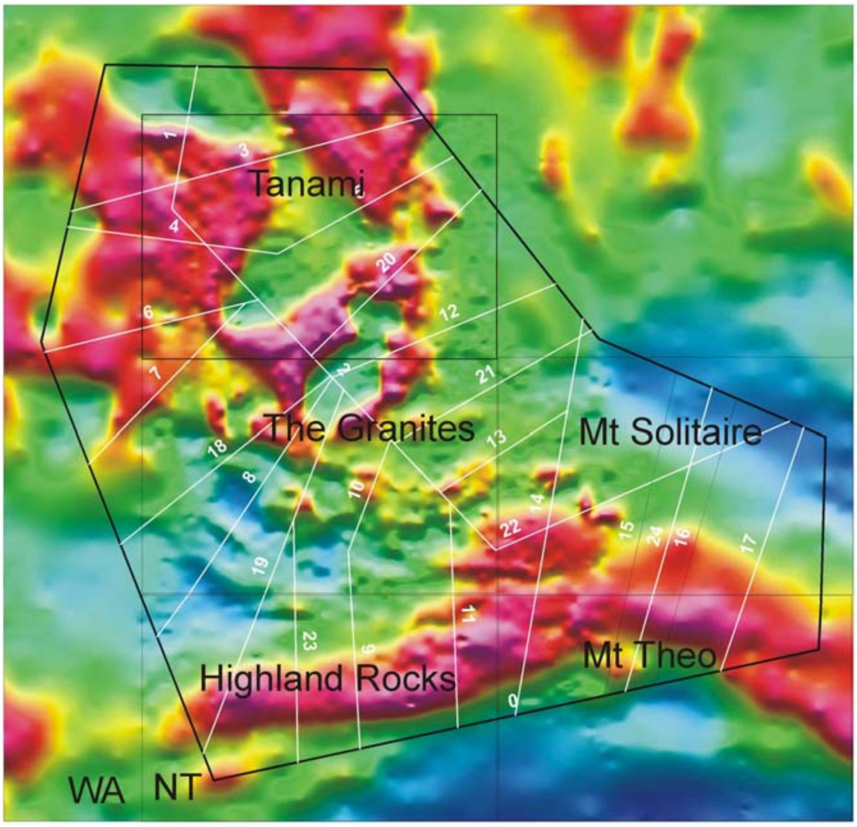

Figure 1. Tanami Region, regional gravity (Bouger; GA and NTGS data) showing positions of modelled cross-section lines. TANAMI, THE GRANITES, MT SOLITAIRE, HIGHLAND ROCKS, MT THEO mapsheets indicated.

Model: features

The following lists the basic features included in the Tanami 3D model:

- Fifteen 21/2-D structural cross-sections through the Tanami region (TANAMI and THE GRANITES) and part of north Arunta (HIGHLAND ROCKS).

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[1] Geoscience Australia, Canberra.

- Fifteen 21/2-D modelled sections derived from the integration of the structural sections with potential field forward modelling of regional gravity and magnetic data (GA and NTGS data).
- Major fault surfaces interpolated in 3D space.
- Regional gravity (11 km grid spacing, GA and NTGS data), regional magnetics (4 km grid spacing, NTGS and GA data).
- Surface outcrop and simplified basement geology.
- Regolith.
- Radiometrics.
- Mineral occurrences.
- DEM, track and tenement maps.
- Geochronological data.

The following features are to be included in the final model to enhance functionality:

- Image draping translucency.
- Dynamic slicing.
- Cursor/pointer locator.
- Context sensitive popup menues.
- Improved menu and toolbar icons.
- Web links to data repositories for download.
- Web links to existing databases and reports.

It is anticipated that 'wormed' gravity data will also be available for release with the model (multi-scale edge analysis, Archibald *et al* 1999). The full potential of this processed data is yet to be explored for the Tanami, but preliminary indications are that the data may be useful in defining major contacts and structural breaks at deep crustal levels.

An additional nine sections covering much of MOUNT SOLITAIRE and MOUNT THEO are planned for completion later this year.

Integrating Geology and gravity/magnetic forward modelling

Geophysical modelling of gravity and magnetic data is a powerful method with which to provide additional constraints on depth to basement and the shape and orientation of structures and bodies (Blewett *et al* 2002, Williamson *et al* 2002). However, without geological constraints, model sections can be created using an infinite number of bodies of different shapes and geophysical properties. Geophysical modelling may also be limited by the resolution of the gravity and magnetic data.

For the Tanami model, serial geological cross-sections were constructed prior to potential field modelling. Potential field modelling was then conducted using ModelVision, a 21/2-D interactive program. Subsequent geological and geophysical revisions resulted in the final modelled sections. The resolution of regional gravity data was limited to 11 km-spaced data and proved useful for modelling deep crustal structure. In contrast, higher frequency magnetic data (4 km spacing) were more suited to modelling near-surface crustal structure.

Cross-section positions were chosen such that many previously identified or interpreted faults, contacts and structures related to mineralisation were intersected at right angles. This effectively simulated a 2D environment along section lines for forward modelling. Where necessary, additional model lines were constructed to minimize 'offline' or 'remnant magnetism' effects.

For section construction, basic stratigraphic sub-divisions for the Tanami were adopted (Hendrickx *et al* 2000). Rock property values used for the modelling included standard density values which took into account metamorphic grade and proportions of various rock types (eg siliciclastic sediments vs mafics). Magnetic susceptibility values broadly took into account the various rock types and fell within acceptable ranges for the given rock compositions.

Serial geological sections and subsequent modelling has resulted in a model that displays a reasonable level of internal consistency. The fact that many section lines intersect the same features at different angles and yield similar results encourages a reasonable level of confidence in modelled geometries. It should be noted that while the model has been constructed to 15 km depth, the ability to confidently model geometries below approximately 8 km depth rapidly diminishes and is dictated by the need to maintain geometrical and stratigraphic consistency. In addition, although fault positions and offsets are reliable, fault geometries are largely hypothetical and additional information (eg seismic data) are needed to further constrain fault architecture.

Preliminary findings

In addition to major contacts and unconformities, the position, gross geometry and displacement of several major faults have been identified. The faults have been subdivided into several categories based on fault type and generation (using the structural scheme describe in Vandenberg 2001). Several of these faults have close spatial relationships with gold-mineralised areas (eg Bluebush Fault at Jims Find and Callie deposits). The identification of several large-scale normal fault systems and preliminary indications of reactivation as late thrusts (post Birrindudu Group inversion) may be directly relevant to the tectono-stratigraphic development and metallogenic history of the Tanami Region.

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HYDROTHERMAL FLUIDS IN THE TANAMI/NORTH ARUNTA BOUNDARY ZONE: PRELIMINARY RESULTS

Andrew S Wygralak and Terrence P Mernagh[1]
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Recent work by NTGS and GA has established stratigraphic correlations between units in the Tanami and north Arunta Regions. Therefore, it is important to examine whether gold-producing hydrothermal systems in the Tanami extend to the southeast into the Arunta. Earlier metallogenic work (Wygralak and Mernagh 2001) concentrated on the study of physico-chemical characteristics, and on the origin and evolution of hydrothermal fluids in areas of known gold mineralisation within the Tanami Region (Tanami, The Granites and DBS Goldfields; Callie and Groundrush Mines). Limited studies were conducted in the Winnecke area, on gold prospects located within the north Arunta Region (Falchion) and on the White Range deposit in the Arltunga Goldfield (Wygralak and Mernagh 2002).

Currently we are extending these studies into the north Arunta Region. The aim of this approach is threefold: (i) to delineate differences in fluid characteristics between gold-bearing localities and those from distant areas; (ii) to trace regional changes in the physico-chemical character of fluids; and (iii) to establish a fluid chronology.

More than 100 quartz vein clusters, located in regions with differing metamorphic grade and in some cases mineralised (Au, Cu, Sn, W, Pb), were selected for sampling on twelve 1:250k mapsheets extending from the Tanami to the Davenport Province. Work done in 2002 concentrated on THE GRANITES, HIGHLAND ROCKS, MOUNT SOLITAIRE and MOUNT THEO. This area was selected for the first stage of the regional investigation because it spans the proposed Tanami/Arunta boundary.

Field observations revealed several textural varieties of vein quartz:

- Epithermal veins, with a range of typical high-level features such as chalcedony, colloform quartz, dog teeth textures and amethyst concentrate along the structural margin with the Wiso Basin (MOUNT SOLITAIRE), in the western part of TANAMI and in the northern part of MOUNT THEO. In many cases, these veins consist of earlier chalcedonic quartz, which is brecciated and cemented by coarse white quartz. These veins are dominated by relatively low temperature (120-180°C) and very low salinity (0.2-0.3 wt% NaCl eq.) fluids, with no gases in the vapour phase of fluid inclusions. A small number of high salinity (18-24 wt% NaCl eq.) inclusions also suggests a second 'boiled off' fluid. A wide range of calculated $\delta^{18}O$ fluid values (-20.4‰ to +5.4‰) supports the presence of more than one fluid, including exchanged meteoric water and magmatic/metamorphic fluid.

- A distinctive zone of east-northeast-trending quartz veins, characterised by granular texture, located in the northern half of HIGHLAND ROCKS. Fluid inclusion data obtained from these veins indicate the presence of two fluids. The first fluid has a temperature range of 230-330°C, low salinity and a vapour phase containing $CO_2>CH_4>(N_2)$. The second fluid has a lower temperature range (120-230°C), high salinity and no gases in the vapour phase. Calculated $\delta^{18}O$ of both fluids are in the range 0.8-4.6‰ and indicate mixed magmatic and/or metamorphic water.

- A zone of predominantly east–west-trending veins in the northwest corner of MOUNT SOLITAIRE and northeast corner of THE GRANITES. These veins contain a variety of quartz textures, but have similar fluid characteristics. Fluid inclusion and Raman microprobe work indicate the presence of two fluids. The first fluid has a temperature range of 320-360°C, low salinity and contains $CO_2>CH_4$±graphite. The second fluid has a temperature in the range 120-230°C, high salinity and no gases in vapour phase. Calculated $\delta^{18}O$ of both fluids range from -0.7‰ to 4.2‰, indicating mixed meteoric plus magmatic and/or metamorphic water.

- An array of quartz veins with unique fluid characteristics is hosted by quartzite at Mount Davidson (MOUNT SOLITAIRE). It is unclear whether the host quartzite represents the lower part of the Tanami stratigraphic sequence, or whether it is a silicified tectonic breccia. At least three fluids were recognised here: *fluid I* with a temperature range of 260-310°C, moderate salinity of 6-8 wt % NaCl eq. and a vapour phase containing $CO_2>>CH_4$; *fluid II* with a temperature range of 140-180°C, salinity of 2-8 wt % NaCl eq. and no gasses in the vapour phase; and *fluid III* with a temperature range of 220-260°C and a moderate salinity of 6-14 wt % NaCl eq. This fluid has a vapour phase completely dominated by CH_4 and in some cases contains up to 8 vol.% $\mathbf{H_2S}$. It is the only locality in the entire Tanami/north Arunta area where H_2S was detected in the vapour phase of fluid inclusions.

- A zone of veining in the southern half of MOUNT THEO. This zone of veining is characterised by the domination of one fluid characterised by low temperature (120-190°C), high salinity (19-30 wt% NaCl eq.) and a lack of gases in the vapour phase.

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[1] Geoscience Australia (GA).

Ar-Ar dating[2] indicates that the sampled veins represent at least two generations. The older generation, located within the Tanami Province, has returned ages similar to those obtained previously from gold-bearing localities (eg Callie) in this Province (Wygralak *et al* 2001). The younger generation located within the north Arunta Region has distinctly younger ages (**Table 1**).

TANAMI REGION		NORTH ARUNTA REGION	
Sample number	**Ar-Ar age in Ma**	**Sample number**	**Ar-Ar age in Ma**
11892	1700 ± 1	11922	1432 ± 12
11889	1708 ± 0.4	11951	1490 ± 1
11888	1718 ± 22	11921	1518 ± 2
11882	1741 ± 15	11961	1518 ± 10

Table 1. Ar-Ar dates obtained during 2002 work.

It is interesting to note that there is a similar 75-100 Ma age difference between quartz veining and granitic intrusives (1844 ± 4 Ma to 1791 ± 4 Ma; Smith 2001) in the Tanami Province, and between quartz veins and the youngest granites in the north Arunta Region (Southwark Granite Suite, 1567 ± 15 Ma; Young *et al* 1995).

The above preliminary data, in addition to existing information (such as differing geophysical signatures, different metamorphic grades, stratigraphic discontinuity), indicate that a northeast-trending line, separating two different terranes, can be drawn across HIGHLAND ROCKS and MOUNT SOLITAIRE. It is proposed that this line reflects a border zone between the Tanami and north Arunta Regions. Noted differences on both sides of this zone include:

1. Tanami Region.

- Higher temperature, low salinity fluids with the common presence of $CO_2 \pm CH_4 \pm N_2 \pm H_2S$.
- Fluids are regionally uniform and are similar to ore-stage fluids studied earlier (Wygralak and Mernagh 2001) in localities with known gold mineralisation (eg Callie, Groundrush).
- Quartz veining of average age 1720 Ma postdates granitic intrusions of this Region and coincides with the Early Strangways Event.
- Almost all known gold occurrences are located within this Region.

2. North Arunta Region.

- Low temperature, high salinity fluids with no gases in the vapour phase.
- Younger quartz veining of average age 1490 Ma, postdating the Southwark Granite Suite dated at 1565 Ma.

These differences should be considered when assessing the mineral potential of both regions.

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[2] Ar-Ar data presented in this study were obtained from the Western Australian Argon Isotope Facility operated by a consortium consisting of Curtin University and the University of Western Australia.

GEOLOGICAL RELATIONSHIPS BETWEEN THE TANAMI AND NORTH ARUNTA REGIONS: EVIDENCE FROM ^{40}AR/^{39}AR GEOCHRONOLOGY

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Considerable uncertainty surrounds the relationship between the Tanami and North Arunta Regions of central Australia. Previous ^{40}Ar/^{39}Ar geochronology in the Tanami Region has revealed an episode of hydrothermal activity, probably associated with Au-mineralisation at the Callie deposit, at about 1730-1710 Ma. This is also the time of the Strangways Orogeny in the Arunta Region to the south, raising the possibility that fluid-flow and mineralisation in the Tanami may have been causally linked to tectonic activity in the Arunta Region. This study investigates potential tectonic links between the Tanami and North Arunta Regions via ^{40}Ar/^{39}Ar thermochronology. New ^{40}Ar/^{39}Ar results reveal systematic variations in thermal histories for the Tanami, North Arunta and intervening regions, helping to elucidate tectonic relationships between the Tanami and regions to the south.

Samples were collected along a northwest to southeast traverse from the Tanami Region to the northwest Arunta, and come predominantly from granitoid rocks, most of which have intrusive ages known from U-Pb zircon analyses. Within the limits imposed by sparse outcrop and low sampling density, the ^{40}Ar/^{39}Ar results fall into three geographic groupings: i) the Tanami Region; ii) the region immediately to the south of the Tanami; and iii) the northwest Arunta Region.

Micas from regional granites in the Tanami preserve ^{40}Ar/^{39}Ar ages in the range 1750-1810 Ma, best interpreted as cooling ages following magmatism and deformation during the Tanami Orogenic Event (TOE; 1835-1820 Ma) and Stafford Event (1810-1800 Ma). K-feldspars from Tanami granites yield age spectra with significant age gradients, suggestive of initial isotopic closure following the TOE and variable isotopic resetting during or immediately after the Chewings Event (1590-1570 Ma). No evidence for events younger than the Chewings Event is found in the ^{40}Ar/^{39}Ar record of rocks from the Tanami.

South of the Tanami lies a region of very sparse outcrop, where correspondingly little is known of the Proterozoic basement geology. Migmatitic gneisses found at Fiddlers Lake, in the southwest corner of THE GRANITES, yield mica ^{40}Ar/^{39}Ar ages of 1550-1570 Ma, indicative of cooling through about 300°C immediately following the Chewings Event. Micas from isolated gneissic and granitic outcrops in the northern part of HIGHLAND ROCKS and MOUNT THEO are indistinguishable from those from Fiddlers Lake. These results indicate that the thermal effects of the Chewings Event, previously recognised in the southeast Reynolds Range, were felt several hundred kilometres further north. K-feldspars from Fiddlers Lake suggest relatively slow cooling following the Chewings event, as shown by steadily rising age spectra with ages in the range 1400-1550 Ma. K-feldspars from the HIGHLAND ROCKS and MOUNT THEO areas show variable isotopic resetting to ages as young as 800 Ma.

Still further south, granitoid samples from the northeast part of MOUNT DOREEN yield ^{40}Ar/^{39}Ar results indicative of more pervasive post-Chewings isotopic resetting. There is evidence for resetting at 1200–1100 Ma, possibly corresponding to the Teapot magmatic event in the southern Arunta, and also at 400 Ma, corresponding to the Alice Springs Orogeny. Evidence for resetting at 1200-1100 Ma is seen in both micas and K-feldspars, whereas the effects of the Alice Springs event are recorded only in the K-feldspars.

Taken together, these results demonstrate the utility of ^{40}Ar/^{39}Ar geochronology as a sensitive indicator of thermal histories. The Ar isotopic record in Palaeo- to Mesoproterozoic granitoids preserves evidence of most of the major tectonothermal and orogenic events known from central Australia (Tanami, Strangways, Chewings, Teapot and Alice Springs events), although each event is recorded with varying intensity from the Tanami to north Arunta Regions.

The general trend in the data indicates that successive overprinting tectonic events increase in intensity to the south. For example, in the Tanami Region, the Chewings Event is seen only in the partial resetting of the least retentive sites in K-feldspars, indicating that temperatures probably did not exceed 200-250°C. This is consistent with the Tanami Region having been exhumed to shallow crustal levels (<10 km depth) within a few tens of million years after the Tanami Orogenic Event. In contrast, immediately to the south of the Tanami, no pre-Chewings Ar ages are preserved in either feldspar or biotite. Such pervasive isotopic resetting suggests temperatures significantly above 300°C in this region during the Chewings event. This difference in apparent intensity of the Chewings event could indicate either: i) a regional gradient in intensity of the Chewings event; or ii) the region south of the Tanami was at a deeper crustal level than the Tanami during the Chewings event. It is not easy to confidently distinguish between these two scenarios. The metamorphic grade of rocks south of the Tanami is higher than that within the Tanami, consistent with these rocks having a deeper crustal origin prior to the Chewings event, which may have been maintained until exhumation during the Chewings event. If this scenario is correct, it has important implications for the prospectivity and style of potential Au-mineralisation south of the Tanami. Most of the known Au occurrences in the Tanami are found in low-grade metamorphic rocks, and appear to have been focused and precipitated along brittle fracture and vein systems. If, as seems likely, the region south of the Tanami was at deeper crustal levels, below the brittle-ductile transition up until Chewings time, the potential for fluid-focusing and mineralisation along brittle deformation features is reduced.

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[1] Geoscience Australia

DEFINING THE TANAMI-ARUNTA BOUNDARY:TECTONIC AND EXPLORATION IMPLICATIONS

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"*Its [the Arunta Block] contact with The Granites-Tanami Block to the north appears to be gradational, and the boundary between the two Blocks is an arbitrary one, taken for convenience, where the units of the blocks are concealed beneath Birrundudu Basin sediments and superficial Cainozoic deposits*." (Blake *et al* 1979, p 26)

Numerous gold deposits are hosted in the Tanami Region, including the >4 million oz Callie deposit. Therefore, defining the extent of highly prospective Tanami rocks will greatly affect prospectivity and exploration models for the Arunta Region to the south. An arbitrary Tanami-Arunta boundary was previously defined, although considered gradational (Blake *et al* 1979), and interpretation of regional gravity data had suggested significant crustal density variations between the two regions (Flavelle 1965). We present evidence that there are substantive differences across the proposed Tanami-Arunta boundary, although both regions shared some important geological events. The proposed boundary requires refinement, but is probably defined by a complex series of faults which repeatedly influenced tectonothermal activity and sedimentation.

Regional gravity and aeromagnetic data show broad contrasts between the Tanami and Arunta Regions and can be used to define an approximate boundary. The east–west-trending Willowra Gravity Ridge in the Arunta Region is up to 60 mgal greater than the Tanami Gravity Complex (Flavelle 1965), indicating that crustal composition or crustal thickness or a combination of both differ between the regions. Gross magnetic intensity is identical between the two regions, suggesting that the Willowra Gravity Ridge does not contain markedly different upper crustal rocks to the Tanami Region and precluding the presence of voluminous mafic rocks to account for the gravity contrast. The most likely scenario is that the Willowra Gravity Ridge corresponds to thinner crust, and hence shallower mantle, although current seismic models are too poorly constrained in the area to test this hypothesis (Clitheroe *et al* 2000). Gravity and magnetic forward modelling indicate that the northern margin of the Willowra Gravity Ridge in HIGHLAND ROCKS dips about 30° north beneath the Tanami Region. The gross shape of the Willowra Gravity Ridge corresponds to a well defined subparallel magnetic texture, quite different from the ovoid magnetic texture in the Tanami Region, providing a further reason for defining a Tanami-Arunta boundary.

The Tanami Region comprises numerous ≤1865 Ma siliciclastic-dominated sedimentary successions that were deposited onto late Archaean gneissic basement. Significant tectonothermal activity from 1844 Ma to 1790 Ma coincided with regional folding, low-grade metamorphism and voluminous granite intrusion. Later tectonic activity was restricted to sedimentation, brittle deformation and hydrothermal veining. The basal succession (Tanami Group) was deposited at 1865-1840 Ma and comprises interbedded siltstone and sandstone with lesser carbonaceous shale and volcanic rocks. Major gold deposits are hosted in the Tanami Group and so it is an important exploration target. The Dead Bullock Formation (middle Tanami Group) contains mafic volcanic and carbonaceous chert units, which provide useful marker horizons for field mapping, and distinct magnetic horizons, which can be traced using magnetic data. The Dead Bullock Formation cannot be traced south of the proposed Tanami-Arunta boundary. However, the Killi Killi Formation (uppermost Tanami Group) does extend south of the proposed boundary and, based on detrital zircon populations, probably correlates directly with the Lander Rock Beds in the wider Arunta Region. Therefore, the boundary constrains the extent of the Dead Bullock Formation, but not the overlying Killi Killi Formation. This situation is consistent with the boundary being an active fault between 1865-1840 Ma, so as to form a Dead Bullock sub-basin, which overfilled during Killi Killi deposition.

The proposed Tanami-Arunta boundary can also be defined by an abrupt change from greenschist-and lowermost amphibolite-facies schists in the Tanami Region to gneisses and migmatites in the northern Arunta. Although there are greenschist-facies rocks further south in the Arunta, there are no known high-grade rocks younger than 1865 Ma in the Tanami Region. Ar-Ar dating of mica and feldspar from various rocks types indicate that the Tanami Region cooled below about 350°C between 1750-1800 Ma with partial resetting of feldspar (about 200°C) at 1580 Ma, whereas the Arunta rocks cooled below about 350°C between 1550-1570 Ma with partial resetting of feldspar at 1150 Ma and 300 Ma (Fraser, this volume). Further evidence of temporal thermal variations between the regions is provided by fluid inclusion compositions and muscovite Ar-Ar ages of veins on either side of the boundary (Wygralak and Mernagh, this volume). Therefore, the Tanami-Arunta boundary marks a significant metamorphic contrast reflecting distinct thermal histories. Such contrasting histories may also explain the limited southern extent of overlying cover successions, including the Birrundudu Group and Antrim Plateau Basalts, in the Tanami Region.

Preliminary zircon dating (SHRIMP U-Pb) of northern Arunta granites indicate the presence of ages similar to those of the Tanami granites (1840-1790 Ma), but with an additional magmatic event at about 1720 Ma which is so far unrecorded, except from Ar-Ar of some biotites, in the Tanami Region. Ongoing geochemical studies, including Nd isotopes, will hopefully provide further constraints between Tanami and Arunta granites, if they exist.

Using the above criteria, the Tanami-Arunta boundary can be quite well defined, although poor outcrop and complex magnetic patterns in some areas, such as around East Granites and the Billabong Complex, makes the precise position of the

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boundary more uncertain. The boundary probably represents a complex series of faults, which were repeatedly active during various tectonic events and affected sedimentation and tectonothermal activity. That said, there are strong similarities between the Tanami and Arunta Regions, including the continuation of the Killi Killi Formation and 1840-1790 Ma granites, and these observations should be considered in any exploration models.

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EXPANDING THE TENNANT REGION: MAPPED AND INTERPRETED GEOLOGY OF THE MOUNT PEAKE AND LANDER RIVER 1:250 000 SHEETS

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Geological mapping and geophysical interpretation have been undertaken in MOUNT PEAKE* and LANDER RIVER in the eastern north Arunta Region as part of the Tennant-Tanami link project. Outcrop is largely confined to ANNINGIE, MOUNT PEAKE, and southern CONICAL HILL in MOUNT PEAKE, and along the southern margin of the Lander Trough in LANDER RIVER. This paucity of outcrop necessitates reliance on geophysical *interpretation* to elucidate the probable Palaeoproterozoic framework in a large part of the area. Some preliminary interpretations are presented here based on 400 m and 500 m line-spaced magnetic data for LANDER RIVER and MOUNT PEAKE respectively, and 11 km-spaced BMR gravity data.

Outcropping geology in MOUNT PEAKE and LANDER RIVER includes phenocrystic biotite-granites, with elongate K-feldspar megacrysts, and wiborgitic and pyerlitic textures typical of classical rapakivi granites. Equigranular two-mica granites are a probable local textural variant of the phenocrystic granites, but also occur as discrete about 1730 Ma (A Cross, Geoscience Australia, pers comm 2002) plutons. All granites are deformed with fabrics ranging from gneissic to combined planar and linear flow structures which are well defined by the K-feldspar megacrysts. Phyllonites are developed locally. Preliminary interpretations suggest that the granites include plutons, which were syntectonic with respect to the Murchison/Stafford Event (1810-1790 Ma), Yambah Event (1770 Ma) and Strangways Orogeny (1730 Ma).

Outcrop in eastern ANNINGIE is dominated by the Neoproterozoic basal succession of the Georgina Basin, the Amesbury Quartzite and Central Mount Stuart Formation. It is possible that rocks previously mapped as the Vaughan Springs Quartzite on MOUNT PEAKE and eastern GILES may in fact correlate with the Palaeoproterozoic Mount Thomas Quartzite of the Reynolds Range Group.

The remaining outcrop comprises the Lander Rock beds and correlative Mount Stafford beds. In the vicinity of the Anningie Tin Field, the Lander Rock beds comprise interbedded slate and sandstone and have been mapped as the Wallabanba Slate. These rocks include andalusite schist proximal to granite. Lander Rock beds outcropping in the Central Mount area are predominantly schistose and have been mapped as the Anningie Schist. These rocks may represent a more distal facies to the probably proximal Wallabanba Slate. However, geophysical interpretation (see below) further suggests that the Anningie Schist is an older lithostratigraphic unit than the Wallabanba Slate. Lander Rock bed stratigraphy, including both the Wallabanba Slate and Anningie Schist, also includes poorly outcropping dolerites and retrogressively metamorphosed mafic rocks. The Mount Stafford beds consist of slate, schist and metasandstone, and their low pressure upper amphibolite to granulite facies equivalents (Vernon *et al* 1990), together with metamorphosed mafic rocks, in the northwestern Anmatijira Range.

Geophysical data show a clear extension of Tennant Region stratigraphy into northern LANDER RIVER. Individual formations of the Hatches Creek Group are readily interpreted in this area. Subdivision of the underlying Ooradidgee Group is more difficult. Ooradidgee Group rocks in this area probably correlate with the Kurinelli Sandstone, which is a facies variant of many of the lithostratigraphic units of the Ooradidgee Group mapped in the Davenport Province. Ooradidgee Group stratigraphy can be traced at depth under the Lander Trough on western LANDER RIVER indicating continuity with the Lander Rock beds on the southern margin of the trough. Similarly, the geophysical data further suggest continuity of Ooradidgee and Hatches Creek Group stratigraphy from the southeast (CRAWFORD and TAYLOR) into the vicinity of Waldrons Hill.

Geophysical data further indicate that much of MOUNT PEAKE and southern LANDER RIVER are dominated by granite. However, consistent with field relationships, there are many pendants and screens of Lander Rock beds within and between these granite bodies. A magnetic character comparable with that of the Junalki Formation in TENNANT CREEK and BONNEY WELL, and the Treasure Volcanics of the topmost Ooradidgee Group in the Davenport Province allow recognition of the base and top respectively of Lander Rock beds stratigraphy in MOUNT PEAKE and LANDER RIVER. A major northwest-trending, faulted syncline and anticline can be recognised in the magnetic data in central MOUNT PEAKE. Alternating magnetic and non-magnetic intervals within these folds suggest that Lander Rock beds stratigraphy can be divided into seven units based on their magnetic character. As noted above, units 1 and 7 are correlated with the Junalki Formation and the Treasure Volcanics respectively. Extrapolation indicates that unit 2 equates with the Anningie Schist and unit 4 with the Wallabanba Slate. These units probably broadly equate with the Woodenjerrie Formation (sedimentary lithofacies) and the Rooneys Formation of the Ooradidgee Group. Unit 3 is a possible correlative of the Woodenjerrie Formation volcanic lithofacies.

It is noted that the volcano-sedimentary Junalki Formation is a time equivalent of the Warramunga Formation. However, it is uncertain whether the Junalki Formation was deformed during the 1860 Ma Tennant Orogeny. Lithologically it is akin to Ooradidgee Group stratigraphy and distinct from the turbiditic Warramunga Formation. Recognition of a probable correlative magnetic unit at the base of the Lander Rock beds (see above) raises an important question concerning the lateral extent of orogeny in the Tennant and north Arunta Regions, penecontemporaneous with the Tennant Orogeny in the Warramunga Province. Prior to resolution of this question, it is suggested that the Junalki Formation should be included in the Ooradidgee Group, and that Lander Rock beds on Mount Peake are probably a correlative of the entire Oorodidgee

Group in the Tennant Region. Magnetic data further indicate that the Bullion Schist in BARROW CREEK is similarly a correlative of the entire Lander Rock beds succession on MOUNT PEAKE. However, whereas intervals analogous to the Junalki Formation and Treasure Volcanics are recognisable within the Bullion Schist, the intervening magnetic material cannot be further subdivided, in contrast to the Lander Rock beds.

Geological mapping and geophysical interpretation indicate that the Lander Rocks beds, the Bullion Schist and Ooradidgee Group are thus equivalent intervals of stratigraphy and predate regional deformation at about 1805 Ma (Stafford/Murchison Event). It is noted that the Ooradidgee Group is characterised by lateral facies variations around localised volcanic centres. Relatively high gravity and total magnetic intensity in the northeast of MOUNT PEAKE may indicate a further volcanic centre. However, it is suggested that the Lander Rock beds, in MOUNT PEAKE, are generally characterised by a more layer-cake stratigraphy than the Ooradidgee Group. This is consistent with a possible shallow marine setting transitional between the proximal Ooradidgee Group and the distal Lander Rock beds turbiditic succession that extends northwest from NAPPERBY and MOUNT DOREEN.

Thus, the indications are that there is lithostratigraphic continuity between the Tennant Region and the north Arunta Region prior to the 1805 Ma Stafford/Murchison Event. Hatches Creek Group stratigraphy can be clearly seen extending northwest from the Davenport Province under cover into LANDER RIVER (and beyond). Correlation between the Hatches Creek Group and the Tomkinson Creek Group (on northern TENNANT CREEK and southern HELEN SPRINGS) is well established. However, direct continuity between these groups is not evident in outcrop and has not yet been demonstrated in the airborne magnetic data. This has an important bearing on the possible regional extent of a domical feature associated with Warramunga Formation and Tennant Creek Supersuite granites in TENNANT CREEK. Continuity is apparent between Hatches Creek Group rocks in the Taylor and Crawford Ranges on BARROW CREEK and the Davenport and Murchison Ranges. In contrast, continuity between Hatches Creek Group and the Reynolds Range Group has not been demonstrated. The regional extent of tectono-lithostratigraphic packages subsequent to the Stafford/Murchison Event may be intimately interrelated with the area of influence of the Yambah, Strangways and Davenport Orogenies. Therefore, they have a very important bearing on unraveling the later Palaeoproteozoic history of the Tennant and Arunta Regions.

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REDEFINING THE WARUMPI PROVINCE

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Introduction

Evidence for an extensive younger terrane on the southern margin of the North Australian Craton was presented at AGES 2002 (Scrimgeour *et al* 2002, Edgoose *et al* 2002), building on the concept of a 'Southern Tectonic Province' in the Arunta that was first recognised by Shaw *et al* (1984). Further collaborative work by NTGS and GA has resulted in the definition of the boundary and evolution of this terrane (newly named the Warumpi Province) and its potential for mineral prospectivity.

The Warumpi Province (**Figure 1**) is an east–west-trending terrane that extends along the southern margin of the Arunta, west of Alice Springs. It can be divided into two fault-bounded domains with discrete protolith ages and metamorphic grades (Edgoose *et al* 2002). In the south, the amphibolite facies Haasts Bluff Domain comprises metasedimentary successions with protolith ages of about 1680 Ma and 1630-1610 Ma, and igneous protolith ages of 1690-1660 Ma. The granulite facies Yaya Domain in the north has a 1660-1650 Ma metasedimentary succession, intruded by 1640-1630 Ma intrusive rocks. Tectonic events occurred in the Warumpi Province at 1640-1630 Ma (Liebig Orogeny, Scrimgeour *et al* 2002), 1590-1570 Ma (Chewings Event), 1150 Ma (Teapot Event) and about 430 Ma (early Alice Springs Orogeny). The entire evolution of the Warumpi Province postdates the 1730-1720 Ma Strangways Orogeny (formally named the Late Strangways Event) that overprints large sections of the Arunta Region.

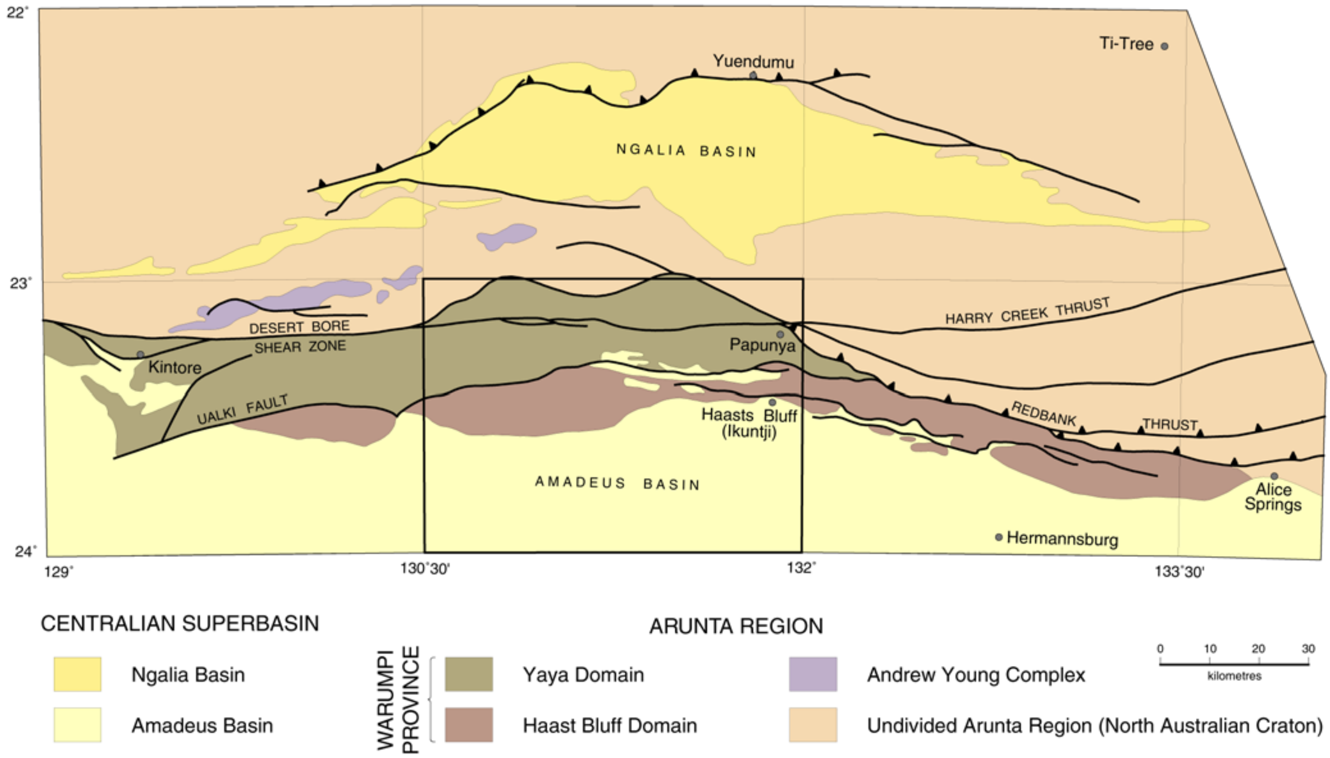

Figure 1. Map showing location of Warumpi Province adjacent to southern margin of NAC and subdivision into Haast Bluff and Yaya Domains.

Defining the boundaries of the Warumpi Province

At AGES 2002, the nature of the northern boundary of the western Warumpi Province remained uncertain (Edgoose *et al* 2002). New geochronology has established that in MOUNT RENNIE, the northern boundary of the Warumpi Province is defined by a major east–west strike-slip structure, the Desert Bore Shear Zone. Immediately north of the Desert Bore Shear Zone, low-grade pelites and psammites have a maximum depositional age of 1858 ± 5 Ma, suggesting that they form part of the Lander package of the North Australian Craton (NAC). These sediments are intruded by 1635 Ma gabbros and norites, and also by granites that have a SHRIMP U-Pb zircon age of 1640-1630 Ma, indicating that magmatism during the Liebig Orogeny extended into the NAC. This provides strong evidence that the Warumpi Province and NAC were juxtaposed by 1640-1630 Ma. Further east, in northern MOUNT LIEBIG, the northern margin of the Warumpi Province has been

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interpreted on geophysical evidence to be a structure north of the Desert Bore Shear Zone, whereas in HERMANNSBURG and ALICE SPRINGS the margin is defined by the Redbank Thrust and Charles River Thrust. The combination of faults that comprises the northern margin of the Warumpi Province is collectively known as the Central Australian Suture. It has been modified by multiple tectonic events during its history.

The Warumpi Province extends into Western Australia, where it includes the Mount Webb Granite and Pollock Hills Volcanics (Wyborn *et al* 1998) and is bounded to the west by the north-trending Lasseter Shear Zone at the western margin of the Arunta Region. The Warumpi Province is bounded to the east by an unconformable relationship between a 1630-1610 Ma cover sequence (Iwupataka Complex) and gneisses that are interpreted to belong to the North Australian Craton (Sadadeen Gneiss). The southern margin of the province is obscured by the Neoproterozoic to Palaeozoic Amadeus Basin. The exposed east–west extent of the Warumpi Province is around 650 km and the maximum exposed width of the terrane is 60 km.

Evolution of the Warumpi Province

The earliest recognised event in the Warumpi Province was large-scale granitic magmatism and felsic volcanism, along with minor sedimentation, during the Argilke Igneous Event at 1690-1660 Ma. This included the eruption of subaerial ignimbrites of the Peculiar Volcanic Complex at 1679 ± 3 Ma. These 1690-1660 Ma rocks are only present in the Haast Bluff Domain (Edgoose *et al* 2002).

At around 1660 Ma, part of the Haasts Bluff Domain was exposed, shedding sediments into a basin of unknown extent. Two distinct sediment packages were deposited, including an interlayered succession of mudstone and sandstone, and a heterogeneous unit of calc-arenites, calcareous sediments, mudstone, siltstone and quartz sandstone. Basaltic volcanism may have accompanied the deposition of some of these sediments. Later extensive tectonic overprinting obscures the original relationship between these two sediment packages. A maximum deposition age of 1660 Ma has been determined for the sediments, with deposition occurring in a marine environment. These successions now comprise the Yaya Metamorphic Complex. Within 10-20 million years of deposition, the sediments were buried to deep crustal levels, and metamorphosed during a major tectonothermal event, the 1640-1635 Ma Liebig Orogeny. During the Liebig Orogeny, large-scale lower crustal melting resulted in the intrusion of voluminous granites, granodiorites and charnockites throughout the Yaya Domain, along with deep crustal granulite facies metamorphism and intrusion of gabbros, including the 1635 Ma Andrew Young Complex. A volcanic succession in western MOUNT RENNIE, interpreted to be coeval with the 1640-1630 Ma magmatism, shows a geochemical continuum from felsic to mafic composition, thereby producing the first rocks of andesitic composition recognised in the Arunta Region (D Rawlings, NTGS, pers comm 2002).

The effects of the Liebig Orogeny varied across the Haast Bluff Domain. Upper amphibolite facies overprinting occurred in the west, whereas in the east, metamorphic grade reached lower amphibolite to greenschist facies. We have interpreted this major orogenic event to have resulted from the collision between the Warumpi Province and the North Australian Craton at 1640 Ma.

The Yaya Domain and Glen Helen Subdomain were rapidly exhumed following the Liebig Orogeny. Within 20 million years, the Haasts Bluff Domain was exposed and unconformably overlain by a succession of siltstone and arkose grading up to quartz sandstone (Iwupataka Metamorphic Complex). Deposition of these sediments probably occurred around 1620-1610 Ma. This was followed by burial of the entire Warumpi Province to depths of 15-20 km, where it was deformed and metamorphosed during a major compressional event, the Chewings Orogeny, from 1590-1570 Ma. Tectonic transport for the Chewings Orogeny was largely south-directed, and upper amphibolite facies non-coaxial strain fabrics developed throughout the Yaya Domain, whereas the Haasts Bluff Domain underwent mid- to lower amphibolite facies metamorphism. The Chewings Orogeny resulted in the juxtaposition of the Haasts Bluff and Yaya Domains along north-dipping shear zones. There is no known magmatism associated with the Chewings Orogeny in the Warumpi Province.

Following the Chewings Orogeny, a greenschist facies retrogressive event occurred at some stage between 1570 Ma and 1150 Ma, with fluid flow and localised deformation resulting in new muscovite growth. A major thermal event at 1150 Ma, the Teapot Event, led to widespread isotopic resetting and pegmatite intrusion, along with localised upper amphibolite facies migmatisation and zircon rim growth. This may relate to the Musgravian Event, which resulted in high-grade metamorphism and granite intrusion in the Musgrave Block at this time.

New ^{40}Ar/^{39}Ar data from MOUNT LIEBIG (S McLaren and J Dunlap, ANU, pers comm 2003) suggests that structural interleaving of the Warumpi Province with basal Amadeus Basin successions occurred in the early stage of the Alice Springs Orogeny at around 430-400 Ma. The Ar/Ar data also suggests that many of the greenschist facies shear zones within the Warumpi Province are Mesoproterozoic rather then Palaeozoic in age.

Mineral Prospectivity

Small but locally high-grade base metal prospects occur within the Haast Bluff Domain at Stokes Yard and Ulpuruta (formerly known as Nickel Hill). The Stokes Yard Prospect (western HERMANNSBURG) has a mineralised zone 75 m long and 15 m wide, with an average grade of 2.8% Pb, 2.8% Zn, 0.3% Cu and 35ppm Ag (Fruzetti 1972). The Ulpuruta Prospect (eastern MOUNT LIEBIG, Barraclough 1975) comprises Pb-Zn mineralisation in two isolated outcrops 300 m apart and its subsurface extent is unknown. The host successions for these deposits comprise calc-silicate (predominantly massive tremolite and actinolite schist) and forsterite marble. These were previously thought to form part of the 1690-1660 Ma Madderns Yard Metamorphic Complex. However, recent preliminary geochronology now indicates the maximum deposition age for the host succession to be about 1640 Ma. At this stage, it is interpreted that this succession represents high-grade equivalents of the 1640-1600 Ma Iwupataka Metamorphic Complex. Pb isotope data from these prospects (Huston *et al*, this volume) suggest that the Pb was derived from a much more primitive source than Pb in the NAC, implying that the Warumpi Province represents more primitive crust than the rest of the Arunta.

A second style of mineralisation within metasediments of the Iwupataka Complex is the Haasts Bluff Cu (±Au) Prospect (Barraclough 1975). At the surface, the prospect is represented by malachite and azurite mineralisation associated with variably sheared and brecciated hematite-rich actinolite schist and hornblende amphibolite. Limited geochemistry by NTGS revealed elevated gold (0.3 ppm), silver (2 ppm), lead and zinc, associated with copper mineralisation (3% Cu). Additional malachite occurrences were observed during field mapping of the area. Stream sediment geochemical results from NTGS (Dunster and Mügge 2001) identified anomalous Au (12.17 ppb), Bi (2 ppm), Pb (91 ppm) and elevated Zn (79 ppm) from the Iwupataka Metamorphic Complex in the Haasts Bluff region, confirming that this succession is prospective for base metals and, to a lesser extent, gold. Recent mapping has established that sediments of the Iwupataka Complex occurs further west in MOUNT RENNIE, where a lower amphibolite facies metasedimentary succession has a preliminary SHRIMP U-Pb maximum deposition age of 1620-1615 Ma. Given the widespread extent and poor outcrop of this prospective succession in MOUNT LEIBIG and MOUNT RENNIE, the Iwupataka Complex should be a focus for future exploration in the region.

Future Work

Geological fieldwork has been completed in MOUNT LEIBIG and MOUNT RENNIE, and maps and explanatory notes will be released during 2003. Investigations in the Warumpi Province in 2003 will focus on the geochemistry of granitic and mafic rocks, with an emphasis on understanding the tectonic environment and metallogenic potential of the magmatic suites. This study is likely to be undertaken by Geoscience Australia in collaboration with NTGS. One aim of the study will be to determine whether any evidence exists for alteration systems with potential for Cu-Au mineralisation, similar to the alteration in the Mount Webb Granite of the Warumpi Province in Western Australia (Wyborn *et al* 1998). In addition, targeted studies of the eastern Warumpi Province in HERMANNSBURG and ALICE SPRINGS will be undertaken, leading to the compilation of a synthesis bulletin for the entire Warumpi Province.

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BASE METAL MINERALISATION IN THE STRANGWAYS METAMORPHIC COMPLEX, ARUNTA REGION, AUSTRALIA: VARIATIONS ON A THEME AND/OR DIFFERENT MINERALISATION STYLES

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Small- to medium-sized base metal prospects occur through much of the Strangways Metamorphic Complex (SMC). Although some of these prospects have been known since the 1950s, no economically viable base metal deposit has been defined. The largest, Oonagalabi, has a poorly constrained resource of about 25 Mt grading 0.5% Cu and 1% Zn (Close 1979). These base metal prospects typically grade less than 3% combined Cu, Zn and Pb, although localised intersections up to 10% combined metal are known. The origin of these deposits is not clear due to the influence of high-grade regional metamorphism and deformation. They were originally grouped and termed the "Oonagalabi-type" by Warren *et al* (1974) and have been interpreted as metamorphosed volcanic-hosted massive sulfide (VHMS) deposits (Warren *et al* 1974, Stewart and Warren 1977, Warren and Shaw 1985).

The "Oonagalabi-type" deposits predominantly occur in granulite facies rocks, or reworked equivalents, and are often complicated by overprinting structures and a complex polymetamorphic history. Sulfide mineralisation is commonly found in silicate or carbonate rocks, and in some cases is associated with Fe-rich units (magnetite or magnetite+amphibole or amphibole) rocks. The sulfide mineralisation is minor, but where present, commonly occurs as disseminated segregations or in veins. As yet, no large massive sulfide bodies have been found in the SMC. Mineralisation also occurs as oxides (eg zincian spinel) in amphibole- or quartz-garnet-bearing rocks. Several small base metal prospects with similar characteristics occur in amphibolite facies rocks in the southeastern parts of the Arunta Region. They appear to be hosted by lithostratigraphic correlatives of the SMC and may be equivalents to the "Oonagalabi-type" at lower metamorphic grade.

Using the mapped regional geology and limited geochronology, it is suggested that the SMC can be divided into three broad stratigraphic packages. The lowermost package comprises sedimentary and probable volcanic (or intrusive?) rocks. These are overlain by a pelite-dominated siliciclastic package with some intercalated quartzite and calcsilicate units. This middle SMC package generally appears to be more Fe-rich than the lower SMC package, and may include volcanic rocks. It is possible that these two packages are in part lateral equivalents. The upper SMC package is very different and is dominated by marbles and calcsilicate rocks. It is interpreted as a carbonate-dominated mixed siliciclastic/carbonate facies association. Most "Oonagalabi-type" prospects occur in the lower SMC package (eg Edwards Creek, Harry Creek, Utnalanama) although some are hosted by the middle SMC package (eg Johnnies Reward and possibly Oonagalabi). Host rocks to the Edwards Creek and Harry Creek Prospects give SHRIMP U-Pb zircon maximum ages of 1802 ± 5 Ma and 1801 ± 3 Ma, respectively. These rocks are interpreted as probable volcaniclastic units, given the compositionally layered nature of the rocks, a single (detrital/magmatic?) zircon population and the absence of complex zircon inheritence patterns. Igneous rocks attributed to the 1770-1780 Ma Yambah orogeny occur throughout the lower and middle SMC packages. These are interpreted as intrusive units and appear to be absent from the upper SMC package. Hence, the majority of the SMC was probably deposited before 1780 Ma. The upper SMC may be younger and a possible unconformity might exist in the SMC. The SMC rocks were metamorphosed to granulite facies conditions during the 1720 Ma Strangways Orogeny.

Warren *et al* (1974) and Stewart and Warren (1977) characterised the "Oonagalabi-type" by an assemblage of three mineralised rock types: (1) fosterite 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. Recent detailed mapping of selected prospects indicates that there are three different host-rock associations and styles are apparent in this group. Most prospects previously assigned to the "Oonagalabi-type" appear consistent with a metamorphosed VHMS deposit model. These prospects occur in the lower SMC package with Edwards Creek, Harry Creek and Utnalanama being the best examples. The Utnalanama Prospect encompasses the Johannsens Phlogopite Mine (related to a later intrusive unit). The Oonagalabi Prospect itself is very different to this group, and it is interpreted to be a metamorphosed carbonate replacement deposit with notably different host rocks and alteration assemblages compared to the Edwards Creek type. The Johnnies Reward Prospect is different again and may have affinities to Fe-oxide-Cu-Au deposits, although a Au rich VHMS deposit is possible (note the magnetite-rich part of the Utnalanama Prospect has elevated gold).

Amphibole is present at all "Oonagalabi-type" prospects and appears to be the most important linking factor used to characterise this group. Amphibole occurs: (1) as essentially monomineralic pods or zones of gedrite? (eg Edwards Creek), anthophyllite (Oonagalabi) or cummingtonite-grunerite series (eg Harry Creek); (2) in lithological layers within orthopyroxene-cordierite-quartz granulites (eg Edwards Creek and Harry Creek); (3) with the quartz-magnetite association (eg Harry Creek and Edwards Creek); (4) with magnetite (eg Edwards Creek, Johannsens Phlogopite Mine, Johnnies Reward, Oonagalabi); and (5) as gedrite? replacing cordierite as part of M_3/D_2? (eg Harry Creek). The type and amount of amphibole varies between, and within individual prospects, probably indicating variations in the protolith composition, proto-alteration assemblages and/or metamorphic conditions. Despite amphibole being present, the most important factor in differentiating these prospects appears to be the type of amphibole and its relationship to other rock types.

Cordierite is ubiquitous in the unmineralised quartz-rich host-rocks associated with the Edwards Creek-type prospects and is considered one of their most unifying features. The host-rocks at these prospects are typically orthopyroxene-

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cordierite-quartz granulites, with minor garnet, biotite-phlogopite mica and gedrite locally present. The amount of garnet is inferred to reflect subtle geochemical/stratigraphic variations within and between the host-rocks of these prospects. The gedrite and mica appear to have grown during M_3/D_2 whilst the remainder are interpreted as M_2 phases. These rocks commonly display lithological layering and are referred to as cordierite “quartzites” by some. Despite being inferred volcanics or volcaniclastic rocks, feldspar is notably absent in these host rocks. They also typically have very low magnetic susceptibility, indicating the absence of magnetite. Cordierite "quartzites", which are always present at the Edwards Creek type prospects, also occur as widespread, apparently stratiform, zones throughout parts of the lower? SMC. These cordierite-rich rocks, particularly where the modal abundance of cordierite is high (greater than about 20%), may represent regionally metamorphosed (stratiform?) chloritic alteration zones. Cordierite is typically forms about 20-50% of the cordierite "quartzites". However in some instances, there is a gradation into zones where cordierite is the dominant mineral phase, forming virtually monomineralic zones or pods (eg Harry Creek and Utnalanama Prospects). These cordierite-rich zones typically have a close spatial relationship with massive amphibole rock and are thought to represent zones of intensely altered rock.

Cordierite is less common or absent in host rocks associated with the prospects in the middle SMC package. Garnet or garnet+biotite is more prevalent instead, suggesting different host or lithogeochemical (alteration?) controls. It should be noted that garnet is present at most prospects, but tends to be a minor component (mostly <5-10%) in the Edwards Creek-type prospects. In contrast, garnet is the dominant phase in some meta-alteration zones at Oonagalabi and Johnnies Reward. Distinct garnet-quartz rocks occur at Oonagalabi and Johnnies Reward. Garnet-biotite-magnetite rocks also occur together at Johnnies Reward in association with amphibole-pyroxene-magnetite rocks, both of which are mineralised. Notably, Johnnies Reward contains elevated gold and is more copper-rich, with minor lead and zinc. These differences are interpreted to reflect differences in the host-rock lithogeochemistry and alteration styles, or variations in metamorphic grades, or a combination of these.

Evidence from the prospects we have examined suggests that widespread hydrothermal/mineralisation systems have operated in the SMC prior to the onset of high-grade regional metamorphism and deformation, and that at least three different styles/variants of base metal mineralisation occur. Recent high-precision Pb isotope data indicates that Pb in the Edwards Creek-type prospects is considerably different to that of the Oonagalabi Prospect and further supports different genetic models for these prospects (Huston *et al* this volume). The Edwards Creek type are older and formed from a more evolved source than that in the Oonagalabi Prospect.

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LEAD ISOTOPE CONSTRAINTS ON THE AGES AND METAL SOURCES OF LODE GOLD AND BASE METAL DEPOSITS FROM THE TANAMI, WARUMPI AND SOUTHEAST ARUNTA PROVINCES

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The timing of mineralisation and the source of metals are two of the more difficult parameters to establish in genetic and exploration models for mineral deposits. A number of techniques, including fluid inclusions, stable and radiogenic isotopes, and trace elements, have been used historically in attempts to constrain these parameters. Of these techniques, radiogenic isotopes are unique in that they provide both age information and an indication of metal source. Of the radiogenic isotope systems, lead is one of the more useful as it is either a ore metal or closely associated with ore metals in many mineral deposit types. This contribution reports new lead isotope data from gold deposits in the Tanami Region and Zn-Cu-Pb prospects in the Warumpi Province and the southeastern Arunta Region.

Gold deposits of the Tanami Region

The Tanami Region is one of the most important emerging gold provinces in Australia, with production and resources well in excess of 10 Moz, that largely were discovered over the last two decades. NTGS and GA have jointly studied aspects of this area to place the deposits in a regional and temporal geologic framework. Historically, these deposits were thought to be related to 1825-1795 Ma granites that, in some cases, are spatially associated with the deposits. However, early results from the NTGS-GA research questioned this model. Preliminary lead isotope results suggested that the lead in the gold deposits was not derived from these granites. A lead isotope array defined by the compositions of ore-related pyrite and arsenopyrite did not pass through the field of granite initial ratios defined by K-feldspar separates (Wygralak *et al* 2001). Moreover, ^{40}Ar/^{39}Ar results of Fraser (2002) indicated that gold was introduced at about 1730 Ma in the Callie deposit.

Our new results indicate, in contrast to the initial results, that the lead in the mineral deposits has a similar, although perhaps not the exact same, source to the lead in the granites. Analyses of galena from the ores are slightly offset from a growth curve defined by K-feldspar from the granites. However, it must be stressed that this does not necessarily mean that the lead in the ores came from the granites. By using the K-feldspar analyses, it is possible to calibrate lead growth curves for the Tanami Region, which can then be used to estimate the age(s) of lead introduction. A lead isotope growth model tied to a K-feldspar analysis from the Inningarra Granite indicates a range in model ages of more than 100 million years from galena and (least radiogenic) K-feldspar in veins from the Tanami Region. It is not clear at this point as to the significance of the model ages, but the data do suggest more than one episode of veining, during which lead was introduced.

Base metal deposits from the southeast Arunta Region and the Warumpi Province

A number of small base metal prospects occur in the Strangways Ranges area of the southeastern Arunta and the Warumpi Province. The deposits in the Strangways Ranges area were grouped together by Warren and Shaw (1985) as the 'Oonagalabi-type' and interpreted as metamorphosed volcanic-hosted massive sulfide (VHMS) deposits. Based on recent field mapping, Hussey and Huston (2002) and Hussey *et al* (this volume) have indicated that the 'Oonagalabi-type' in fact included three groups of deposits with quite distinct alteration assemblages and ore mineralogies. Although they agreed with Warren and Shaw (1985) that the most abundant deposits are probably VHMS deposits, they suggested that Oonagalabi itself and Johnnies Reward had sufficiently different characteristics to classify them separately.

Warren *et al* (1995) compiled lead isotope data from these and other deposits in the Arunta and Tennant Creek Regions, developed theoretical lead isotope evolution models and used these models to estimate ages of mineralisation. We have expanded this database and added newer, higher precision (double spike and ICP-MS) data. In addition, zircons from samples of the host rocks to a number of deposits have been analysed to determine depositional ages. In most cases, the zircons had simple age populations indicating derivation from a volcanic rock or immature volcaniclastic sediment and an age close to that of sedimentation.

Strangways volcanic-hosted massive sulfide deposits

Using these new data, a lead isotope evolution curve for the northern and central Strangways Metamorphic Complex, which hosts the inferred VHMS deposits, was constructed using an age of 1802 ± 5 Ma for the Edwards Creek host rocks. Model ages, which are broadly similar to those calculated by Warren *et al* (1995), indicate that these deposits formed between 1810 Ma and 1800 Ma, possibly with several pulses. The lead isotope data also suggest a second lead introduction event at about 1790 Ma for the Edwards Creek deposit.

Data from the Jervois deposits also indicate two lead introduction events, one at 1790 Ma and the second at 1770 Ma. Both ages are younger than the depositional age of the host Bonya Schist (1807 Ma), which suggests an epigenetic origin for these deposits. The magnetite-associated Johnnies Reward Cu-Au-Zn prospect also has multiple model ages of about

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1795 Ma and about 1770 Ma. Although the host stratigraphy of this deposit has not been dated, we interpret that it is also epigenetic. The lead isotope data from all of the Strangways Ranges deposits indicate that the lead was derived from an evolved crustal source, particularly when compared to the lead in the Oonagalabi prospect and the prospects in the Warumpi Province.

Use of the Edwards Creek-based model on epigenetic ironstone-hosted Au-Cu-Bi deposits in the Tennant Creek Region gives ages (1830-1835 Ma) which are very close to the age of 1830-1825 Ma estimated using ^{40}Ar-^{39}Ar analyses of ore-related muscovite (Compston and McDougall, 1994). K-feldspar data from the 1713 ± 7 Ma Mount Swan Granite (Zhao and Bennett 1995) return a model age of 1700 Ma. This suggests that the Edwards Creek-based model lead isotope evolution model may have a greater applicability elsewhere in the North Australia Craton.

Oonagalabi prospect

Hussey *et al* (this volume) indicated that the Oonagalabi prospect differs from the Strangways VHMS deposits in terms of alteration assemblage, and preliminary zircon SHRIMP U-Pb analyses indicate the host rocks are younger at about 1760 Ma (maximum depositional age; reinterpretation of unpublished data from Shensu Sun, Geoscience Australia). The lead isotope characteristics also differ from the VHMS deposits. Consequently, a separate lead isotope evolution curve was calculated for this deposit assuming formation at about the same time as the host rocks. This model, which gives maximum age of mineralisation, indicates that the Oonagalabi prospect formed from a slightly more primitive source.

Warumpi Province

The Stokes Yard prospect, which is one of several small Zn-Pb occurrences in the Warumpi Province (Close *et al* this volume), is hosted by marbles and tremolite schists. Detrital zircons from pelitic schists suggest a maximum depositional age for the host of about 1640 Ma (A Cross, Geoscience Australia, pers comm 2003). Using this point to constrain lead isotopic evolution for the Warumpi Province indicates a much more primitive lead source and, by inference, a more primitive crust relative to the Arunta Province to the north. This may enhance the prospectivity of the Warumpi Province for Zn-Pb mineralisation, as suggested by Scrimgeour *et al* (2002).

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EVENT CHRONOLOGY IN THE ARUNTA REGION

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The event evolution of the Arunta Region has always posed a special challenge to geochronology. It was recognised in the earliest mapping that serial overprinting by multiple events is a defining characteristic of the exposed Proterozoic rock associations. Even with today's microbeam techniques of U-Pb dating (SHRIMP), there is real difficulty in unravelling the complexity, and surprises continue to emerge; the recent recognition of Palaeozoic granulites in the eastern Arunta was little suspected when Collins and Shaw published their framework of orogenic events as recently as 1995.

The main problem has been sparse coverage of modern SHRIMP U-Pb dating, except in certain locations that have attracted dating studies from university groups, such as the Reynolds Range. In an attempt to redress this deficiency, Geoscience Australia and the Northern Territory Geological Survey have collaborated to put in place a systematic coverage of SHRIMP zircon U-Pb dates over the Arunta Region, in parallel with a remapping program, and to extend the coverage to abutting regions of the North Australian Craton such as the Tanami.

From three years of sustained dating effort, a consistent crustal event framework for this part of the North Australian Craton is now emerging. The major crustal systems have different magmatic or metamorphic expressions in different areas, but they do fall into distinct correlated episodes. The complexity arises because the rocks have experienced an unusual number of major crustal events – more than a dozen – over a period of more than 1500 Ma (see Table 1 in Scrimgeour, this volume). However, it is beginning to be possible to construct large-scale regional correlations across the Arunta region and at a wider scale between the Arunta and time-equivalent processes in the Tanami. An important correspondence is also emerging between the events recorded in Arunta basement rocks, processes in the MacArthur and Mount Isa Basin systems in the north of the North Australian Craton, and more widely, with other Australian Proterozoic terranes (Neumann *et al*, this volume).

One important outcome is the abandonment of the 'North-Central-South' division of the Arunta Region, proposed from mapping of the 1960s and 1970s, and used as the framework for most subsequent studies. The new dating and mapping correlations do not support a distinction between the 'north' and 'central' zones, which are both part of the North Australian Craton. However, the new data do support much the 'southern' division as a distinct terrane abutting the North Australian Craton along the Central Australian Suture (CAS; see Close *et al*, this volume).

North of the Redbank Thrust Zone, the first major event is recorded at 1810 Ma and is locally known as the Stafford Event. It is represented by some major plutonic massifs such as Mount Hay, which record the deformations of multiple subsequent events. A second, mainly magmatic, episode at 1780 Ma is also registered as local metamorphism of the earlier plutons. The major Strangways Orogeny at 1730 Ma is the first regionally widespread metamorphic episode and has expression ranging from zircon overgrowths in high-grade metamorphic rocks in the Strangways region, to lower temperature Ar/Ar ages recorded by micas in Tanami vein systems. In sectors of the Strangways area, some units record an earlier event system at 1750 Ma, which is not well understood. Another enigmatic event at 1690 Ma is known only from metamorphic zircon overgrowths in four rocks, and the magmatic age of one mafic dyke.

A separate evolution is recorded in units south of the Redbank Thrust Zone in what is now recognised as the separate Warumpi Province (Close *et al*, this volume). These rocks include magmatic and sedimentary units formed in the period 1680-1660 Ma, and overprinted by the Liebig Orogeny at 1640 Ma. The Liebig Orogeny corresponds with a major deflection in the Proterozoic Polar Wander Path constructed from magnetic poles elsewhere in the North Australian Craton, and with a distinct period in the basin systems of the McArthur and Mount Isa regions.

The separate evolutions of the systems north and south of the CAS are united by the 1590 Ma Chewings Orogeny, which is the second regionally widespread crustal episode. This is recorded by metamorphic zircon overgrowths in the Warumpi Province, as both magmatic and high-grade metamorphic expressions to the north of the CAS, and as lower temperature Ar/Ar ages in the northern Arunta (Fraser, this volume). This event corresponds with similarly important crustal systems in the Gawler and other Proterozoic terranes.

Across the region there is evidence of a local 'Grenvillian-age' thermal and magmatic event at 1130 Ma (Teapot Event) in the form of plutons such as the Teapot granite, and the Mordor Igneous Complex. The tectonic context of these magmatic systems is not well understood.

Finally, the region was affected by two major Palaeozoic processes. The origin and propagation of high-grade metamorphism during the Ordovician 'Larapinta Event' in the eastern Arunta is the current subject of intensive study. The later Alice Springs Orogeny, which lasted into the Carboniferous, is evident mainly as movement along crustal-scale faults and may have been responsible for the exhumation of the deep crustal rocks now exposed at the surface.

An important case study of the utility of high-precision geochronology in defining events in the Arunta is recent work on the Ngadarunga Granite (MOUNT DOREEN). This S-type granite has a published SHRIMP U-Pb zircon date of 1880 ± 5 Ma (Young *et al* 1995), based on the dominant population in a relatively small number of analysed zircons. The granite was locally derived by partial melting of the surrounding Lander Rock beds, and thus the 1880 Ma age was interpreted to be the age of metamorphism, which was known as the Yuendemu Event. However, new detailed SHRIMP

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analysis of zircons in the granite, as well as detrital zircon analysis of pelites and psammites from nearby country rock, have shown that the granite has the same detrital zircon populations as the sediments, which are typical Lander Rock Beds with a maximum deposition age of around 1830 Ma. Furthermore, the psammite contains metamorphic zircon with an age of 1803 ± 5 Ma, indicating that partial melting and granite formation occurred during the Stafford Event rather than at 1880 Ma. The 1880 Ma zircons of Young *et al* (1995) are now recognised to be part of the inherited population in the granite and the Yuendemu Event is no longer considered to be valid.

Dating work is now focused on the sedimentary basin systems which operated between the main basement events. The dominant rock association of the Arunta, about half of the mapped exposure, consists of metasedimentary units of low to moderate metamorphic grade with local names such as ‘Lander package’, ‘Bonya schist’, etc, and their high-grade or partly melted equivalents in areas of more intense metamorphism. So far, dating of detrital zircons has established that the earliest sequence, the Lander package, was deposited after about 1840 Ma and is intruded by Stafford Event plutons at 1810 Ma. This sediment package has identical age and provenance character to the Killi Killi Formation in the Tanami Region to the north, implying a linked depositional system. Detrital zircons in units of the Reynolds Range, currently mapped as Lander package (based on lithological similarity), belong to a separate series, because they have a maximum deposition age of 1805 ± 5 Ma, suggesting that they postdate the Stafford Event. In the Reynolds Range, the widely recognised unconformity separating these sediments from the overlying Reynolds Range Group has now been shown to correspond with the Early Strangways (now Yambah) Event in the basement, because the basal quartzite of the Reynolds Range Group contains detrital zircons derived from that event. With new data such as these, it is intended to develop first-order correlations of the main sedimentary systems of the Arunta Region, to complete the overall event framework.

Acknowledgements

This summary draws together work from the collaborating Geoscience Australia and NTGS teams remapping and studying the Arunta and Tanami Regions; shares expertise from the Geochronology Group at the Research School of Earth Sciences, Australian National University; and owes a debt to the observational science of the original mapping teams in these regions during the 1960s–1970s.

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TIME-SPACE-EVENT PLOTS FOR THE AUSTRALIAN PROTEROZOIC – PLACING THE ARUNTA IN A REGIONAL CONTEXT

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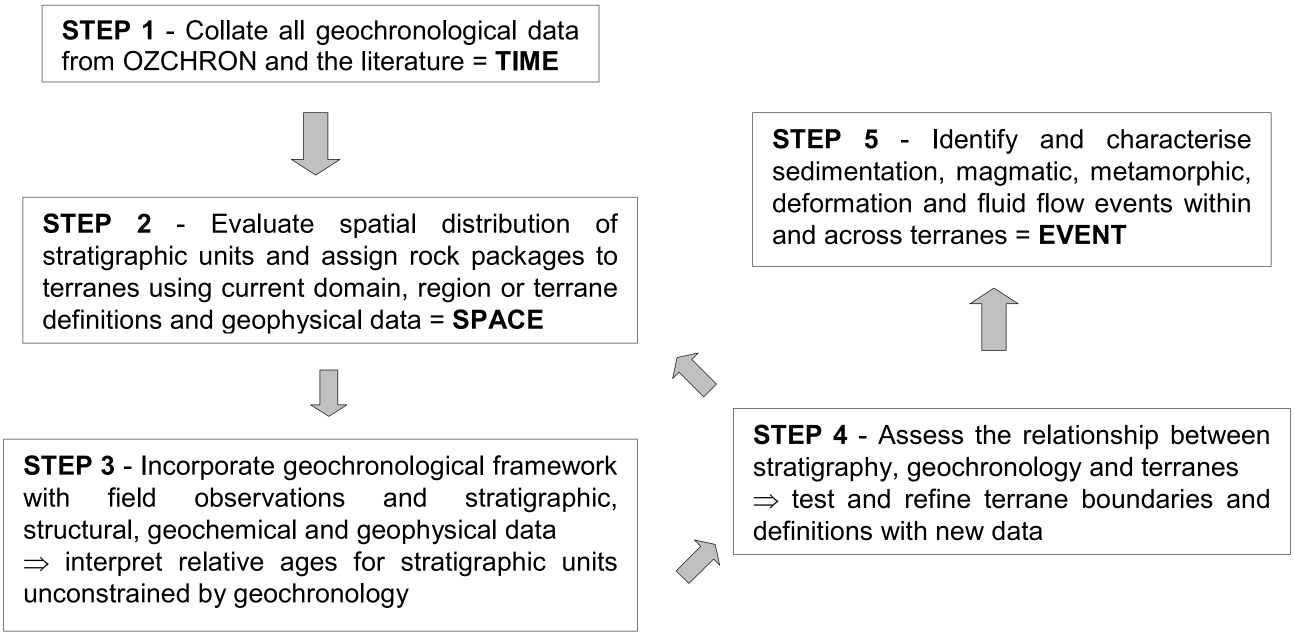
Many Australian Proterozoic regions contain a complex but periodic history of sedimentation, magmatism, tectonism, metamorphism, fluid flow, and mineralisation. Time-space-event plots provide valuable insights into the geological history and processes recorded in these regions and assist in the identification of events associated with mineralisation in different areas. They also provide the basis for event correlations between regions, tectonic models and discussions regarding the evolution of the Australian Proterozoic. The Australian Proterozoic Events project is compiling the data and knowledge from current and recently completed Minerals Division regional projects of Geoscience Australia (GA), together with state and territory projects, to provide the most up-to-date tectonostratigraphic information for selected Australian Proterozoic regions. This discussion will focus on the Mount Isa Inlier and McArthur Basin, Arunta and Tanami Regions, and Gawler Craton.

The approach used to construct time-space-event plots for Australian Proterozoic regions is summarised in **Figure 1**. Geochronological data (including SHRIMP U-Pb, conventional U-Pb, Ar-Ar, Rb-Sr, and Sm-Nd isotope data) from GA's OZCHRON database and the literature provide the basis for the plots. These data are used to constrain the age of stratigraphic units and metamorphic, deformation and fluid flow events within a region. The interpreted geochronology is evaluated on either a regional basis or according to current terrane definitions, and integrated with regional geophysical data to identify or confirm areas with different tectonothermal and/or stratigraphic histories. This framework is combined with field information and geochemical studies to include stratigraphic units not constrained by geochronology. Boundaries between these terranes will be refined and new terranes identified as more geochronological and geophysical data become available. It should be noted that although our ultimate aim is to define terranes for the Australian Proterozoic, in the interim, some areas are termed domains.



STEP 1 - Collate all geochronological data from OZCHRON and the literature = **TIME**

STEP 2 - Evaluate spatial distribution of stratigraphic units and assign rock packages to terranes using current domain, region or terrane definitions and geophysical data = **SPACE**

STEP 3 - Incorporate geochronological framework with field observations and stratigraphic, structural, geochemical and geophysical data
⇒ interpret relative ages for stratigraphic units unconstrained by geochronology

STEP 4 - Assess the relationship between stratigraphy, geochronology and terranes
⇒ test and refine terrane boundaries and definitions with new data

STEP 5 - Identify and characterise sedimentation, magmatic, metamorphic, deformation and fluid flow events within and across terranes = **EVENT**

Figure 1. Flow chart for the development of time-space-event plots for the Australian Proterozoic.

The construction of detailed, descriptive time-space-event plots for Australian Proterozoic regions provides a powerful framework for the identification of new terranes, and events within and across these terranes. Although geochronological data provide the basis for the time-space plots, it is essential to incorporate this framework with detailed field observations and stratigraphic, structural and geochemical data to define processes and events not discernible by geochronology alone. The resulting time-space-event plots provide a succinct integrated summary of:

- sedimentary events through the combination of focused geochronology and detailed facies, sequence stratigraphic and structural studies to identify accommodation and tectonic events represented by periods of deposition, erosion and uplift
- magmatic events, using the geochronological framework to identify periods of voluminous magmatic activity, and integrated with petrological, geochemical and isotopic studies, to constrain source regions, depths of melting, and magmatic processes

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- metamorphic and tectonic events, identified from the integration of detailed petrology and geochronology using a range of isotopic systems and minerals to constrain the structural and thermochronological histories of poly-deformed metamorphosed regions.

Given that these events are often temporally and spatially related, the integration of these studies can then be used as the basis to develop framework models, which can be integrated with metallogenic data to identify mineral systems. They are also an essential prerequisite for descriptions of tectonic settings and continent-wide plate reconstructions during the Australian Proterozoic.

Time-space-event plots for the Australian Proterozoic

Time-space-event plots for selected Proterozoic terranes from the Mount Isa Inlier-Southern McArthur Basin, Arunta-Tanami Regions, and the Gawler Craton show a number of first-order regional correlations (**Figure 2**). Magmatism associated with the Barramundi Orogeny (1850 Ma) is recorded in all three regions, suggesting that this is a continent-scale thermal event. Felsic magmatism during the 1790-1780 Ma Yambah Event in the Arunta Region is temporally associated with bimodal, dominantly extrusive magmatism and the development of the 1800-1750 Ma Leichhardt Superbasin in the Mount Isa region. The 1730 Ma Strangways Orogeny, recorded in the Arunta Inlier, is coeval with felsic magmatism in the Gawler Craton (early Kimban Orogeny) and the Eastern Fold Belt of the Mount Isa Inlier.

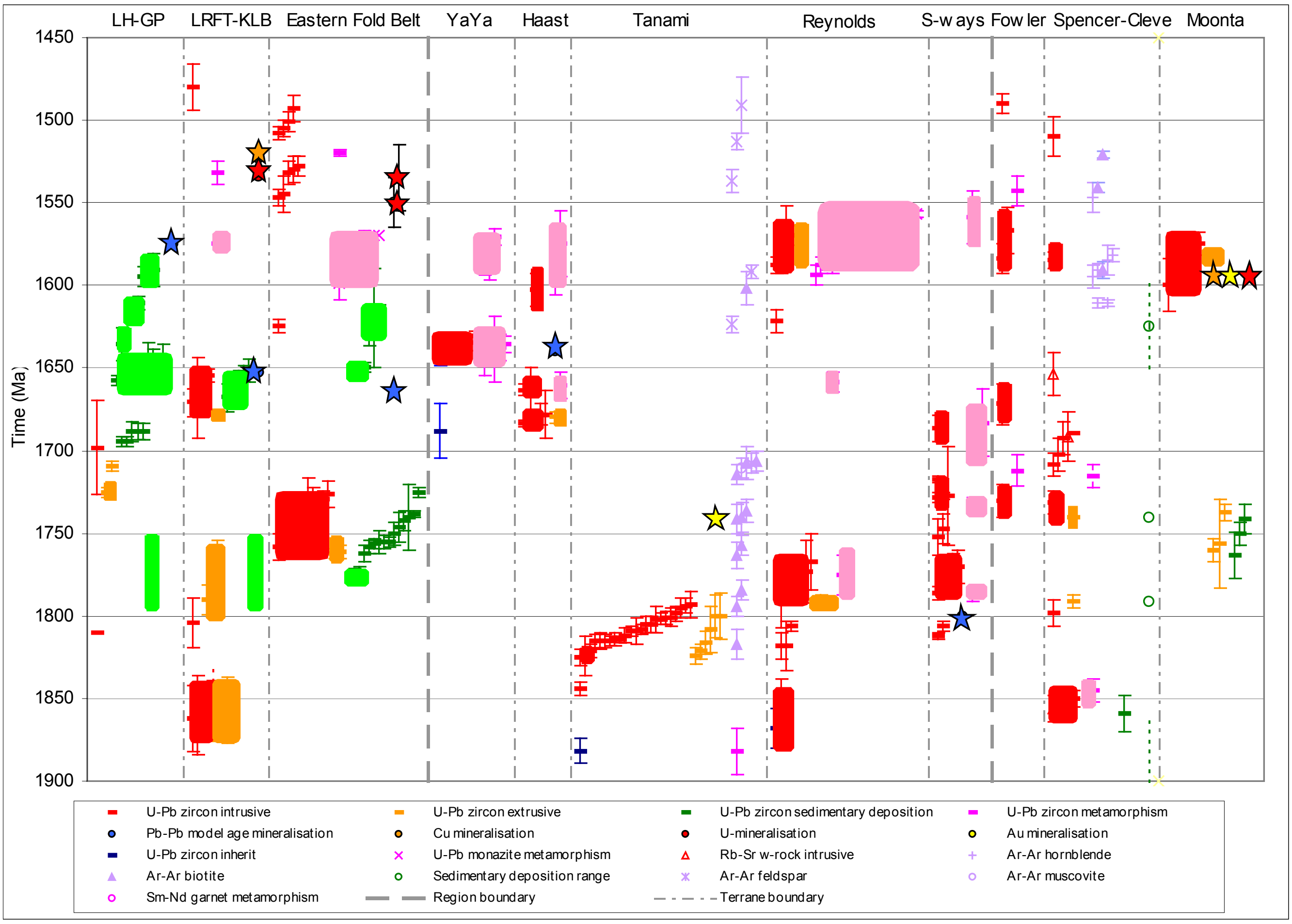

Figure 2 – Time-space-event plot for selected Proterozoic terranes from the Mount Isa Inlier-Southern McArthur Basin, Tanami-Arunta Inliers, and the Gawler Craton. Solid lines indicate errors on geochronological ages, with dashed lines indicating correlative or maximum depositional ages. The stratigraphic units within each terrane are ordered according to age. Events discussed in the text are highlighted. Terrane abbreviations: LH-GP = Lawn Hill Platform-Gunpowder; LRFT-KLB = Leichhardt River Fault Trough-Kalkadoon Leichhardt Belt; S-ways = Strangways Ranges. Mineralisation stars: blue = Pb; red = U; orange = Cu; yellow = Au. The plot has been constructed using data from many sources – please contact us for a reference list.

Felsic magmatism during 1680-1660 Ma in the Warumpi Province of the Arunta Region is temporally correlated with magmatism in the Mount Isa Inlier (the Sybella Event). The younger 1640 Ma Liebig Orogeny is coeval with inception of the River Supersequence (Isa Superbasin) in the Mount Isa Inlier-Southern McArthur Basin, and Pb mineralisation in the Warumpi Province and at Mount Isa and McArthur River. These events may also be associated with the onset of the 1650-1540 Ma Kararan Orogeny in the northwestern Gawler Craton (Daly *et al* 1998). Another continent-scale event is record at 1590 Ma, associated with the Chewings Orogeny in the Arunta Region and the widespread Hiltaba magmatic event in the Gawler Craton. These events are also coeval with the inception of the Wide Supersequence (Isa Superbasin) and deposition of organic-rich siltstone in small wrench sub-basins in the McArthur Basin, one of which hosts the Pb-Zn Century deposit (Southgate 2000). This was followed by initiation of the Isa Orogeny in the Mount Isa Inlier.

The development of three Proterozoic sedimentary basins in the Mount Isa Inlier-Southern McArthur Basin has been well constrained through the integration of detailed geochronology with seismic data and facies and sequence stratigraphy studies (Southgate 2000). Sedimentary depositional ages for sequences from the Arunta-Tanami Regions and the Gawler Craton are sparse, although available data does suggest the possibility of temporal associations with the Mount Isa-McArthur Basins.

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DEVELOPING A REVISED FRAMEWORK FOR THE ARUNTA REGION

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Introduction

The Arunta Region is one of the most complex geological areas in Australia, with a stratigraphic, igneous and tectonic history spanning the Palaeoproterozoic to the Palaeozoic. Assessments of the prospectivity of the Arunta have been hampered in the past by difficulties in making regional correlations, uncertainity in interpreting tectonic environments and the lack of a detailed regional framework. In 2000, NTGS, in collaboration with Geoscience Australia (GA), began an intensive work program in the Arunta, with the goal of producing a well constrained Arunta framework, accompanied by seamless basement interpretation maps. This presentation represents a snapshot of our current improved understanding of the Arunta, at around the halfway point in this process.

The first serious attempt to produce a framework for the Arunta was by the BMR (now GA) in the 1980s, who divided the region into three tectonic provinces (northern, central and southern) and three broad lithostratigraphic divisions (Shaw *et al* 1984, Stewart *et al* 1984). The onset of high precision SHRIMP U-Pb geochronology over the following decade highlighted a number of problems with these subdivisions, particularly once it was recognised that the Arunta had undergone multiple overprinting metamorphic events. In response to this new data, a more complex framework was proposed by Collins and Shaw (1995), which questioned parts of the earlier model and recognised a large number of stratigraphic and tectonic events. Nearly a decade has passed since this most recent framework was published, and a large amount of geological and geochronological information since that time has led to further major changes in our understanding of the Arunta. The first attempt at an Arunta framework by NTGS was by Pietsch (2001), who presented a framework in the form of stratigraphic packages and a time-space diagram at AGES 2001. Given the large amount of data that NTGS and GA have produced in the past two years, we are now in a position to produce a more comprehensive and well constrained framework for the region.

Defining new provinces in the Arunta

Our current geological understanding suggests that most of the Arunta forms part of the North Australian Craton (NAC), and is geologically continuous with the Tennant and Tanami Regions (Green *et al*, this volume, Donnellan and Johnstone, this volume). However, two discrete terranes have been identified, forming provinces with protolith ages and histories that are different from the rest of the Arunta. Given that the Arunta represents a geological region, but not a single distinct province or terrane, the term Arunta Region is more appropriate than previously used terms such as Province or Inlier.

Perhaps the most fundamental discovery in the Arunta in the past decade has been the recognition that the Harts Range Group in the eastern Arunta represents a Neoproterozoic to Cambrian succession that was metamorphosed during the Ordovician Larapinta Event (Mawby *et al* 1999, Buick *et al* 2001, Maidment *et al* 2002). This succession is entirely fault-bounded, and was juxtaposed against the surrounding Strangways Complex during the early Alice Springs Orogeny at 450-440 Ma (Mawby *et al* 1999, Scrimgeour and Raith 2001). We propose here the new name Irindina Province, for this fault-bounded terrane.

A second distinct terrane occurs along the southwestern margin of the Arunta, extending west from Alice Springs. This terrane is similar to the Southern Province of Shaw *et al* (1984) except that it has a broader extent to the west, and does not extend east of Alice Springs. This terrane, newly defined as the Warumpi Province (Close *et al*, this volume), can be divided into two domains. In the south, the amphibolite facies Haasts Bluff Domain has protolith ages of 1690-1660 Ma and a 1630-1600 Ma cover succession, whereas the largely granulite facies Yaya Domain in the north has protolith ages of 1660-1630 Ma. The boundary between the Warumpi Province and the NAC is a series of major structures, including the Redbank Thrust, Charles River Thrust and Desert Bore Shear Zone, which together form the newly defined Central Australian Suture. The only place where the Warumpi Province is not fault-bounded is at its eastern extremity near Alice Springs, where a 1630-1600 Ma cover succession overlies granite belonging to the NAC.

The remainder of the Arunta forms part of the NAC and is geologically continuous with the rest of the craton, although the complexity of the geological history and degree of metamorphism generally increases with the transition from the Tanami Region and Davenport Province into the Arunta.

Sedimentary packages and their metallogenic potential

Deciphering a lithostratigraphic framework for the Arunta has always been difficult due to the highly variable metamorphic grade, along with facies variations and diachronous sedimentation across this vast area. The packages outlined below are an expansion and modification of those proposed by Pietsch (2001). These packages represent an over-simplification of a complex stratigraphic evolution, but provide a starting point in the identification of broad groupings of stratigraphy across the region.

Lander package (1865-1820 Ma)

The Lander package is the most widespread lithological package over the northern and western Arunta, and is dominated by interlayered pelites and psammites of turbiditic to shallow marine origin. The metamorphic grade is most commonly greenschist facies, but localised rapid variations in grade up to granulite facies occur. Across much of the northern Arunta, the package typically has a youngest detrital zircon population of 1840-1830 Ma and appears to be equivalent to the Killi Killi Formation of the Tanami Group (Green *et al*, this volume). Donnellan and Johnstone (this volume) has also recognised direct stratigraphic continuity from the Ooradidgee Group in the Davenport Province into the northeastern Arunta Region. Sedimentary environments suggest a general deepening from shallow marine (with sporadic volcanic input) in the northeast to turbiditic sediments further west and south. However, this interpretation is complicated by apparent variations in the age of deposition across the Lander package. In the Lake Mackay area in the southwest, maximum deposition ages of turbiditic sequences are as old as 1865 Ma. The Lander package is predominantly of low metamorphic grade and correlates with parts of the Tanami Group and the Ooradidgee Group (Tennant Region), making it the most prospective package in the Arunta for gold mineralisation.

Ongeva package (1810-1790 Ma)

The Ongeva package comprises much of the Strangways Metamorphic Complex, as well as the Bonya Schist (Jervois), Deep Bore and Cackleberry Metamorphics, and Kanandra and Bleechmore Granulites in ALCOOTA and HUCKITTA. The package is dominated by pelites and psammites, with subordinate calc-silicates, and with felsic and mafic gneisses of an intrusive or extrusive origin. The package is metamorphosed at granulite to amphibolite facies. Geochronological data from the Strangways Metamorphic Complex, Bonya Schist and Deep Bore Metamorphics consistently give a single zircon population in the age range 1807-1800 Ma, suggesting probable volcaniclastic sedimentation at this time (Scrimgeour and Raith 2001, Hussey *et al* this volume). Recent geochronology in the Reynolds Range (Claoué-Long, this volume) suggests that some rocks mapped as Lander Rock beds are younger than 1805 Ma, and thus may also belong to the Ongeva package. This package is economically significant, as it hosts base metal and skarn mineralisation in the Jervois area, as well as VHMS-style base metal mineralisation in the Strangways Range.

Reynolds package (about 1780 Ma)

The Reynolds package occurs across the northern Arunta as the Reynolds Range Group, a shallow marine to intertidal succession of quartzite grading up into pelite and minor calc-silicate that unconformably overlies rocks of the Lander (and locally Ongeva) packages. The succession is intruded by the 1780 Ma Coniston Schist, but is believed to have been deformed during the 1780-1770 Ma Yambah Event. Quartz-rich sediments and pelites of the 1772 Ma Nicker beds (Young *et al* 1995) are tentatively included within this package. No economic mineralisation has yet been identified in the Reynolds package.

Cadney package (1780-1760 Ma?)

The Cadney package comprises the upper Strangways Metamorphic Complex rocks of Hussey *et al* (this volume). It is a carbonate-dominated succession with variable clastic input that outcrops within the Strangways Range region. In general this succession lacks the VHMS-style base metal deposits that are scattered throughout the Ongeva package in the Strangways Range, but remains prospective for carbonate-hosted base metal and skarn mineralisation. The age of the Cadney package is poorly constrained, but it probably postdates the 1780-1770 Ma Yambah Event.

Ledan package (1760-1740 Ma)

The Ledan package comprises the Ledan Schist, Mendip Metamorphics and Utopia Quartzite, which unconformably overlie metamorphic rocks of the Ongeva package in ALCOOTA. They package is dominated by quartz-rich sediments, quartzite and pelites, and minor calc-silicate rock, and is metamorphosed to amphibolite facies or higher. The Ledan package is interpreted to have been deposited between the Yambah Event and Strangways Orogeny.

Madderns package (1690-1670 Ma)

The Madderns package comprises lower amphibolite facies flow-banded rhyolites and minor laminated Fe-rich and manganiferous sediments and calc-silicates in the Haasts Bluff domain of the Warumpi Province. The rhyolite has a SHRIMP U-Pb zircon age of 1679 ± 3 Ma (A Cross, GA, pers comm, 2002). Minor metasediments in the more highly metamorphosed Glen Helen Metamorphics also belong to this package.

Yaya package (1660-1650 Ma)

The Yaya package is restricted to the Yaya domain of the Warumpi Province, and comprises granulite to upper amphibolite facies metapelite, psammite, quartzite, calc-silicate and massive cordierite granulite. Mafic granulite interlyered with pelites may reflect basalts or intrusive sills. SHRIMP U-Pb dating of detrital zircons gives a maximum deposition age of 1661 ± 10 Ma for these sediments, which were then metamorphosed in the deep crust at 1640 Ma, suggesting that they were deposited in active (plate margin?) setting. Small copper shows near Papunya form the only known mineralisation in these rocks, but the timing of deposition of these sediments falls within a highly prospective interval for base metals in the Australian Proterozoic, and large areas are obscured by sand cover.

Iwupataka package (1620-1610 Ma)

The Iwupataka package is a succession of metapelites, quartz-rich sediments, calc-silicate rock and minor volcanics, with an upper quartzite unit (Chewings Range Quartzite). The package is widespread across the Haasts Bluff domain of the Warumpi Province, and is metamorphosed to upper greenschist-middle amphibolite facies. The package has maximum deposition ages in the range 1635-1615 Ma across the domain (A Cross, GA, pers comm, 2002) and a presumed metavolcanic in the east has an age of 1615 ± 11 Ma (Zhao and Bennett 1995). It hosts Fe-oxide Cu-Au mineralisation in amphibolites north of Haasts Bluff community. Recent geochronology by A Cross (GA, pers comm, 2003) suggests that Pb-Zn mineralisation within tremolite- and actinolite-rich calc-silicate and marble in the Haasts Bluff region may also be hosted by this package.

Irindina package (850-500 Ma)

The Irindina package consists of a succession of pelites, calc-silicate rocks and layered amphibolites that are interpreted to reflect rift sediments containing variably reworked mafic volcanics. These sediments, comprising the Irindina Supracrustal Assemblage of the Harts Range Group are restricted to the Irindina Province, and contain very similar detrital zircon populations to units of an equivalent age in the Amadeus and Georgina Basins (Buick *et al* 2001, Maidment *et al* 2002). This suggests that the package was deposited in a deep sub-basin of the Centralian Superbasin, prior to high-grade metamorphism during the Larapinta Event.

Tectonic and thermal events in the Arunta

The following event chronology documents the known major tectonic, thermal and igneous events known to have affected the Arunta (see also Claoué-Long, this volume). In the following description, the term 'orogeny' is restricted to those events interpreted to have involved significant compressional deformation and mountain-building.

Stafford Event (1810-1800 Ma)

The Stafford Event is widespread across the Arunta Region, as well as the Tennant Region (where it is known as the Murchison Event) and the Tanami Region. Across the northern Arunta, it is characterised by localised high-temperature, low-pressure metamorphism, with rapid lateral changes in metamorphic grade. This localised high-grade metamorphism is interpreted to reflect advection of heat by felsic and mafic magmas. In the eastern Arunta, no metamorphism is recognised in association with this event, but it is associated with widespread volcanism and volcaniclastic sedimentation (the Ongeva package), as well as felsic and mafic magmatism.

Yambah Event (1780-1770 Ma)

This event was previously known as the Early Strangways Event, and is characterised by felsic and less abundant mafic magmatism, and variable metamorphism and deformation across much of the Arunta. Yambah-age magmatism is widespread in the eastern Arunta, where it includes the Jervois and Dneiper Granites and Attutra metagabbro in the Jervois region, and abundant intrusions in the Strangways Range region (Zhao and Bennett 1995). Mafic magmatism at Mount Chapple occurred at this time (Hoatson and Claoué-Long 2002), along with the Carrington Granite Suite in the Mount Doreen region and other granites across the northern Arunta (Young *et al* 1995). Evidence for metamorphism during the Yambah Event has been documented in the eastern Strangways Range and the Mount Hay region (Hoatson and Claoué-Long 2002), and pervasive low-grade fabrics across much of the northern Arunta are likely to be related to the Yambah Event.

Inkamulla Igneous Event (1760-1740 Ma)

The Inkamulla Igneous Event is an episode of voluminous granitic and minor mafic magmatism that was restricted to the southern and eastern Arunta, most notably in the Alice Springs region, the western Strangways Range, Entia Dome, southwestern ILLOGWA CREEK and the far eastern Arunta in TOBERMORY. There is no known metamorphism during this event, which separates the two episodes previously known as the Early and Late Strangways Events.

Strangways Orogeny (1730-1715 Ma)

The Strangways Orogeny (formerly the Late Strangways Event) is the dominant tectonic event in the eastern Arunta. It resulted in granulite facies metamorphism throughout the Strangways Range, and amphibolite facies metamorphism south of the Harry Creek and Illogwa Shear Zones. It also led to high-T, low-P metamorphism at amphibolite to granulite facies, north of the Delny Shear Zone (Jervois, Deep Bore Metamorphics, Scrimgeour and Raith 2001). Granite intrusion occurred throughout the eastern Arunta at this time, with some granites reflecting partial melting of surrounding country rock (Wuluma Granite, Lafrance *et al* 1995; Woodgreen Granite, P Haines, NTGS, pers comm 2002). There is no known mafic magmatism associated with his event. The effects of the Strangways Orogeny extend beyond the eastern Arunta, with granite intrusion occurring sporadically in a northwest-trending belt across the northern Arunta, and 1730 Ma granites and localised high-grade metamorphism occurring at Fidlers Lake on the edge of the Tanami Region. The effects of this event extend into the Tanami, where it may be related to a mineralising event at the Callie Mine.

Unnamed Event (1690 Ma)

This event is poorly understood, and has only been identified from metamorphic rims in mafic rocks in the eastern Strangways Range and at Mount Hay, and from one dolerite dyke in the eastern Strangways Range (Hoatson and Claoué-Long, 2002).

Argilke Igneous Event (1680-1660 Ma)

The Argilke Event is restricted to the Haasts Bluff Domain of the Warumpi Province. It was previously believed to have involved migmatisation at upper amphibolite facies, but recent work by NTGS suggests that the Argilke Event only involved granite intrusion and felsic volcanism, and it is therefore downgraded to a purely igneous event. Migmatisation of these 1680-1660 Ma felsic rocks is now believed to have occurred during the subsequent Liebig Orogeny.

Liebig Orogeny (1640-1630 Ma)

The Liebig Orogeny is a major orogenic event that affected the Warumpi Province and immediately adjacent parts of the NAC at 1640-1630 Ma (Scrimgeour *et al* 2002). In the Yaya Domain, it resulted in granulite facies metamorphism that was locally as high as 9 kbar and 900°C, along with voluminous granite, charnockite and less common gabbro intrusions. It is characterised by rapid burial and exhumation, consistent with crustal thickening. Immediately to the north of the Central Australian Suture, large mafic complexes and granites intruded the Lander package, with associated high-T, low-P metamorphism. These mafic complexes, including the Andrew Young Complex, have high potential for Ni-Cu sulfide mineralisation. The Liebig Orogeny correspons to a hairpin bend in the apparent polar wander path for northern Australia, and is interpreted to reflect the collision of the Warumpi Province with the NAC.

Ormiston Igneous Event (1615-1600 Ma)

This event involved minor felsic magmatism in the eastern part of the Haasts Bluff Domain of the Warumpi Province that was previously believed to be syntectonic with the Chewings Orogeny (Collins *et al* 1995). These granites have a Nd isotopic signature that suggests a much more primitive source than any other granites in the Arunta (Zhao and McCulloch 1995).

Chewings Orogeny (1590-1560 Ma)

The Chewings Orogeny had a variable impact across the Arunta. It is expressed as pervasive amphibolite facies fabrics through the Warumpi Province, which most commonly suggest a south-directed transport direction. The earliest movement on the Redbank Thrust is now considered likely to be a product of this deformation. Elsewhere, the effects of the Chewings Orogeny are most strongly developed in the southeastern Reynolds Range, where long-lived high-T, low-P metamorphism may be related to burial of high radiogenic heat-producing granites in the region (Hand and Buick 2001). In the remainder of the Arunta, the effects of the Chewings Orogeny are largely restricted to lower grade deformation and metamorphism, with Ar-Ar evidence for deformation and/or isotopic resetting of this age across the Arunta (Fraser, this volume). There is no magmatism associated with the Chewings Orogeny, with the exception of the 1570 Ma Southwark Suite in the Mount Doreen region (Young *et al* 1995).

Teapot Event (1150-1130 Ma)

The Teapot Event is a predominantly thermal and magmatic event that affected the southern half of the Arunta. In the Warumpi Province the Teapot Event resulted in the intrusion of the Teapot Granite (1136 ± 6 Ma, Black and Shaw 1995) as well as localised migmatisation (1149 ± 3 Ma) and widespread resetting of isotopic systems. In the eastern Arunta, the layered igneous Mordor Complex intruded at 1132 ± 5 Ma (Hoatson and Clauoé Long 2002), and has high potential for PGE mineralisation.

Larapinta Event (500-460 Ma)

The Larapinta Event resulted in upper amphibolite to granulite facies metamorphism of Harts Range Group sediments within the Irindina Province. It was first recognised by Mawby *et al* (1999), and subsequent work by Buick *et al* (2001) and Maidment *et al* (2002) have confirmed that this is the major metamorphic event in the Irindina Province. However, the Larapinta Event appears to have had little or no effect in the surrounding Palaeoproterozoic rocks. Mawby *et al* (1999) suggested that the Larapinta Event was extensional, on the basis of deepening isopachs towards the eastern Arunta in the Cambrian, extensional kinematic indicators in the Harts Range Group and tholeitic mafic dykes synchronous with metamorphism.

Alice Springs Orogeny (450-300 Ma)

The Alice Springs Orogeny is a long-lived event, and the intensity of deformation varied spatially and temporally across the Arunta. It commenced with basin inverson of the Irindina Province and its juxtaposition against Strangways Complex rocks along mid- to upper-amphibolite facies shear zones at 450-440 Ma. Thick-skinned deformation and exhumation along major crustal-scale structures, such as the Redbank and Delny Shear Zones, occurred during the Late Silurian and Devonian. Deformation was more restricted in extent during the Carboniferous, with greenschist to amphibolite facies shear zones in the Reynolds Range, parts of the Strangways and Harts Range, and formation of the Arltunga Nappe Complex. Large-scale fluid flow during the Alice Springs Orogeny was responsible for Winnecke-style gold mineralisation, widespread REE mineralisation, and possibly hydrothermal PGE mineralisation in the eastern Arunta.

Palaeo-Mesoproterozoic tectonic evolution of the Arunta

A schematic summary of the lithostratigraphic packages and event chronology described above is given in **Table 1**. The growing body of knowledge on the Arunta allows us to construct a geological and tectonic evolution for the region during the Palaeo-Mesoproterozoic. Although parts of the evolution described below remain speculative, ongoing programs by NTGS and GA are aimed at providing better constraints on this evolution.

During the period 1865-1820 Ma, much of the Arunta was a broad basin with shifting depocentres. Sediments were being shed from the NAC in the north onto probable Archaean basement, and were deposited in a shallow marine to turbiditic setting that probably deepened to the southwest. There were varying degrees of volcanic input into the basin. By about 1820 Ma, granites began intruding these sediments, and advection of heat by granites and mafic magmas led to localised high-T, low-P metamorphism in an intraplate setting at 1810-1800 Ma, with associated compressive deformation. In the eastern part of the Arunta, volcanic activity was widespread around 1805-1800 Ma, along with felsic and mafic intrusions, and clastic and volcaniclastic sedimentation (Ongeva package). Volcanic activity during this period led to the formation of small VHMS deposits within the Ongeva package. A marine transgression occurred around 1790-1780 Ma, with a quartz-rich intertidal to shallow marine succession deposited in the northern Arunta (Reynolds package). This was rapidly followed by widespread deformation, felsic and mafic magmatism and localised metamorphism at 1780-1770 Ma (Yambah Event), although the tectonic environment for this event remains unclear. Erosion of the uplands from this event was followed by marine transgression in the northeastern Arunta and the deposition of quartz-rich sediments (Ledan package). Carbonate-rich sedimentation in the Strangways area (Cadney package) is also interpreted to have followed the Yambah Event. In the eastern and southern part of the Arunta, large-scale felsic magmatism and minor mafic magmatism at 1760-1740 Ma may form part of a continental back-arc environment prior to the Strangways Orogeny at 1730-1715 Ma. The Strangways Orogeny is most intense in the eastern Arunta, and resulted in high-grade metamorphism and granitic intusion, associated with deformation that may have been largely west-directed. It is interpreted to reflect the collision of an unknown fragment of continental crust with the NAC near the southeastern margin of the Arunta. The effects of this event extended into the craton, with intraplate magmatism and localised deformation and metamorphism extending in a northwest-trending belt towards the Tanami.

Large-scale felsic magmatism at 1690-1660 Ma occurred within a fragment of continental crust that may have been outboard of the NAC at the time (Haasts Bluff domain). Sediments shed from these felsic rocks accumulated to form a sedimentary basin to the north at around 1660 Ma (Yaya package). This terrane (Warumpi Province) is interpreted to have collided with the NAC at 1640 Ma, resulting in voluminous magmatism, deep crustal metamorphism and exhumation, and fault reactivation and fluid flow across the NAC. Adjacent regions of the NAC were also intruded by granites and mafic rocks during this event. Erosion of the highlands from this event was largely completed by around 1620 Ma, and a succession of shallow marine quartz-rich sediments were deposited on the exhumed metamorphic rocks. At 1590 Ma, intense south-directed compressional deformation and metamorphism occurred in the Warumpi Province, possibly in response to continuing accretional tectonic activity to the south. The degree of intraplate reactivation within the craton to the north was dependent on variations in the thermal strength of the crust, and varied from granulite facies metamorphism to regional uplift and cooling. An additional, largely passive uplift event may have also occurred at 1500-1400 Ma.

Table 1. Simplified schematic summary of timing and broad distributon of lithostratigraphic packages and tectonic events across the Arunta Region. Signficant deformational and metamorphic events are shown in bold, and less significant magmatic and thermal events in italics.

Age (Ma)	**WARUMPI PROVINCE**	**NORTH AUSTRALIAN CRATON**				**IRINDINA PROVINCE**
		Dufaur Domain[1]	Northern Arunta[2]	Narwietooma area[3]	Strangways/Jervois[4]	
450-300	**Alice Springs Orogeny**					
500-460						**Larapinta Event**
850-500						Irindina Package
1150-1130	*Teapot Event*			*Teapot Event*		
1590-1570	**Chewings Orogeny**					
1610-1600	*Ormiston Event*					
1620-1610	Iwupataka Package					
1640-1630	**Liebig Orogeny**					
1660-1650	Yaya Package					
1680-1660	*Argilke Igneous Event*					
1690-1670	Madderns Package					
~1690				*Unnamed event*		
1730-1710		?	**Strangways Orogeny**			
1760-1740				*Inkamulla Igneous Event*		
1780-1740			Ledan package		Ledan, Cadney packages	
1780-1770		**Yambah Event**				
~1780			Reynolds Package			
1810-1790			Ongeva Package	?	Ongeva Package	
1810-1800		?	**Stafford Event**	?		
1865-1820		Lander Package	Lander Package	Lander Package		

1. Northern MOUNT RENNIE, southern MOUNT DOREEN (south of Ngalia Basin)
2. LAKE MACKAY, northern MOUNT DOREEN, HIGHLAND ROCKS, MOUNT THEO, MOUNT PEAKE, NAPPERBY
3. Northern HERMANNSBURG (Mt. Hay—Mt Chapple area)
4. Strangways Range, Alice Springs region ILLOGWA CREEK, ALCOOTA, HUCKITTA

A major thermal event affected the southern Arunta at 1150-1130 Ma, coincident with the latter stages of the Musgravian Event in the Musgrave Block to the south, leading to localised magmatism and migmatisation, and regional thermal resetting of isotopic systems. This was followed by dolerite intrusion in the southern Arunta as part of regional extension, possibly relating to mantle plume activity at 1080 Ma.

Breakthroughs, Unresolved problems and future directions

Although our understanding of the evolution of the Arunta continues to improve, there are still many unresolved problems in the Arunta that need to be addressed.

Major advances in our understanding of the Arunta in the past few years include the recognition that:

- the Ooradidgee-Lander-Killi Killi sedimentary package is geologically continuous from the Tanami through the north Arunta to the Davenport Province
- the Warumpi Province is a distinct terrane, and contains a previously unknown 1660-1650 Ma metasedimentary succession
- a major orogenic event affected the Warumpi Province at 1640-1630 Ma, and may relate to collision with the NAC.
- the Chewings Orogeny in the Warumpi Province has an age of 1590-1570 Ma, not 1610-1600 Ma as previously believed, and thus can be correlated with metamorphism in the Reynolds Range
- the Chewings Orogeny is interpreted to be the timing of early movement on the Redbank Thrust, and the 1450 Ma Anmatjira Uplift is considered to be a minor regional uplift and cooling event
- the Stafford Event is the dominant high-T, low-P metamorphic event in the northern Arunta, and the previously proposed 1880 Ma Yuendemu Event does not exist
- much of the base metal mineralisation in the eastern Arunta is hosted in 1810-1800 Ma metasediments of probable volcaniclastic origin
- effects of the Strangways Orogeny continue northwest to the Tanami, with localised high-grade metamorphism at Fidlers Lake and evidence for 1730-1715 Ma gold mineralisation at the Callie Mine.

Numerous problems remain to solved and will be a focus of future programs over the next 3-4 years. These include resolving the tectonic setting of late Palaeoproterozoic events in the Arunta, and determining how these relate to the intervening sedimentary packages. In particular, we need to resolve whether these events can be related to plate margin and subduction-related tectonics. The age and evolution of the southeastern margin of the Arunta remains very poorly understood and the identification of any suspect terranes would have a major bearing on our understanding of the tectonic evolution of the Arunta. In the far-east Arunta in TOBERMORY, recent geochronology suggests an 1846 Ma intrusive age for granitic rocks beneath the southern Georgina Basin. This suggests that the ‘Altjawarra domain’ (which largely underlies the southern Georgina Basin) may be older than the rest of the Arunta. Furthermore, the evolution of the Mount Hay-Mount Chapple area, and its relationship to the rest of the Arunta, remains problematical.

To address these issues, NTGS is planning to continue a strong focus on the Arunta over the next four years. During 2003, current investigations of the Warumpi Province will be wound up, although an investigation of the metallogenic potential and tectonic implications of intrusive rocks in the Warumpi Province is planned by GA in collaboration with NTGS. Beginning late this year, a new project (Arunta Southeast) will focus on the southern margin of the eastern Arunta, south of the Harry Creek and Illogwa Shear Zones, where poorly understood amphibolite facies rocks may be lower grade equivalents of the Strangways Range granulites, and may hold important clues to the tectonic evolution of the Arunta. In addition, the Tennant-Tanami Link will be finalised this year, and a longer term goal will be to link the sedimentary successions in the northern Arunta and Davenport Provinces, through NAPPERBY and ALCOOTA into the eastern Arunta. The ultimate goal is to provide a coherent framework and seamless geological interpretation for the entire Arunta, enabling easier identification of prospective sedimentary packages and fertile tectonic environments.

Acknowledgements

This summary is based on work undertaken and new ideas generated by numerous Northern Territory Geological Survey, Geoscience Australia and university geologists. In particular the following people are acknowleged for their significant geological and geochronological input (in no particular order) NTGS: D Close, A Crispe, N Donnellan, C Edgoose, M Green, K Hussey, L Vandenberg; GA: J Claoué-Long, A Cross, D Hoatson, D Huston, D Maidment; External: M Cobb, P Kinny (Curtin University), M Hand (Adelaide University).

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DIAMOND INDICATOR MINERAL DATABASE (DIM)

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Diamond explorers have flocked to the Northern Territory in recent years, pegging large areas of land. This influx is due to the North Australian Craton (NAC) becoming known as a highly prospective diamond terrain. The Northern Territory Geological Survey, in a bid to assist diamond explorers, is currently developing a Diamond Indicator Mineral Database (DIM). The database contains sample locations and indicator mineral results from open file company data that will be freely available to diamond explorers when completed (**Figure 1**). DIM contains data from gravel, loam, barrage, bulk gravel and drill spoil sampling.

Data capture began in July last year and is due for completion in mid 2003. Historically, diamond exploration has occurred on 877 ELs in the NT and data capture has been completed for around 450 of these. To date, DIM has captured 36 000 open file and 2300 closed file sample points. We estimate that the process is around 60% complete. DIM will assist companies in target area selection by allowing them to identify indicator mineral and microdiamond anomalies from the office, before setting foot on the ground. Along with freely available NTGS airborne geophysical data and geological maps, diamond explorers will have many of the tools they need to vigorously pursue economic diamond discoveries.

To complement DIM, a Diamond Mineral Chemistry Database (DMC) will also be developed at a later stage and linked to DIM by sample number, although hardly any mineral chemistry data is provided in company reports. Most indicator mineral results in the DMC database should at least be possibly kimberlitic if not definitely kimberlitic.

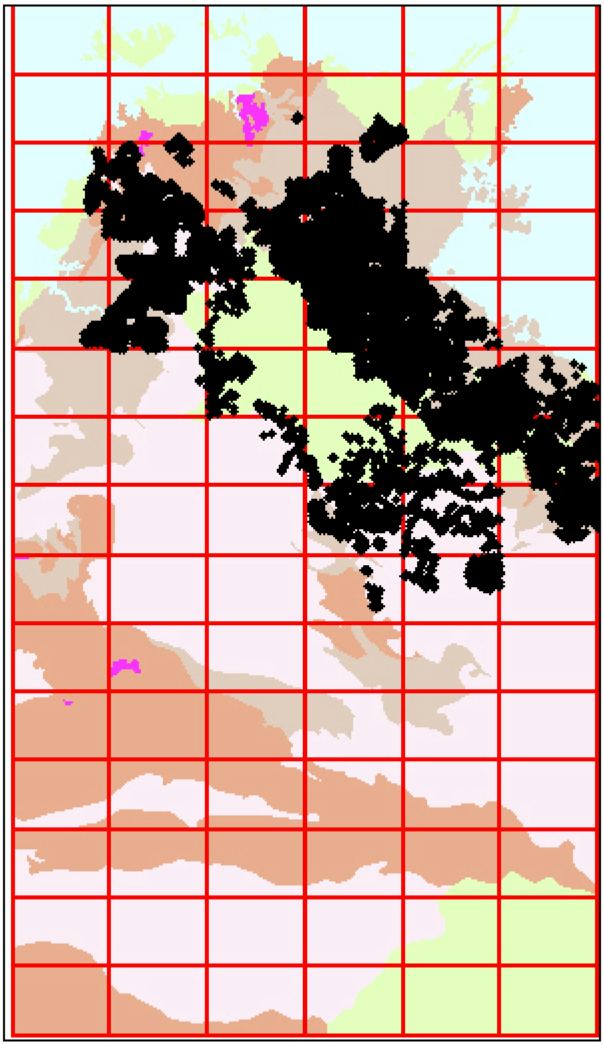

Figure 1. Total open file sample points in the DIM, as of March, 2003.

INDUSTRY INFORMATION SERVICES

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All industry information services in the Northern Territory Geological Survey (NTGS) are provided through the Minerals and Energy Information Centre. Services include:

- library services (loans, document supply, collection access)
- reference services
- minerals industry reports/data management and distribution
- petroleum industry reports/data management and distribution
- NTGS publication and geophysical data distribution
- database management and maintenance
- developing and maintaining GIS and database policies and standards
- NTGS website development and maintenance.

NTGS also has a number of tools on its website to help industry clients and the general public find information. These include the following:

- Geophysical Image Web Server (IWS).
- Industry Reports Management System (IRMS) databases.
- Historical EL and airborne geophysical survey index GIS layers.
- Product catalogue, including index maps.
- COREDAT database.
- LEDA library catalogue.

In the past 12 to 18 months, NTGS has completed a number of information projects. Those of particular interest to industry include: the capture of Arunta open file geochemistry data; a reduction in the number of closed file reports overdue for release to open file; the scanning of many NTGS Technical reports, the production of a historical EL GIS layer; and provision of internet access to LEDA. The scanning of mineral industry reports continues and as of the end of February 2003, 74% of open file reports and 66% of all reports have now been scanned.

The Arunta Province open file geochemistry data capture project covered eighteen 1:250 000 mapsheets and was undertaken over two years. Datasets were collected on 36 228 drillholes, 36 766 soil, 9690 rock chip and 22 630 stream sediment samples. The data was released in MapInfo and Excel formats on CD as a Digital Information Package (DIP 005) in October 2002.

For various reasons, many closed file reports have been overdue for release to open file and in late 2001, a project to systematically review all closed file reports was commenced. At this stage, we have reviewed all reports back to 1983, resulting in an additional 1500+ reports being open filed to the end of October 2002.

The unpublished NTGS Technical Reports or “GS” series goes back to 1920 and many of the older reports are becoming unreadable or have missing pages, maps etc. Therefore it was decided to scan the reports to serve the dual purposes of preservation and increased access. To date about 600 of 850 reports have been scanned and are available on CD or via email if file size is small enough.

An historical EL/ATP GIS layer was compiled in MapInfo format to provide spatial access to the IRMS mineral database. Each tenement with at least one company report was digitised and basic attributes including relevant company report numbers added. The layer enables clients to search in an area and identify relevant company reports. Further information can be gained by searching the IRMS database to narrow the list of reports required from NTGS. The layer can be downloaded from the web at www.dme.nt.gov.au/ntgs/downloads/Downloads.html#exports. An ArcView version of the layer will be available shortly.

The library catalogue, LEDA, was added to the website in December 2002. The library catalogue includes records on serials, books, conference proceedings and maps held by the Information Centre. It is also the main source of information on NTGS Technical Reports and all Department of Mines and Energy reports and publications, and provides more information than the product catalogue on the NTGS Explanatory Notes, Report and Record series and on NTGS maps.

There are two major information projects in progress at the moment: the provision of a web mapping interface for geological GIS data; and the upgrading of the IRMS minerals database. A tender for the provision of web mapping software is currently being evaluated and a web mapping application will be available on the website later in 2003. The IRMS minerals database has many incomplete or inconsistent records due to limitations in previous database software, database migration, lack of data entry guidelines etc. A project to upgrade the worst records has been initiated and will continue for some time to come, as there are a large number of records to be upgraded and the work is time-consuming.

MOUNT DRUMMOND REGION – EXPLORATION UPSIDE

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The Mount Drummond region lies on the Barkly Tablelands adjacent to the NT-Qld border, in the heart of the Carpentaria Zinc Belt. It incorporates the northwestern extension of Lawn Hill Platform into the NT, flanked to the north by the Murphy Inlier (Tectonic Ridge) and onlapped to the south by the Georgina Basin (**Figure 1**). Basement in the region is 1900-1850 Ma turbidites, volcanics and granites of the Murphy Inlier (**Figure 2**). These are overlain unconformably by 1750-1600 Ma coarse siliciclastics, bimodal volcanics, mudstones and carbonates of the Lawn Hill Platform succession, and in turn by coarse siliciclastics and mudstones of the 1500-1450 Ma South Nicholson Basin. The region is thinly covered by Late Neoproterozoic to Cambrian Georgina Basin carbonates and basaltic volcanics, Mesozoic sediments and Cenozoic blacksoil plains.

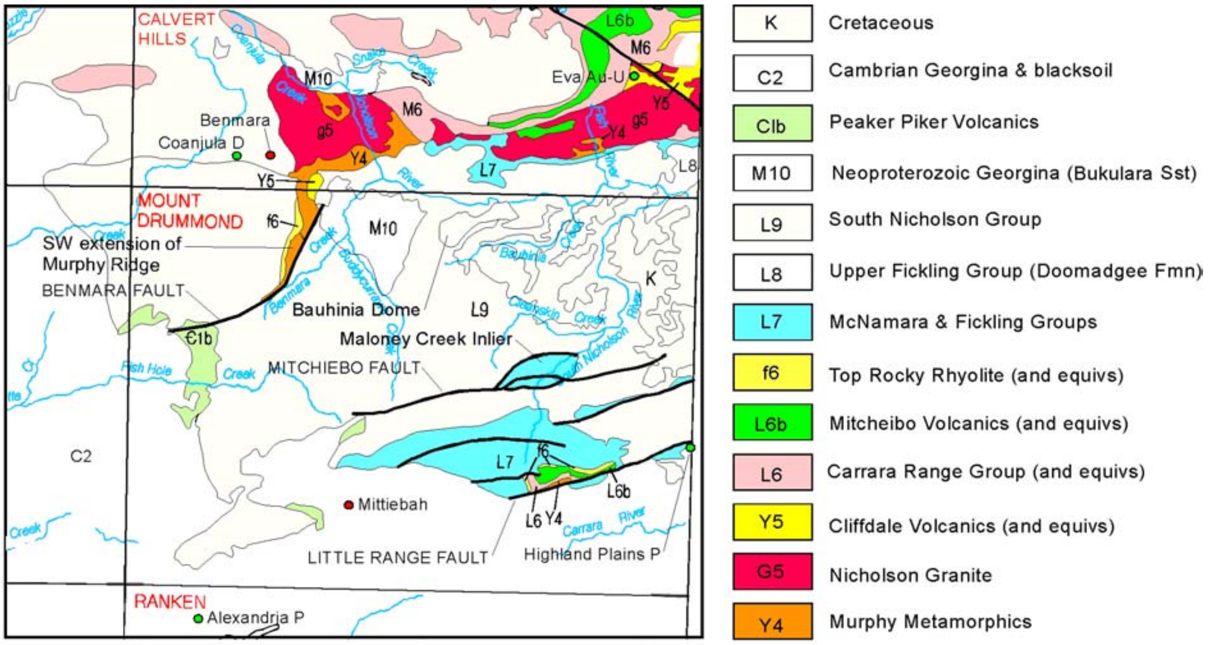

Figure 1 Regional geological map for the Mount Drummond region as at March 2003. Adapted from NT Geology Map 2002.

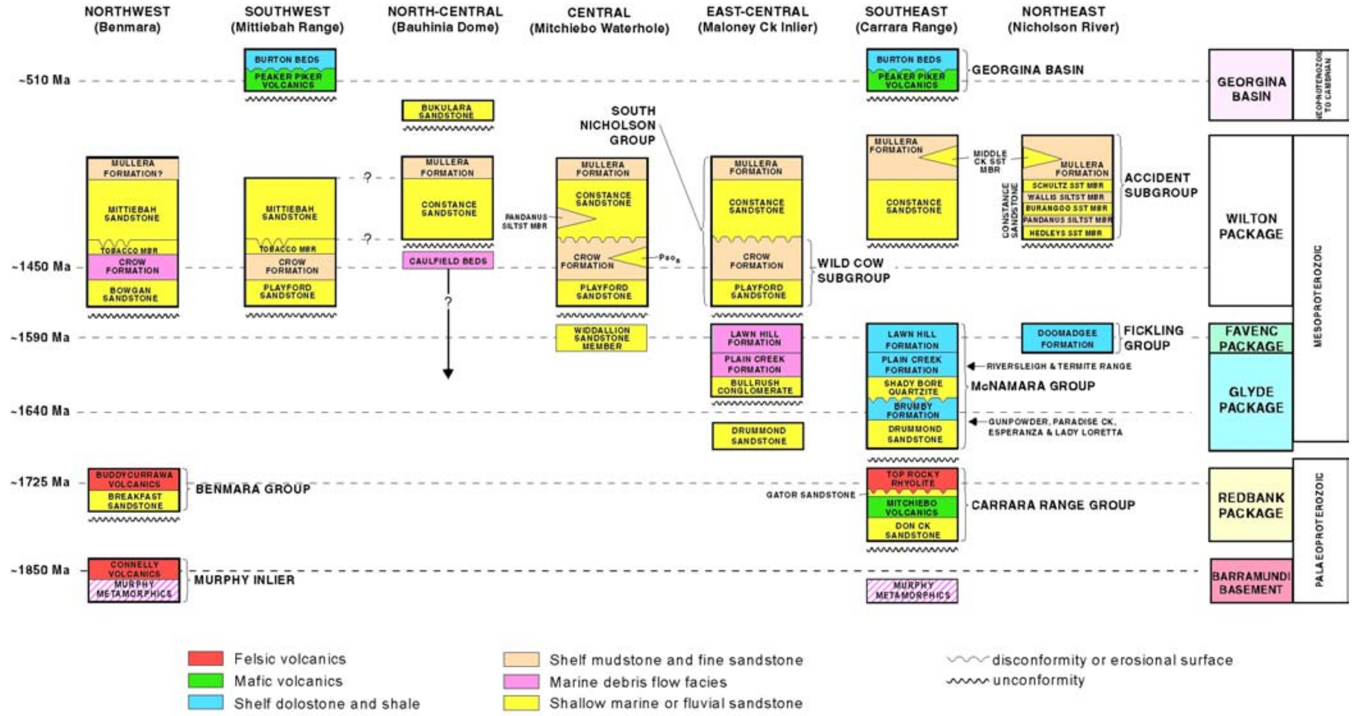

Figure 2 Stratigraphic column for the Mount Drummond region as at March 2003.

NTGS undertook regional geological studies during 2001-2003 in order to: (i) resolve geological and stratigraphic relationships; (ii) provide a detailed description of the geology for geological synthesis, exploration and land use purposes; and (iii) enhance exploration for base metals, iron, diamonds and petroleum. Field mapping is being integrated with interpretation of aerial photographs, TM7, radiometrics and magnetics. Samples were collected systematically for wholerock geochemistry (for petrogenetic and metallogenic studies) and geochronology (to develop a temporal framework), and opportunistically for stream sediment geochemistry (to complement existing company data). These datasets are available free from NTGS. A summary of the metallogenic outcomes thus far is reported here.

Murphy Inlier (Y4, Y5, G5 in Figure 1)

Interstratified within turbidites of the Murphy Metamorphics (Y4) are 2-10 m thick banded ironstones (BIFs) that are locally structurally upgraded to >50% Fe_2O_3. Quartz veining (some epithermal) is ubiquitous and clay alteration zones have been recognised locally within various rock units. The Murphy Inlier is also characterised by regionally anomalous gold stream sediment values. A number of Au and polymetallic prospects are known to the north, but the south has never been adequately tested.

Carrara Range and Benmara Groups (L6)

The Carrara Range Group includes a 500-1000 m thick flood basalt sequence (L6b), not unlike the Eastern Creek Volcanics in the Mount Isa Inlier. Base metal anomalism is common in stream sediment samples draining these volcanics along the Little Range Fault (Figure 1), suggesting that they have potential for small Redbank-style Cu-Co-Ni deposits. More importantly, these two groups have suitable characteristics to be the ‘engine room’ for a larger regional-scale metallogenic system that potentially may have formed a spectrum of deposits in the overlying or adjacent stratigraphy (eg McArthur River, Kupferschiefer and MVT styles). Localised rhyolite domes, cryptodomes and epiclastic aprons (f6) have epithermal Au-Ag-U prospectivity, based on the likelihood of abnormally hot emplacement temperatures and the naturally radiogenic nature of the rocks. However, rhyolite has anhydrous (‘dry’) or A-type geochemistry, so hydrothermal systems would have needed to rely upon the surrounding groundwater system.

McNamara Group (L7)

Included in this group is an approximately 1600 m thick carbonate, sandstone and shale succession, the Plain Creek and Lawn Hill Formations, that hosts the world-class Century Zn-Pb deposit 60 km to the east in Qld. In the Mount Drummond region, this succession is widely distributed at surface, but can also be extrapolated into the subsurface under the Georgina Basin south and west of the Little Range Fault (Figure 1). The distribution of the L7 chronometric division was expanded during NTGS mapping. In the Maloney Creek Inlier, ‘tectonic facies’, including massive polymictic breccia, conglomerate and sandstone beds, are interdigitated with background clastic facies (including carbonaceous shales and carbonates) adjacent to the Mitchiebo Fault (Figure 1). These are interpreted as turbidites and debris flows that emanated from an active (synsedimentary) ‘growth’ fault scarp into shallow to deep water environments. In this respect, they are analogous with the Barney Creek Formation and Cooley Dolomite at the McArthur River mine. There, stratiform base metal sulfide mineralisation is interpreted to have formed by exhalation of metalliferous saline basinal fluids into a localised deep-water brine pool along a regional strike-slip fault system. In the Mount Drummond region, a McArthur River model can be applied to the McNamara Group adjacent to major east–west-oriented fault systems, such as the Little Range and Mitchiebo Faults. An oil-gas play Century model can be applied to areas of regional-scale folding distal to these primary faults (hydrocarbon traps), adjacent to second order faults (metalliferous fluid pathways).

Fickling Group (L7, L8)

A narrow EW-trending belt of Fickling Group outcrop, including shales and carbonates of the Doomadgee Formation, flanks the southern edge of the Murphy Inlier (Figure 1). The Walford Creek Pb-Zn prospect, with similar characteristics to the McArthur River deposit, occurs 30 km east along strike in Queensland, at the faulted northern margin of the Lawn Hill Platform. Prospectivity for similar deposit types has not been fully tested on NT side of this outcrop belt.

South Nicholson Group (L9)

This group underwent substantial stratigraphic revision during NTGS mapping. It is a 7 km thick succession of sandstone, conglomerate, siltstone, variably carbonaceous shale and ironstone. Deep marine facies are recognised in the Crow and Mullera Formations, and interdigitated ‘tectonic facies’ and coincident thickness changes are prevalent in the Crow Formation adjacent to the Benmara Fault and Murphy Inlier (Figure 1). In the Bauhinia Dome, rocks formerly mapped as Fickling Group (now Caulfield beds) are interpreted as fan delta turbidites and debris flows that entered a marine shelf from a tectonically active hinterland, the Murphy Tectonic Ridge. Although generally thought to be unprospective for base metals, features such as these suggest that the South Nicholson Group (and Roper Superbasin) has some potential for McArthur

River-type stratiform base metal deposits. Currently, there are no significant stream sediment geochemical grids over this group, apart from recent NTGS data, suggesting further testing is warranted.

The iron ore prospectivity of the South Nicholson Group has been recognised for some time, but little wholerock data or deposit descriptions exist for the NT. Only the Constance Range deposits in Queensland have been properly assessed and documented. New NTGS mapping has improved knowledge regarding the distribution of favourable horizons and iron occurrences and has identified three types of iron occurrence: (i) primary synsedimentary; (ii) remobilised fault-controlled hydrothermal; and (iii) lateritic supergene-enriched. NTGS wholerock geochemical data indicate up to 84.7% Fe_20_3 (average 51.4%; n=19).

Exploration for oil and gas within this group has been suppressed for ten years. This has been partly due to poor results (ie low TOC) obtained from wells drilled into interpreted source rocks in the Mount Drummond region (eg DD92SN1). However, new NTGS mapping and stratigraphic studies indicate that exploratory drilling had inadvertently focused on the Crow Formation, which had been incorrectly mapped as the highly-prospective Mullera Formation. The petroleum potential should now be reassessed in terms of a revised stratigraphy and map (Figure 2). The region contains large untested tracts of 'true' Mullera Formation with submature to mature high-TOC source rocks (up to 10%) and favourable structural and stratigraphic plays. Deeper parts of the succession are predicted to have mature to overmature source rocks.

Georgina Basin (C2)

Significant phosphate potential exists in the lower Georgina Basin succession, based largely on the presence of the nearby Alexandria, Border Waterhole and Wonara Prospects and basin margin facies. In addition, infill stream sediment geochemical data collected by NTGS indicates broad base metal anomalism in the lower Burton beds (Figure 2). Follow-up sampling of 2001 zinc values up to 450 ppm and lead up to 52 ppm confirmed the overall base metal anomalism at this level, but failed to repeat the largest Zn anomaly.

Diamonds

The subeconomic Coanjula prospect and coincident 'NT microdiamond swath' have been unresolved controversies since their discovery. A tentative model is proposed here, involving emplacement of kimberlites and synmagmatic fluidised sediment intrusions at Coanjula to form roughly concordant diamondiferous mudstone bodies. Local synchronous eruption and recycling of the sediment slurry into the active South Nicholson Basin generated the broad microdiamond 'swath'. The northeast-trending Benmara Fault is interpreted to penetrate the lithosphere and may have been the focus of kimberlite-lamproite intrusions in this region. As such, the southwestern extension of the Murphy Inlier along this fault (Figure 1) has substantial diamond exploration upside.

MCARTHUR BASIN SEISMIC PROJECT – BATTEN TROUGH TRANSECT

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In late 2002, approximately 150 km of reflection seismic data was acquired across the central Batten Trough in the southern McArthur Basin. The project is jointly sponsored by NTGS, GA, pmd*CRC[3], ANSIR[2] and Anglo American, with a total budget of $550 000 (half mobilisation and demobilisation; half acquisition). Some of the objectives of the project are to:

- determine the thickness, detailed stratigraphy and structure of the Tawallah, McArthur and Nathan Groups within the Batten Trough and Bauhinia and Wearyan Shelves
- assess if simple extension and inversion formed the Batten Trough, or whether it is a strike-slip basin
- investigate the nature of the Emu Fault and its relationship to the Batten Trough
- determine if the western edge of the McArthur Group represents the edge of the depositional basin, or a post-depositional structure
- define the eastern edge of the McArthur Group and assess what influence the Emu Fault had on deposition of this succession
- determine the nature of the Tawallah Fault and its association with the Emu and Mallapunyah Faults
- investigate what influence stratigraphic and structural architecture had on mineralisation in the region.

The project began in mid 2001 with a year of preparatory work including: (i) planning and prioritisation of the route; (ii) land access negotiations and community consultation (pastoralists, traditional owners, NLC and regional councils); (iii) development of a work and environmental management plan; and (iv) assessment of environmental, safety, infrastructure, utilities, government regulatory and mineral exploration risks.

In mid October 2002, line clearing took place. In late October, the route was surveyed and gravity data was collected at 240 m spacing. Seismic experiments and acquisition began in late October and continued (without significant rain) for 12 days into early November. Two lines were acquired (**Figure 1**):

- Line 1 trended east–west from Borroloola to Bauhinia Downs Station and was 130 km long.
- Line 2 trended north–south, was centred approximately half way along Line 1 near Cow Lagoon and was 20 km long.

During the program, 40 km of re-cleared gridline and 110 km of gravel or bitumen road were utilised. The station interval was 40 m and the geophone recording spread 12 km long. The source used was three tandem ‘birdwagen’ Hemi50 vibroseis vehicles, operated by Trace Energy. The shot interval was generally 80 m (locally 40 m), producing 60 fold data (120 fold at corners). Owing to the predicted deep moho, ‘listening time’ was 20 or 22 seconds (60 km depth).

Shot point data quality varies according to sediment cover and bedrock characteristics along the line. Data quality in the east is excellent, due to the ideal situation of bitumen road over layercake Roper Group. Although shot points were also located over the Roper Group in the west, quality is generally patchy due to the varied thickness of unconsolidated sand coverage, in which there is poor geophone coupling. Data quality in the central Batten Fault Zone is variable. Shot points above shallow bedrock of Tawallah Group and siliciclastic McArthur Group units have derived good data, except where there is subsurface geological complexity (eg Tawallah Fault). Carbonate units of the McArthur Group (eg Balbirini Dolomite) proved to have deep seismic-defined ‘regolith’ and therefore poor penetration of energy into the crust. Presumably, this is due to the development of modern karst systems.

Overall, the preliminary seismic stacks resolve over the full 20 seconds in some areas, imaging McArthur Basin, immediate basement, middle-lower crust and Moho. There also appears to be good but preliminary imaging of various Emu and Tawallah fault splays and partial basin geometry. These will be resolved when the data has been fully processed in April-May.

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[1] Geoscience Australia
[2] Australian National Seismic Imagine Resource
[3] Predictive Mineral Deposits – Cooperative Research Centre

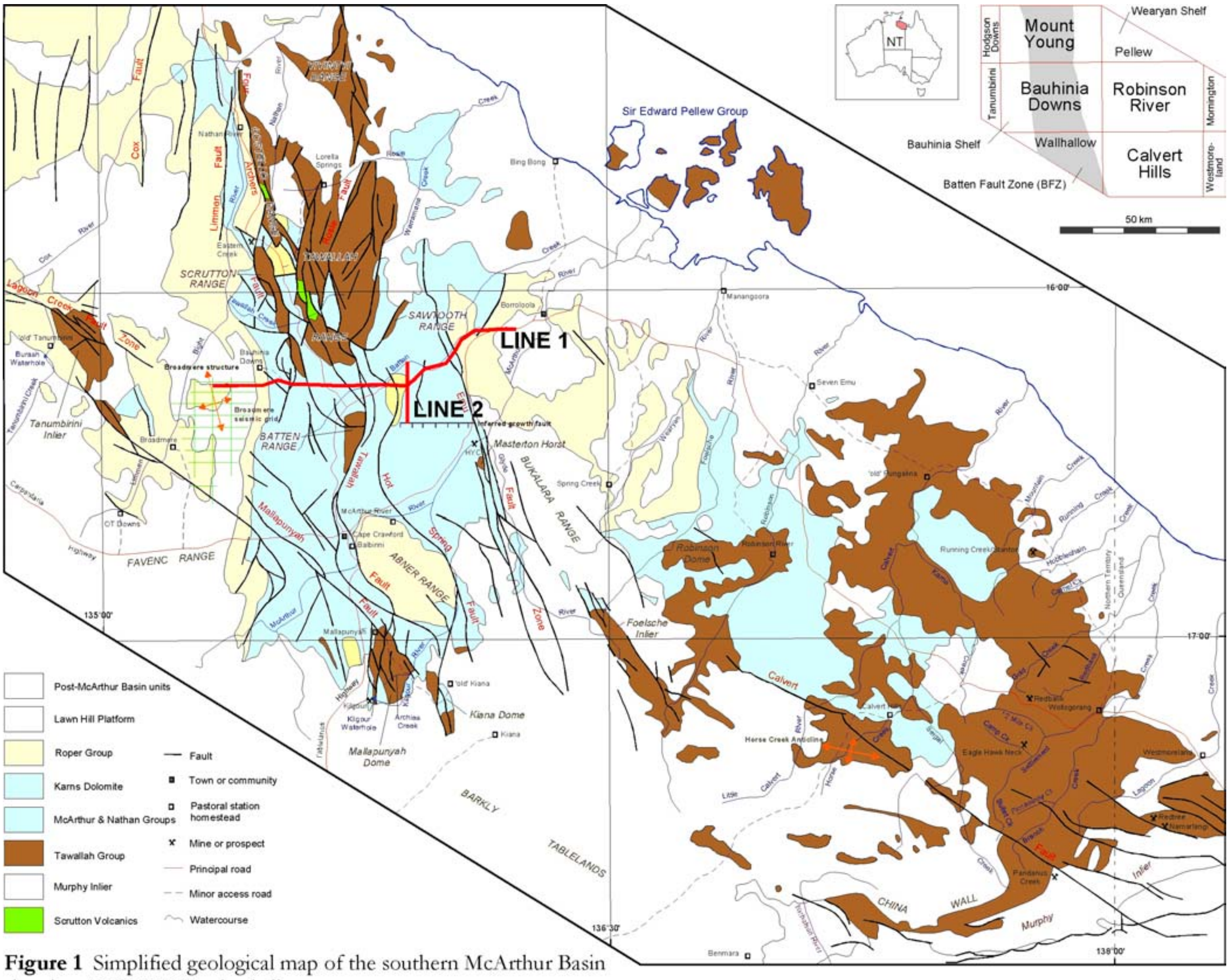

Figure 1 Simplified geological map of the southern McArthur Basin showing ANSIR 2002 seismic lines.

EASTERN PINE CREEK OROGEN – URANIUM (±GOLD±PGE) DEPOSITS AND IMPLICATIONS OF MINERALISATION MODELS

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Introduction

The eastern Pine Creek Orogen (PCO, **Figure 1**) is recognised as a world-class uranium province and contains over 350 000 tonnes U_3O_8 (past production plus resources), generally within large-tonnage low-grade deposits. Gold, platinum and palladium are also known in association with uranium and are found in appreciable quantities at Jabiluka (0.3 Moz Au, subeconomic Pd), Koongarra (0.1 Moz Au) and Coronation Hill (1 Moz Au, 50 koz Pt, 0.25 Moz Pd). Base metal deposits are not known in the area, although several base metal anomalies were found by Geopeko during exploration in the early 1970s. However, these have never been followed up (A Browne[1], GeoSynthesis Pty Ltd, pers comm 2003). The creation of Kakadu National Park in 1979 prevented further investigation of the resource potential of a large part of the eastern PCO and the area to the east and north of the East Alligator River remains under-explored. Mineralisation models suggest that there is potential for deposits of base metals, in addition to the U, Au and PGE deposits already known.

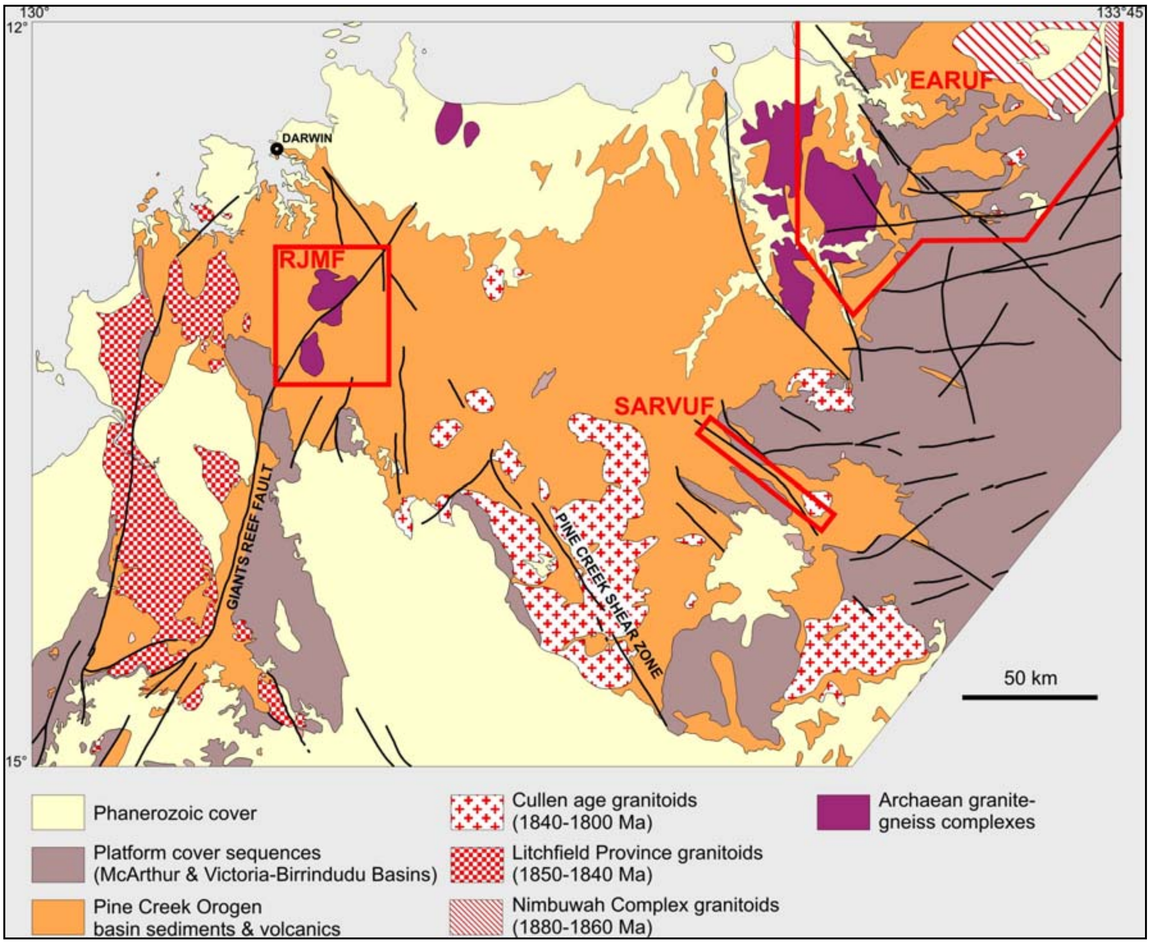

Figure 1. Map of the Pine Creek Orogen, showing locations of areas mentioned in text. RJMF: Rum Jungle Mineral Field, SARVUF: South Alligator River Valley Uranium Field, EARUF: East Alligator River Uranium Field. Eastern Pine Creek Orogen refers to SARVUF and EARUF.

Geology

Stratigraphic columns for the Rum Jungle, South Alligator and East Alligator mineral fields are given in **Figure 2**. A succession of Palaeoproterozoic sediments and volcanics were deposited unconformably on Archaean granite-gneiss basement in an intracratonic basin between 2100 Ma and 1880 Ma. Deformation, metamorphism and intrusion of syntectonic granitoids occurred during the Barramundi Orogeny (1870-1850 Ma). This was followed by post-orogenic granite intrusion

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[1] A Browne was a geologist for Geopeko and subsequently North Ltd, overseeing exploration in the Alligator Rivers area for a number of years.

from 1840-1825 Ma. In the South Alligator Valley at about 1825 Ma, there were two cycles of sub-basin formation, volcanism, deposition of clastic sediments and folding (El Sherana and Edith River groups). For the purposes of simplicity, these folded successions are hereafter referred to as 'basement'. Regional uplift and erosion preceded deposition of fluvial to shallow marine platform-cover sediments of the Katherine River Group in the east and the Tolmer Group in the west, starting at 1780 Ma and continuing until 1700 Ma. Clastic material within both groups was locally derived from erosion of basement rocks. The Katherine River Group also includes basaltic volcanic units near the base of the succession and felsic volcanic units at the top. The total thickness of the Katherine River Group overlying the eastern PCO by 1700 Ma was probably 3500-4000 m. At 1720 Ma, 100-300 m thick lopolithic sills of the Oenpelli Dolerite intruded basement and platform cover rocks.

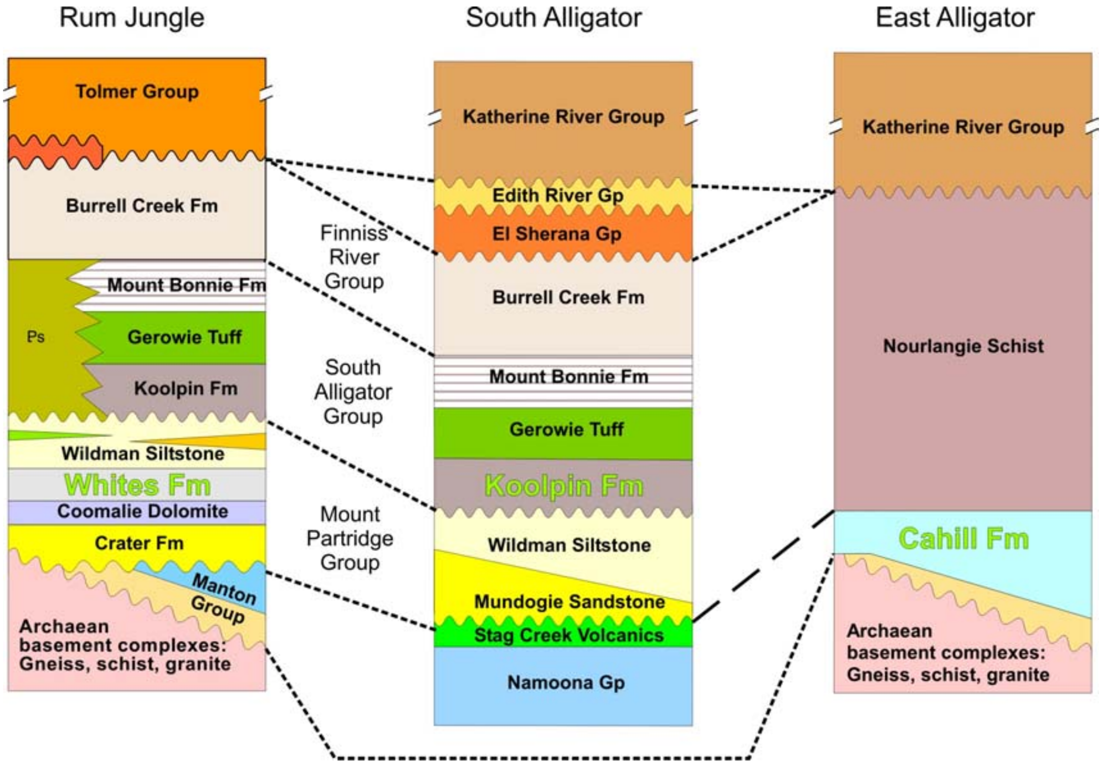

Figure 2. Schematic stratigraphic columns for the three areas shown in **Figure 1**. Green text highlights those units that host most of the known uranium mineralisation in each area.

Setting and characteristics of ore deposits

In all cases, uranium mineralisation is associated with reverse or strike-slip fault movement that postdates the Katherine River Group, although the amount of inferred movement varies from tens of metres (Nabarlek) to more than 200 m (Koongarra). Some of these faults, particularly the South Alligator Fault, are reactivated pre-Barramundi structures.

All deposits are contained entirely within basement lithologies and only patchy alteration extends into the overlying sandstones. Mineralisation is commonly hosted by carbonaceous metapelitic rocks that have undergone intense chlorite alteration. At Coronation Hill, Au-PGE mineralisation is within quartz-feldspar porphyry, quartz diorite and volcaniclastic rocks. Although there is a broad association between uranium mineralisation and carbonaceous rocks, detailed geochemistry on deposits shows there is no direct correlation between high ore grades and total carbon (eg Eupene *et al* 1975, Frishman 1983). However, several studies have shown a link between Fe^{2+} chlorite and uranium grade (eg Ewers and Ferguson 1980, Polito and Kyser 2002). The orebodies generally taper and decrease in grade with depth.

Age of mineralisation

Reliable ages of uranium mineralisation are difficult to obtain because uraninite is readily remobilised by post-mineralisation fluids. Dating of the freshest parts of uraninite and co-precipitated phengite at Nabarlek provides an age of 1640 Ma (Polito and Kyser 2002). This correlates well with previous studies of the ages of alteration minerals at Nabarlek and Jabiluka, and also corresponds to sedimentation and Zn-Pb mineralisation at McArthur River, the Leibig Orogeny in the Arunta Province and a hairpin bend in the apparent polar wander path for northern Australia. Polito and Kyser (2002) suggested that intraplate stresses during this event caused the basement faulting seen in PCO uranium deposits.

Source of ore fluids and precipitation mechanisms

Studies of fluid inclusions, alteration petrology, geochemistry and stable isotopes (REFS) all concur that ore fluids were acidic, oxidised Na-Ca-K-Mg brines at 150°-200°C. Uranium, gold and PGEs are readily transported under such conditions as chloride complexes, as are base metals (**Figure 3**). $\delta^{18}O$ and δD compositions (2 ± 2 and –25 ± 10, respectively) of ore fluids, as calculated from alteration minerals, indicate a source from meteoric water or seawater modified by long periods of residence within an aquifer (Polito and Kyser 2002). There is no stable isotope evidence for the involvement of magmatic fluids. This has led to the conclusion that the principal source of ore fluid was pore water within sandstone and conglomerate of the Katherine River Group.

Precipitation of metals occurred by reduction or neutralisation (pH increase) from reaction with basement lithologies. Some published studies consider that fluid mixing also occurred, because of traces of CH_4 found in some fluid inclusions. At Coronation Hill, Mernagh *et al* (1994) considered that neutralisation by reaction with K-feldspar precipitated Au+PGE and reduction by carbonaceous basement rocks precipitated U±Au±PGE.

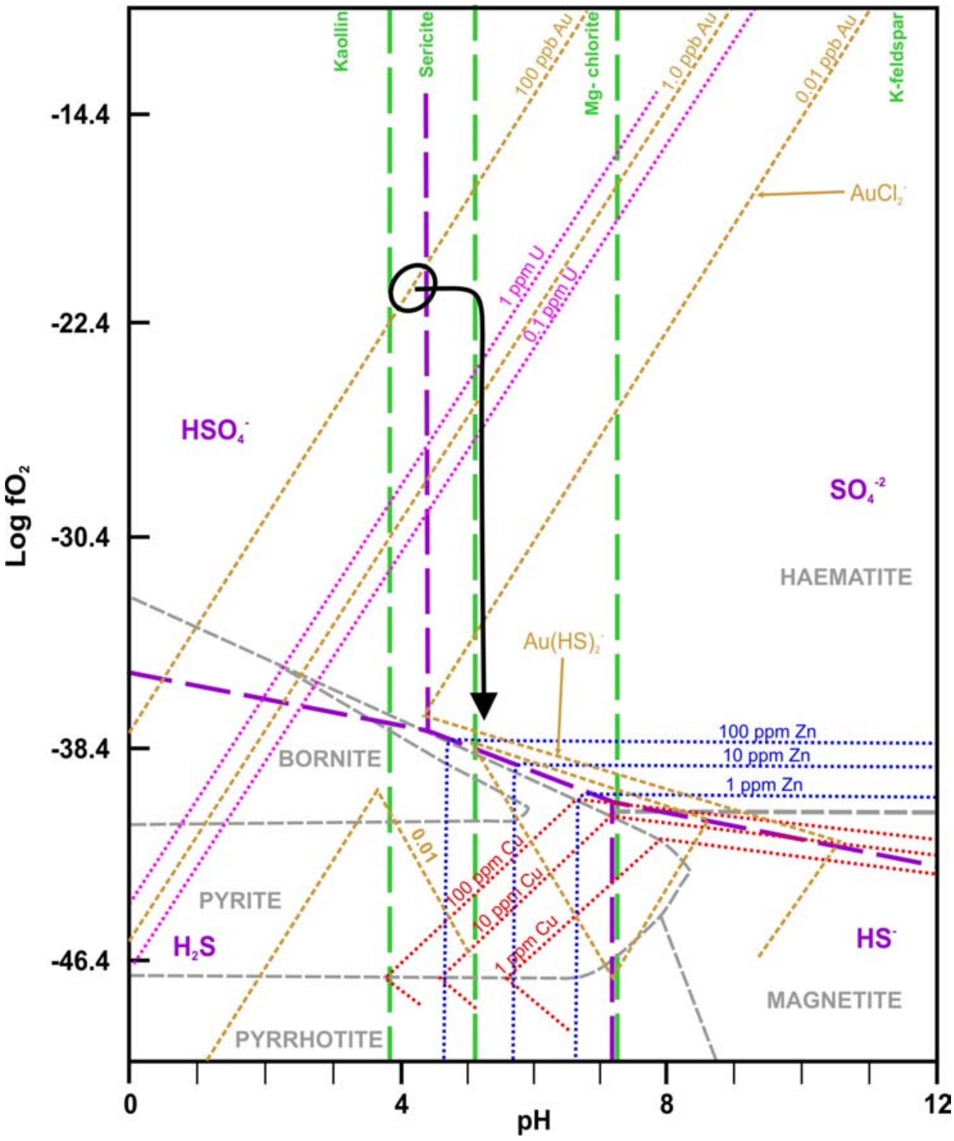

Figure 3. Geochemistry of ore fluids. Oxidised, acidic brines are capable of transporting gold and uranium as chloride complexes (as well as PGEs). Neutralisation and/or reduction (black line) of fluid will precipitate ore minerals. Continued reduction-neutralisation could also precipitate copper. Solubility fields refer to fluid at 200°C, 2 m Cl, 10^{-3} m S.

Source of metals

The source of metals for the uranium deposits remains a contentious issue and there are two main models. In the first case, all the metals were derived by dissolution of clastic components within the Katherine River Group during diagenesis (eg Hoeve *et al* 1980, Polito and Kyser 2002). In the second case (eg Solomon and Groves 1994) metals were leached from basement lithologies during large-scale fluid circulation confined to the Katherine River Group aquifer and remained in solution in the oxidised pore waters. In both models highly radiogenic Archaean- and Barramundi-age granite-gneiss and granite were the most likely sources of uranium, and other metals could have been derived from either basement rocks or volcanics within the Katherine River Group.

Mineralisation models

As already stated, there is reasonable evidence for a fluid source within the Katherine River Group. The association of known deposits with faults and the overall geometry of the deposits indicates that ore fluids were focused into the basement along highly permeable zones created by fault movement. The primary mineralising event occurred at 1640 Ma, about 50 Ma after deposition of the Katherine River Group. Reaction between ore fluid and basement lithologies (and perhaps basement fluids) resulted in reduction and/or neutralisation and precipitation of metals, principally uranium, but also gold, platinum and palladium. Trace quantities of base metal sulfides (galena, sphalerite, chalcopyrite) also occur with the ore metals.

Solomon and Groves (1994) suggested a two-stage model for deposit formation. In the first stage, a closed circulation system operated within the Katherine River Group, which leached metals from the basement into the aquifer waters. In the second stage, faulting caused highly permeable zones to extend from the basement and connect with surface waters. Descending, highly oxidised brines carried metals from the aquifers into reducing basement lithologies and formed uranium deposits. This two-stage model is very similar to that proposed by Large *et al* (2002) for the formation of the McArthur River Zn-Pb deposit, which is based on results from numerical modelling of fluid flow. The major difference is that reduction of ascending oxidised ore fluids and mineral precipitation occurs at the surface through interaction with a reduced brine pool.

Polito and Kyser (2002) suggested a slightly different model for uranium mineralisation. From detailed studies of alteration paragenesis and alteration mineral dating at the Nabarlek deposit, they recognised that multiple alteration and fluid-flow events affected the basement rocks over a protracted period of time from 1750 Ma to 900 Ma. Ore fluid and metals were sourced only from the overlying sandstone aquifer, without pre-mineralisation basement leaching. Reverse movement along the Nabarlek Fault allowed dense, high-salinity brines to descend into the basement at various times during the evolution of the deposit. Fluids in the overlying aquifer were compartmentalised by aquitards created during diagenesis. The breaching of different aquitards at various times caused pre-ore chlorite alteration, uranium mineralisation and uranium remobilisation.

Implications for mineralisation

The oxidised, slightly acidic ore fluid that transported U, Au, Pt and Pd is also capable of transporting high concentrations of other metals, particularly Cu, Pb and Zn. The limitation to forming metal sulfide mineralisation is the availability of sulfur in reducing host rocks. One possible source would be sedimentary pyrite preserved within basement rocks, which include pyritiferous carbonaceous mudstones that are usually targeted for uranium deposits in the eastern PCO.

Proposed models for Coronation Hill demonstrate that neutralisation is a possible precipitation mechanism, and potential host rocks for Au-PGE deposits include K-feldspar-rich granites. Barramundi-age granitoid intrusions are abundant in the eastern PCO and some may be suitable host rocks.

Favourable structures in the basement that allow a large amount of fluid-rock interaction are necessary, but may not have an obvious expression through the overlying platform cover rocks. For example, Jabiluka 2 deposit reverse faults in the basement do not connect to a recognisable fault or fracture zone in the overlying sandstone. There have been no studies on fluid-flow modelling within the Katherine River Group aquifer and it is unclear what parameters would have controlled the rate and amount of flow into the basement. Possibilities include the geometry of the platform cover–basement unconformity, the effects of basalt and Oenpelli Dolerite ‘layers’, and radiogenic heat production from Archaean and Barramundi granites.

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RESOURCE POTENTIAL OF THE SOUTHERN GEORGINA BASIN

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The southern Georgina Basin (south of 21°S) in the Northern Territory is prospective for a range of commodities including petroleum, base metals, diamonds, manganese and phosphate. This area has been the subject of a multidisciplinary study by NTGS. Some of the key findings, particularly those of relevance to base metal exploration, are presented. The final multi-commodity report will be GIS-based.

Lithostratigraphy has been revised based on second edition mapping, relogging of drill core, stratigraphic drilling and correlations of petrophysical logs. Nomenclature has been simplified and new group names are proposed.

A major SRK and inhouse geophysical interpretation of basin thickness and basement composition has been undertaken. NTGS aeromagnetics, limited seismic data, additional ground gravity and a database of density and magnetic susceptibility measurements of core enhanced this study. In excess of 1.5 km of Neoproterozoic sedimentary rocks are preserved in downfaulted blocks and half-grabens. Depocentres and synclines along the southern structural margin contain several kilometres of overlying Palaeozoic section. Previous estimates of as much as 9 km, based on magnetic depth modelling, appear not to have recognised low-magnetic intensity granites and hence have overestimated basin thickness.

Basement in the west is dominated by folded and faulted Palaeoproterozoic felsic gneiss intruded by syn- to post-tectonic granitoids. The eastern domain is relatively undeformed and consists of Palaeoproterozoic (and possibly Archaean) mafic-intermediate intrusive bodies and younger non-magnetic granitoids. SHRIMP U-Pb zircon ages of basement range from 1846 ± 6 Ma to 1749 ± 8 Ma.

Eight tectonic events have been recognised and dozens of major basement-penetrating faults have been mapped. The complex fault kinematics are annotated in a GIS layer.

Known base metal prospects and occurrences have been documented and additional studies undertaken. All available mineralised intercepts have been reassayed using a standardised technique. The best Cu occurrences are in Neoproterozoic clastics. Known Pb-Zn prospects and occurrences are areally widespread and are throughout the succession from Neoproterozoic clastics to Lower Ordovician carbonates and mixed carbonate/siliciclastic rocks. There is a wide range of mineralisation styles. Galena and barite occur along 6.5 km of strike in the Arrinthrunga Formation at Box Hole. Mineralisation is stratabound epigenetic replacement and vug-fill associated with stromatolites and a possible fault feeder. About 15 t of ore, averaging 65-70% Pb and 60 g/t Ag, has been handpicked. This mineralisation has most similarity to MVT. Visible Zn-Pb mineralisation (up to 1.2% Zn) occurs in and just below a shale cap at the contact of the Arthur Creek Formation and Thorntonia limestone in Baldwin 1 and may have affinities to stratiform shale-hosted base metal mineralisation of the Mount Isa/Century style. A fault breccia at the Boat Hill Prospect contains two intervals with percent levels of Zn. NTGS drilling in the Thorntonia Limestone in this area also intersected percent levels of Zn and visible galena, which considerably extends the area of known mineralisation. Previously undocumented visible galena was recognised in the Neoproterozoic Elyuah Formation at the Mount Skinner Prospect. This core contains 2.44 m assayed at 0.3 m intervals all of which are >2000 ppm Pb.

Pb isotope data have been acquired for galena in host rocks ranging from Neoproterozoic to Late Cambrian–Early Ordovician age. These, and previously published data from Queensland, show a close correlation to a single isochron, indicating a single mineralising event with an initial ratio close to crustal Pb (no mixing). This is interpreted as a 1840-1780 Ma Pb source and a 420-280 Ma mineralisation age, corresponding to the Alice Springs Orogeny.

Various techniques have been used to map thermal anomalies areally and temporally. Several petroleum wells have present geothermal gradients >35°C, which is well in excess of the world average. Tmax, determined from petroleum studies, shows relative hot spots centred on Ammaroo and Boat Hill. A waterbore at Ammaroo had a gas blowout in what would otherwise have been thought of as a less-mature oil-prone part of the basin. Limited conventional fluid inclusion studies show areas of highest fluid temperature at Boat Hill (av 190°C) and in the central basin (NTGS01/1 av 211°C). Inclusions in sphalerite from the southernmost basin average 117°C and testify to the fluid temperatures responsible for this mineralisation. Barite, intimately associated with galena at Box Hole, has an average fluid inclusion temperature of 90°C. Temperatures of 495-520°C, previously reported in the literature, could not be corroborated.

Thermal anomalism in the southern Georgina Basin probably results from a combination of causes including the lateral migration of hot fluids under a shale blanket. It is not simply related to ‘hot’ granites as supposed by some previous workers. Timing has been constrained by AFTA studies. Although these data are not yet publicly available in full, they support a major heating event during the Alice Springs Orogeny with possible overprints in the Late Triassic–Early Jurassic, Mid-Cretaceous and Tertiary (locally up to 105°C).

NTGS has compiled the available company exploration geochemical data into Explorer3. Surface geochemistry has to be treated with caution because of scavenging in the regolith. Contouring of rock chip Pb highlights the Box Hole Prospect. Zn anomalies are centred on the Box Hole and Boat Hill Prospects. Cu in soils over Cambrian carbonates was considered unreliable by previous explorers, but there are clearly anomalies within the Neoproterozoic Central Mount Stuart Formation.

Five genetic models are proposed for base metal mineralisation in the southern Georgina Basin. Potential target areas have been mapped by filtering selected criteria for each model using GIS.

A generalised sediment-hosted Cu model targets syn-rift to early sag phase Neoproterozoic formations containing permeable clastics and redox boundaries in close proximity to a suitable fault feeder. Mount Skinner Cu prospect falls within the target areas generated. A more specific analogy is drawn with the Zambian Cu-belt. A correlation of global glacial rocks indicates that the Plenty Group in the southern Georgina Basin would be analogous to the Roan Supergroup that contains the Zambian Ore Shale. The lowermost shale in the Plenty Group would be a target. Thus, previous Cu exploration that focused on the Central Mount Stuart Formation may have been looking too high in the succession.

Stratiform sediment-hosted Pb-Zn of the Mount Isa, HYC or Century style is usually thought of in terms of Palaeoproterozoic host rocks in Australia but Early Cambrian examples exist overseas. The epigenetic (Century-style) variant was targeted using potential shale hosts in the Adam Shale, basal Arthur Creek Formation or intra-Thorntonia Limestone and fault feeders that mark a fundamental change in basement composition and were active during the Alice Springs Orogeny. Very localised targets exist in ELKEDRA and HUCKITTA. Other, classic syngenetic exhalative models could also be developed for the same target formations. EM is seen as a viable technique to locate suitable hosts.

Most previous base metal exploration in the Cambrian of the Georgina Basin has used an MVT model. All available data support this. Targets were modelled using Cambrian or Cambro-Ordovician carbonates on the shelf break, which are cut by postdepositional faults that tap basement. The Box Hole Prospect falls within the target areas generated.

Irish-style and Manto deposits are higher temperature than MVT and have a stockwork feeder. If ore bodies of this type are to be found, they will be in Cambrian carbonates in areas of highest thermal maturity and fed by a suitable dilational fault. Such targets are present in ELKEDRA, SANDOVER RIVER and TOBERMORY.

Epigenetic sandstone-hosted Pb is infrequently used as an exploration model in Australia but is becoming increasingly important as giant deposits such as Jinding in China become better understood. This style of deposit is hosted in the first transgressive sandstone or arkose at the start of a basin phase, in this case the basal Neoproterozoic, near the depositional or structural edge of the basin, <100 m above basement and cut by a suitable fault feeder. This constrains drillable targets to the southern basin margin and includes the newly reported galena occurrence in the Elyuah Formation at Mount Skinner. The association with evaporites in the Elkera Formation is seen as favourable for a Jinding model.

In summary, previous explorers have underestimated the base metal potential of the southern Georgina Basin because of the misconception that all visible mineralisation was surficial enrichment, the perceived lack of suitable faults as plumbing, a preoccupation with MVT models or stratigraphically misplacing the best Cu targets. In contrast, this study has generated new base metal targets.

Much of the southern Georgina Basin is currently under tenure for diamond exploration. Prior to work by Elkedra Diamonds NL, the area had yielded 1 macrodiamond, 13 microdiamonds and numerous DIMs. Elkedra has located an additional 4 microdiamonds and hundreds of high-Cr chromites. Two newly discovered microdiamonds, in their Wanda target, come from a drainage of only a few square kilometres in well-outcropping Ninmaroo Formation.

This multidisciplinary study of the southern Georgina Basin has drawn together stratigraphic revision, geophysical and structural interpretation, studies of thermal maturity and Pb isotopes, prospect descriptions, new assays of prospective horizons and surface geochemistry. Targets for a range of commodities have been mapped.

NORTHERN TERRITORY EXPLORATION AND MINING TENURE ON NATIVE TITLE AND ABORIGINAL LAND

Bob Adams[1]

The Northern Territory determined to use the *Native Title Act* procedures to grant mining and petroleum tenure on 21 March 2001. Since then, about 500 Exploration Licences have been granted on non Aboriginal land. This presentation details the events impacting on the processing of tenure pursuant to the *Native Title Act.*

Almost 50 percent of the area of the Northern Territory is Aboriginal freehold land and there is a concern that the administration of the grant of mining tenure on Aboriginal land is delaying the grant of exploration tenure. The Federal Government is reviewing the operation of the *Aboriginal Land Rights (Northern Territory) Act* and this presentation reviews the activities associated with that review.

The tenure statistics to the end February 2003 are prescribed for Aboriginal land and land subject to native title. Other issues relating to the operation of the *Mining Act* and the management of tenure are discussed including Northern Territory Government participation in inquiries concerning the national downturn in exploration expenditure.

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INDIGENOUS LIAISON – THE WAY FORWARD

Mark Nolen[1]

With approximately 50% of the Northern Territory being Aboriginal freehold land and much of the remainder subject to Native Title, a pro-active attitude of involving Indigenous people and their representative bodies at an earlier rather than later stage is essential to achieve progress on land access for all parties involved.

There has been significant change of recent years in relation to exploration and mining in the Territory, eg Native Title, expedited procedures etc. It is evident that there has also been a change of attitudes by all parties including government, land councils and industry in regard to resource development. A number of commercial ventures happening 'on country' and driven by local people have also emerged.

There has never been a better time for resource developers, land councils and government to re-think how we can all maximise the benefits of exploration and mining in the Territory.

By its nature, exploration and mining takes place in the remote regions of the Territory and has the potential to contribute significantly to regional economies and remote communities. In general, industry has gone to great lengths to engage local people in their businesses and provide avenues for economic return. However, there are a number of impediments which prevent a greater number of Indigenous people from becoming involved in the industry. Companies currently operating in the Territory would be fully aware of issues such as poor numeracy and literacy levels, access to full medical checks, drug and alcohol awareness, cultural issues and the fact that not all people want to work in the mining industry. There are numerous examples of where industry's 'normal working conditions' just don't suit: fly in/fly out, 12 hour shifts, 7 days on/7 days off, and so on.

Experience has shown that when industry is engaging in employment ventures with local communities they should try to find jobs that suit the people, not people to suit the jobs. This does not mean that willing and suitably qualified people should be excluded from employment opportunities in mainstream mining, but rather that the industry should look at where people could effectively contribute to their operations.

The minerals and petroleum industries are extremely efficient operators. They have to be in order to survive. Margins are minimal, competition is strong and commodity prices are at best average. So when it comes to exploring, evaluating and mining, industry needs to do this in the most efficient, cost effective and socially acceptable manner available. Industry is always looking for the best available technologies to remain cutting-edge and reduce overheads. When it comes to working with local Indigenous communities and their representative bodies, we must also do the same.

There has never been a better time to discuss new options with all parties involved. A number of companies are already thinking outside the box to achieve their objectives and obligations. Doing business anywhere in the Northern Territory necessitates engagement of the Indigenous community, and to move forward companies may need to extend themselves and their thinking to maximise the returns for all stakeholders.

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