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CONTENTS

[1] PowerPoint presentation (by Richard Brescianini) includes 'NT exploration overview 2004' (Dunster and Brescianini) and 'Regional phosphate prospectivity' (Khan *et al*).

NT EXPLORATION OVERVIEW 2004

John Dunster[1] and Richard Brescianini

Mineral exploration expenditure in the Northern Territory in 2003–04 was A$42.4 million, a decline of 13.9% on the previous year, and the lowest recorded level since the Australian Bureau of Statistics began desegregating Australian expenditure statistics by individual State/Territory in 1988–89. This decline was in sharp contrast to national exploration expenditure, which rose by 7.4% over the same period, consistent with global expenditure increases of similar or greater magnitude.

Expenditure levels in the NT over this period are, however, inconsistent with other observations tracking exploration activity. For example there is a clear upward trend in the Department's processing and evaluation of statutory exploration reports, from 1000 reports in 1999, to over 2700 in 2004. Further evidence indicating enhanced exploration activity comes from the processing of applications for exploration licences (ELs). In 2004, 196 EL applications were received, and 123 were granted. The NT Government's track record in granting ELs since 2000–01 has been very impressive. During this time there have been:

- 825 EL grants on land subject to Native Title, using the expedited procedure available under the *Native Title Act*
- 198 EL grants on Aboriginal freehold land, using established processes under the *Aboriginal Land Rights (NT) Act*
- 18 Indigenous Land Use Agreements registered.

As at 24 February 2005, there were 768 granted ELs and 663 EL applications in the NT (**Table 1**).

TERRANE	AREA (Km^2)	% OF TERRANE UNDER ELs	% OF TERRANE UNDER ELAs	% OF TERRANE VACANT
McArthur Basin	143 570[1]	29	33	38
Victoria-Birrindudu Basin	79 830	21	9	70
South Nicholson Basin	14 870	1	13	86
Pine Creek Orogen	44 120[1]	29	17	54
Tennant Region	43 500	25	16	59
Tanami Region	32 070	44	47	9
Arunta Region	200 380	31	31	38
Musgrave Block	29 380	21	59	20

Table 1. approximate proportion of several of the NT's major (exposed) Proterozoic terranes occupied by various classes of tenure
[1] Excludes Kakadu National Park.

This analysis indicates that significant portions of several of the Northern Territory's mineral prospective terranes are vacant. Somewhat more surprisingly, two terranes that are generally considered to be more "mature", the Pine Creek Orogen and Tennant Region, have more than 50% vacant land.

Exploration and resource highlights during 2004 from four of the Territory's better-known terranes are outlined below.

McArthur Basin

- *Gravity Diamonds*: discovery of diamond bearing kimberlite in Abner Range, near Borroloola.
- *Striker Resources*: 30% increase in overall ct/t diamond value at Merlin; inferred resource of 17.3 Mt @ 0.16 ct/t for 2.8 Mct.
- *Xstrata*: planned McArthur River Mine open pit 1600 x 1400 x 400 m; will increase reserve fourfold.

Arunta Region

- *Arafura Resources*: significant REE/phosphate drilling intercepts at Nolans Bore, eg 25 m @ 4.6% REO and 19% P_2O_5 from 12 m; inferred resource of 5.8 Mt @ 3.9% REO and 16.5% P_2O_5.
- *Olympia Resources*: Harts Range alluvial garnet testing has shown greatly increased recovery; resource of 98 Mt containing 6 Mt garnet and 24 Mt aluminomagnesian hornblende.
- *Reward Minerals*: encouraging results from Jervois project – Bellbird up to 4 m @ 7.93% Cu from 63 m; Green Parrot 3 m @ 5.25 g/t Au and 78 g/t Ag from 14 m (above Pb/Zn zone).
- *Tennant Creek Gold*: new JORC resource at Molyhil from bulk samples and drilling – 2 Mt @ 0.5% WO_3 and 0.2% MoS_2 to 150 m.

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Pine Creek Orogen

- *Arafura Resources*: Native Title agreement reached at Mount Porter; new resource 355 000 tonnes @ 3.0 g/t Au; pit design completed; Frances Creek drill intercepts including 4 m @ 47.5 g/t Au and 5 m @ 19.1 g/t Au from 30 m.
- *Renison Consolidated Mines*: further encouraging intercepts at Toms Gully of up to 2 m @ 11.5 g/t Au from 246 m; total underground resource of 1.82 Mt @ 8.1 g/t for 472 000 oz Au; mining contractor chosen for 40 000 oz per annum.
- *Burnside JV (Northern Gold / Harmony Gold)*: Zapopan reserve up 22% to 247 300 t @ 13.1 g/t for 103 700 oz Au within total Burnside Pine Creek resource of 5.2 Mt @ 2.1 g/t for 346 000 oz contained Au; Cosmo Deeps drill intercepts 16.8 m @ 5.71 g/t Au; new resource figure of 7.5 Mt @ 4.3 g/t for 1.0 Moz Au.
- *Compass Resources*: new total resource at Browns project of 40 Mt @ 0.5% Cu, 4.52% Pb, 13 g/t Ag; global resource (including Browns East) totalling 84 Mt.

Tennant Region

- *Giants Reef Mining*: Malbec North 9 m at 73 g/t Au from 21 m; Malbec West 52 000 t @ 11.5g/t Au (19 300 oz) to 60 m; mining commenced 18 weeks after discovery; small high-grade deposits such as Edna Beryl, Cats Whiskers and Billy Boy being explored and developed.
- *Bootu Creek Resources*: Bootu Creek 11 Mt @ 27% Mn; mining tenement secured; infrastructure being constructed; $24 M capital investment; 5–10 year mine life.

Other areas

Bonaparte Basin

- *Tennant Creek Gold*: Sandy Creek MVT granted exemption from previous Reserve from Occupation under Ord River Scheme; existing non-JORC of 3.2 Mt @ 4.38% Pb, 2.45% Zn, 15 g/t Ag; potential for 10–20 Mt of open pit high-grade mineralisation.

Money Shoal Basin

- *Matilda Minerals*: auger drilling at Puwanapi mineral sands prospect on Bathurst Island has outlined 920,000 t @ 6.2% HM; Valuable Heavy Mineral suite contains >44% zircon plus rutile; Mineral Lease applications lodged in December 2004.

REGIONAL PHOSPHATE PROSPECTIVITY

Mazhar Khan, Phil Ferenczi and Masood Ahmad[1]

Palaeozoic successions of northern Australia host a number of phosphate deposits. Phosphorite occurs in Middle Cambrian and Middle Ordovician rocks within these successions and several deposits have been outlined in the Georgina Basin, including the Duchess, Phosphate Hill, Lady Annie and D Tree deposits in Queensland, and Wonarah, Alexandria, Alroy and Highland Plains in the Northern Territory. Previous studies (Howard 1972, 1990, Freeman *et al* 1990) have also outlined the presence of phosphorite in the Wiso and Daly basins.

The Wonarah deposit, which contains an inferred resource of 72 Mt @ 23% P_2O_5, was recently (2000–2002) examined by Rio Tinto Exploration. They concluded that the NPV of the deposit was negative. This deposit has a waste-to-ore ratio of 2:1 and is located about 200 km east of the nearest railhead at Tennant Creek. By contrast the existing mining operations at Phosphate Hill have similar grade and waste-to-ore ratios, but are serviced by a railhead at Duchess, close to the deposit.

The Northern Territory Government has an active program to promote the development of gas and resource processing industries via investigation of potential new industries. Fertiliser production is one of the major opportunities for gas and mineral processing in the Territory. The large Timor Sea gas resources and potential phosphate resources close to existing and proposed infrastructure strongly favours the development of fertiliser industries in the NT.

The prospect of finding a deposit closer to the railway corridor and Darwin is reasonable, as the prospective phosphatic rocks trend adjacent and parallel to the railway. These rocks have not been investigated in significant detail.

With the completion of the Alice Springs–Darwin Railway and future gas pipeline development, NTGS identified a need to thoroughly investigate the phosphate potential of the Northern Territory. New deposits closer to this infrastructure, or those with higher grade (>30% P_2O_5) within a reasonable distance, may prove to be economically viable. This project aims to provide further evidence for the location of such deposits by, in the first instance, identifying and analysing selected rock chip samples from water bores.

More then 4000 RC holes have been drilled for water supply in the Georgina, Wiso and Daly basins, and cuttings from 1/3 of these boreholes are preserved at NTGS drillcore storage facilities in Darwin and Alice Springs. The work program involves sampling of Cambrian holes from the Georgina, Wiso and Daly basins within 100 km of the Alice Springs–Darwin Railway (**Figure 1**). Cuttings from 214 water bores have thus far been logged and tested for phosphate by using ammonium molybdate reagent. In all a total of 5300 samples at 3 m intervals have undergone qualitative testing.

The current project has been designed to augment the work of Howard (1984), who selected and qualitatively tested rock chips from 83 water bores. Most of these were from the western Georgina Basin, with fewer samples from the western edge of the Wiso Basin. All water bores sampled during his study were excluded from the current project, with the exception of samples obtained from the Lady Judith (Buchanan Hill) discovery in the Winnecke Creek area (western Wiso Basin), from which Howard reported an interval of 32.1% P_2O_5.

Intervals showing positive reaction with ammonium molybdate (indicated by yellow precipitate) were recorded. Drill chips from these anomalous intervals were submitted to AMDEL for quantitative phosphate and whole-rock major element analysis. The analytical method used by AMDEL was IC4, involving total digest (alkaline fusion) followed by ICP analysis. In all, 182 samples from 50 boreholes have thus far been submitted for quantitative analysis. Intervals from several boreholes have returned >2% P_2O_5. These anomalous intervals are listed in the **Table 1** and their locations shown on **Figure 1**.

HOLE ID	MGA EAST	MGA NORTH	MGA ZONE	1:250K SHEET	INTERVAL	ASSAY (P_2O_5)
RN020989	723728	7920921	52	Winnecke Creek	15–18m	**28.2%**
RN020989	723728	7920921	52	Winnecke Creek	72–75m	**2.22%**
RN006257	420127	7700169	53	Bonney Well	10–20m	**2.19%**
RN010258	452127	7840168	53	Tennant Creek	43–46m	**2.04%**
RN010533	350593	7852701	53	Tennant Creek	40–43m	**3.2%**
RN011609	365583	7813028	53	Tennant Creek	84–87m	**2.43%**
RN013015	586305	7589953	53	Elkedra	30–75m	**Range 2.28–16.9% Average 6.7% over interval**
RN016928	436367	7845375	53	Tennant Creek	24–27m	**2.69%**
RN016930	354634	7857275	53	Tennant Creek	36–39m	**2.21%**
RN016930	354634	7857275	53	Tennant Creek	39–42m	**5.54%**

Table 1. Drillholes showing greater than 2% P_2O_5 intersections.

In general phosphate reaction was stronger in fine-grained clayey sediments than in crystalline limestone. Very few sandstone samples showed any reaction with ammonium molybdate. It is possible that much of the fine-grained soft sediments were lost during water bore rock chip sampling procedures.

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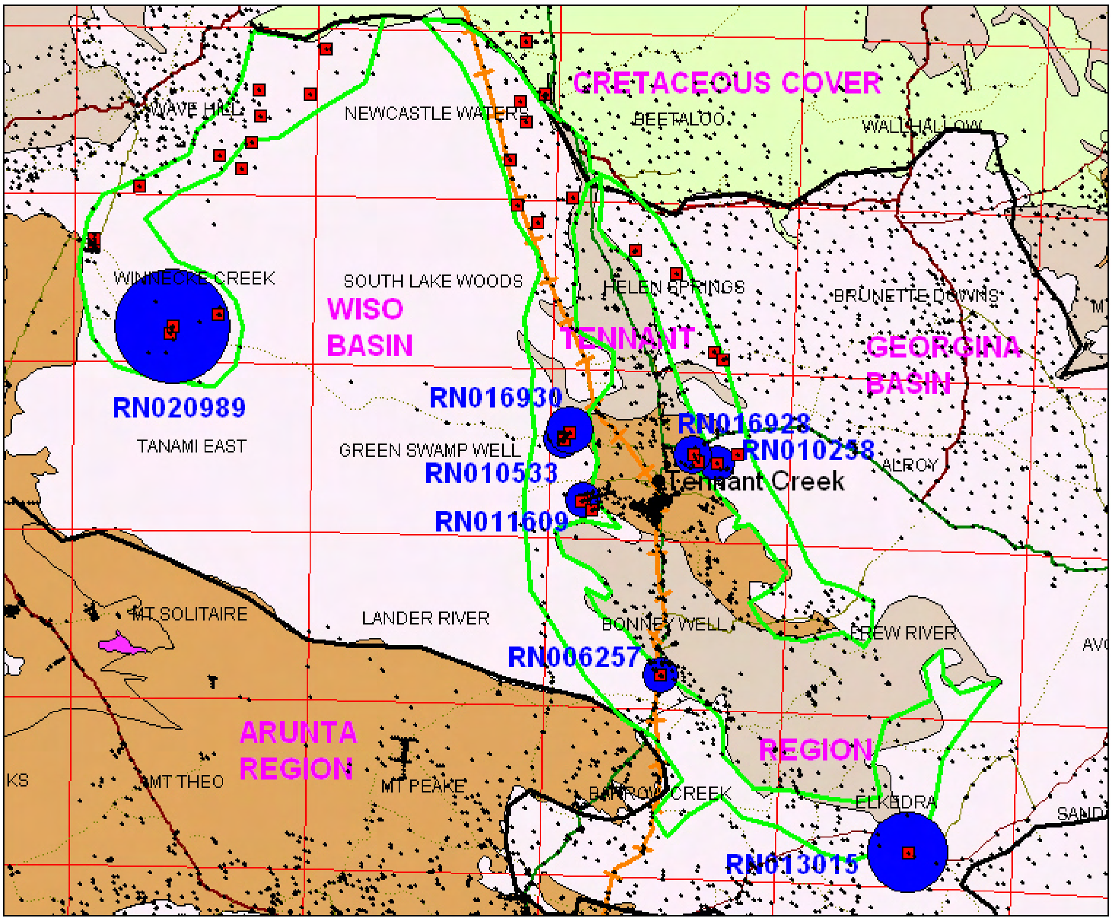

Figure 1. Interim results of Regional Phosphate Prospectivity Project. Area is centred on the town of Tennant Creek, and 1:250 000 map sheets are shown. Approximate area of examination in the Georgina and Wiso basins is indicated by the green polygons. Alice Springs–Darwin Railway is shown in orange. The location of water bore samples showing P_2O_5 analyses >2% are indicated by blue dots, with sample identification numbers alongside. Red squares are samples submitted for geochemical analysis on the basis of positive reaction with ammonium molybdate. Black dots are water bores.

Additional sampling of water bore cuttings and diamond drillholes remains to be completed. Testing of water bores across the Wonarah deposit was also undertaken for comparison purposes. A total of 30 samples from 6 water bores were quantitatively analysed and returned assays of between 0.22 and 9.19% P_2O_5.

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NORTHERN TERRITORY REGOLITH PROJECT – A PROGRESS REPORT

Mike Craig[1]

Project Scoping

The beginning phase of this project involved a major scoping meeting in Alice Springs with staff from the Northern Territory Geological Survey and CRC LEME[2]. This meeting was responsible for establishing the overall strategic plan and general work plan for the life of the project. The staffing mix, individual roles and responsibilities within the life of the project were clearly defined at that meeting. The task was essentially to provide a framework map of the Northern Territory with supportive regolith characterisation, to shed some light on the evolution of major landscape domains and their associated weathering history.

The initial task of surveying and consolidating relevant published and unpublished datasets on the characteristics and distribution of the Northern Territory regolith has been achieved.

A key decision of the scoping meeting was to undertake a Trans-NT regolith traverse. Its purpose was for team members to observe, first hand, the major regolith-landscape variations (domains) from south to north, with lesser excursions to east and west, as time permitted and needs dictated. All aspects of logistics for the Trans-NT regolith traverse, which began from Alice Springs on 21 September 2003, were provided by NTGS. This was a unique exercise that was going to provide a broad view of the regolith-landform domains across the territory, provide insights to regolith material characterisation needs for the project, and allow us to target representative and complex domains that required more intense fieldwork.

Deliverables

The main deliverables from this project are:

1 Northern Territory regolith framework map (1:2 500 000 scale)
2 atlas of NT regolith materials
3 summary report.

Getting started

A simple geomorphic "provinces" map was prepared as a result of decisions at the scoping meeting. It was prepared at the meeting from some existing data for later use during the traverse and to serve as a general guide for later fieldwork. The geomorphic provinces map served as a general guide for field mapping operations and provided the project with its initial working context.

The Trans-NT traverse was completed during September–October 2003. The Stuart Highway was the major access route from south of Alice Springs through to the Darwin coastal plain. Such a large-scale regolith calibration traverse has not been previously undertaken in the NT or, perhaps, anywhere else in Australia. A wide range of imagery eg, radiometrics, Landsat TM, magnetics, elevation data and Aster imagery was used during the traverse, to assist in recognising regolith variations and sampling contexts.

Early traverse results suggested that particular regolith materials and landscapes have complex relationships, and that some materials are likely to be more widely distributed in some areas than has been previously recorded. Of the two samples collected during the Trans-NT regolith traverse for trial age determination, one sample from a road cutting north of Tennant Creek proved to be highly successful, the other from near Mataranka was not. Further samples were then planned for collection during the main project fieldwork in mid to late 2004. The results are outlined in *Selected project highlights*.

Telling our secrets

A regolith materials and mapping workshop was conducted, in Darwin, at the end of the NT Gabfest from January 18–21 2004. The audience was essentially NTGS staff and invited industry representatives. The workshop focus was on regolith materials and mapping techniques, and was presented by Mike Craig, Ravi Anand and David Gray. Feedback indicates that NTGS staff and industry participants gained a better and wider understanding of regolith materials, regolith in the context of exploration, and regolith mapping approaches.

Early results

Immediately following on from the 2003 traverse, 58 regolith specimens underwent X-ray diffraction mineralogical analysis and X-ray fluorescence analysis at the Perth CRC node. Thin and polished sections were prepared. The XRF analysis was for 21 major and minor elements and LOI (loss on ignition). This enabled the team to generate a simple overview of the range of materials that we would be dealing with during the major fieldwork program. Two palaeomagnetic samples were sent to ANU

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[2] Cooperative Research Centre Landscape Evolution and Mineral Exploration

for age determination. Datasets from field capture and some 500 photos were then edited for later integration into project datasets. Field data helped form the basis for planning later major field work and identifying any complementary data that would be required. Traverse results also identified an issue with our digital data collection strategy. The issue was that the existing platform and software was not up to the size of the task. A new platform and software was urgently required for the successful field operations at the NT scale.

The big push

The major field work phase was conducted during May 2004 through to September 2004. Again, field logistics were provided by NTGS. The work was divided into four distinct regolith domains, as determined from scoping results and the Trans-NT regolith traverse. The first area was centred on the Harts Range. The second area was centred on the Barrow Creek–Tennant Creek districts. The third area involved the Darwin coastal plain and immediate hinterlands. The fourth and final area focused on the Tobermorey district, ending with minor visits to Glen Helen and a traverse along the Tanami Road. This work was not intended to repeat existing detailed work, but to act as a supplement to it.

Project Milestones

1 Known data compiled and consolidated.
2 Additional support data generated.
3 Trans-NT regolith traverse undertaken.
4 Traverse results used for area selection.
5 Pilot samples processed – guide sample program.
6 Pilot palaeomagnetics program successful.
7 Atlas data collected – materials being prepared.
8 Product generation now in progress.

Selected project highlights

Over 250 regolith samples were collected during project fieldwork and are currently undergoing analysis, sectioning or slabbing. These will form the basis of entries in an NT regolith atlas. All the sites visited are supported by a photo database containing about 2000 entries. Some entries will become part of the atlas and the others will become part of the overall digital record of the project.

A pilot palaeomagnetics sample program was conducted to help address the issue of the lack of age control in NT regolith materials and landforms. Overall palaeomagnetic ages ranged from 2 Ma in a weathering profile along the Darwin foreshore to 295 Ma in a road cutting at Tennant Creek. A small cluster of ages occur around 5–10 Ma, from samples taken from the hinterland of the Darwin coastal plain. A single age of 47 Ma comes from near Glen Helen Gorge, west of Alice Springs. Project results generally fall within three major age clusters, determined from a very much larger range of samples being amassed by Brad Pillans (Research School of Earth Sciences, Australian National University, pers comm). In view of the results of our pilot program, a much clearer understanding of the timing of the NT regolith, weathering and landscape development can be derived from a more focused palaeomagnetic age determination program across the Territory. This would be a welcome addition to the understanding of the NT regolith.

Not all our efforts have led to the results we had first hoped for. Some considerable effort was focused on attempting to find a way to determine a "base" of regolith through the processing of magnetics data. In the Tennant Creek region, this exercise did not prove to be successful. Instead, the investigations were able to highlight, in 3D, the major ironstone bodies in the area. Another test area is to be considered soon. However, on a more positive note, the magnetics data do contain information about magnetically-signatured subsurface palaeodrainage lines. This should prove to be a valuable element in any future palaeochannel investigations within the Northern Territory.

Project members are confident that our results will lead to better guidance and understanding of regolith-related issues. especially for mineral exploration in the Territory.

NT Regolith Project Team:

Project research staff
Mike Craig – CRC LEME/GA Canberra
Christine Edgoose –NTGS Alice Springs
Ian Robertson – CRC LEME/CSIRO Perth
Roger Clifton – NTGS Darwin

Project associate staff
Ravi Anand – CRC LEME/CSIRO Perth
Masood Ahmad –NTGS Darwin
Amanda Cornelius – CRCLEME/CSIRO Perth
Colin Pain – CRC LEME/GA Canberra.
Jodie Smith – GA Graduate Program, Canberra

PRECAMBRIAN OF THE NORTHERN TERRITORY

Masood Ahmad[1]

Precambrian rocks of the Northern Territory are divided into two principal geological provinces, the North Australian Craton (NAC) and Central Australian Mobile Belts (CAMB). These are unconformably overlain by the North Australian Platform Cover (NAPC) and Central Australian Platform Cover (CAPC), respectively.

The NAC comprises Archaean basement inliers and overlying Palaeoproterozoic strata of the Pine Creek Orogen, Murphy and Arnhem Inliers, Warramunga Province and Tanami Region. It underwent orogenic activity, granite emplacement and regional metamorphism between 1860 Ma and 1840 Ma (Barramundi Orogeny) followed by late- to post-orogenic igneous activity, contact metamorphism and lesser deformation between 1830 Ma and 1780 Ma.

Included within the CAMB are the Palaeoproterozoic Warumpi Province, Mesoproterozoic Musgrave Province and Neoproterozoic to Cambrian Irindina Province. It represents areas of prolonged tectonic activity, metamorphism, deformation and igneous activity between 1640 Ma and 300 Ma.

The Aileron Province of the northern Arunta Region spans the NAC/CAMB overlap, and represents a large area with major orogenic events taking place between 1810–1690; these are overprinted by younger orogenesis, metamorphism and igneous activity characterising the CAMB.

The North Australian Platform Cover (NAPC) represents Palaeo- to Mesoproterozoic shallow marine to fluvial sedimentary rocks, with interbedded felsic and mafic volcanics and associated intrusives. Except for areas near the NAC/CAMB interface, this succession is mildly deformed and is mostly unmetamorphosed. The NAPC includes the McArthur and Victoria-Birrindudu basins, and the Ashburton and Davenport provinces.

The intracratonic Centralian Superbasin (CS) represents Neoproterozoic strata at the base of the Palaeozoic basin successions. These strata are represented by marine and fluvial sandstone followed by lacustrine carbonates, evaporates, fine siliciclastics and glaciogenic sediments.

The early Cambrian Kulkirindji Flood Basalt Province (KFBP) extends over much of the northern and central Northern Territory and adjoining parts of Western Australia and Queensland. It includes the Antrim Plateau, Helen Springs and Peker Piker volcanics, which form the base of the CAPC. The CAPC comprises the Amadeus, Ngalia, Georgina and Wiso basins, which overlie KFBP or CS. The southern basins were deformed by the Petermann Orogeny at the end of Neoproterozoic (570–530 Ma) and, again, by the Devonian to Carboniferous Alice Springs Orogeny (400–300 Ma). The Neoproterozoic to Cambrian Irindina Province in the eastern Arunta Region is a highly deformed, fault-bounded metamorphic terrain, represented by metapelite, metabasite, amphibolite, gneiss, marble and quartzite.

Several periods of tectonic activity, metamorphism and igneous activity have been recorded in the NAC and CAMB. The earliest phase of deformation and metamorphism predated 2500 Ma granitic intrusions and is represented by the Manton and Dirtywater Metamorphics in the Pine Creek Orogen. The 1860–1840 Ma craton-wide Barramundi Orogeny is largely confined to the NAC. Although felsic and subordinate mafic magmatic events with accompanying deformation are recorded at 1825–1780 Ma intervals, the NAC was cratonised by this time and there are no subsequent major orogenic events. The craton margin Aileron Province underwent repeated deformation, metamorphism and igneous activity at 1810–1800 Ma (Stafford Event), 1780–1760 Ma (Yambah Event), 1730–1690 Ma (Strangways Orogeny) and 400–300 Ma Alice Springs Orogeny. It is also affected to some extent by subsequent deformation events, which were more dominant in the Warumpi, Musgrave and Irindina provinces. Major deformation in the Warumpi Province was at 1640 Ma (Liebig Orogeny) and 1590–1570 Ma (Chewings Orogeny). The 1200–1160 Ma Musgrave Orogeny and 570–530 Ma Petermann Orogeny mostly affected the Musgrave Province, but have their imprints in the Warumpi and Aileron provinces. The Irindina Province suffered deformation at 480–460 Ma (Larapinta Event) and 400–330 Ma (Alice Springs Orogeny).

The Proterozoic of the Northern Territory is divided into ten lithostratigraphic packages (P1 to P10). P1 represents the earliest known Proterozoic strata, unconformably overlying the Archaean Rum Jungle and Nanambu complexes. It is separated from the overlying P2 succession by a minor unconformity. The age of P1–P2 is constrained in the range 2000–2500 Ma. These successions host major uranium (Ranger, Jabiluka, Rum Jungle) and base metal (Browns) deposits. The unconformably overlying P3 succession includes the South Alligator Group in the Pine Creek Orogen and hosts significant Au mineralisation. The P1–P3 successions are not yet recognised outside the Pine Creek Orogen. However, the Dead Bullock Formation in the Tanami Region has remarkable lithological similarities with the South Alligator Group.

P4 is the most widespread pre-Barramundi succession. It is present in the all the orogenic domains of the NAC and hosts major gold deposits of the Pine Creek Orogen, and Tennant and Tanami regions. The lower Lander Rock Beds are likely equivalents in the Aileron Province. P5 is represented by late- to post-orogenic granites, felsic volcanic rocks and arenites in the NAC and hosts U, Au and PGE mineralisation. The Strangways Metamorphic Complex and upper Lander Rock Beds in the Aileron Province are correlated with this succession. P6 commences with the basal unit of the NAPC and comprises fluvial to shallow marine arenite, mafic and felsic volcanic rocks, and subordinate carbonate lithologies. This succession hosts minor uranium mineralisation in the Westmoreland area and unconformably overlies the world-class uranium deposits in the Alligator Rivers area. The P6 succession is correlated with the Reynolds Range Group in the Aileron Province. The overlying P7 succession is dominated by carbonate and hosts the world-class McArthur Zn-Pb-Ag deposit in the Territory

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and several other major base metal deposits in adjoining Queensland. In the Warumpi Province, the Madderns Yard and Iwupataka metamorphic complexes, comprising felsic and pelitic gneiss, schist, orthoquartzite, amphibolite, migmatite and calc-silicate, represent P7. This succession is considered to have significant potential for base metal deposits, but remains virtually unexplored. P8 is dominated by shallow marine carbonates and is present in the McArthur and Victoria-Birrindudu basins, and in the Ashburton Province. The P9 succession is dominated by marine arenites in the NAPC, whereas in the CAMB, it consists of felsic and mafic granite, gneiss, schist and quartzite. Basalt and mafic intrusives are also present locally. P10 represents the Centralian Superbasin and comprises arenite, carbonates and glaciogenic sediments. It has significant potential for gas and oil. The Bukalara Sandstone, covering a large part of the McArthur Basin and the Duerdin Group in the Victoria Basin are included in P10.

The Northern Territory contains over 2500 mineral occurrences of a wide spectrum of mineral commodities. Most mineral occurrences are within the following Proterozoic tectonic units: Pine Creek Orogen (1156[2]), Arunta Inlier (498), Tennant Region (310), McArthur Basin (293), Tanami Region (103), Victoria Basin (41) and Murphy Inlier (38). The Phanerozoic Basins contain only a few mineral occurrences: Bonaparte Basin (36), Amadeus Basin (39), Money Shoal Basin (23), Georgina Basin (81), Daly Basin (119), Ngalia Basin (15) and Carpentaria Basin (5). The predominant mineral commodities include Au (657), Cu (430), Sn (324), U (304), Pb (155), Mn (107), W (101), Fe (96), Zn (36), Al (25), Ni (5), industrial minerals (209), heavy mineral sands (29) and gemstones (9).

The Palaeoproterozoic contains about 77% of the Northern Territory's mineral occurrences, the Mesoproterozoic 7%, Neoproterozoic 3%, Palaeozoic 3%, Mesozoic 1% and Cenozoic 9%. Cenozoic occurrences are mostly alluvial gold and tin deposits.

Uranium is dominant in the early Palaeoproterozoic (P1–P2), which hosts world-class uranium deposits; small uranium occurrences are also noted in the late Palaeoproterozoic and in the Phanerozoic. Most gold is within the middle Palaeoproterozoic (P3–P4), which also contains the bulk of vein-type Sn and base metal occurrences. Stratabound/stratiform base metal occurrences are common in the late Palaeoproterozoic (P7 and P8).

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[2] Numbers within brackets represent total number of mineral occurrences.

THE MUSGRAVE PROVINCE – NT'S MOST UNDEREXPLORED TERRANE

Ian R Scrimgeour[1], Christine J Edgoose, Dorothy F Close and Ben P Wade[2]

Most mineral exploration within the Palaeo- to Mesoproterozoic of the Northern Territory has been focused on the Palaeoproterozoic basement terranes of the North Australian Craton and on Northern Australian platform cover rocks such as the McArthur Basin. In comparison, the more juvenile Proterozoic crust that lies to the south of the North Australian Craton, including the Warumpi Province (southwestern Arunta) and Musgrave Province[3], has received little attention from explorers. The Musgrave Province within the NT is one of the most underexplored Proterozoic terranes on the Australian continent, with an average of 1 drillhole for every 210 km^2. The geological framework of the Musgrave Province was a focus of NTGS studies in the 1990s (*see List of selected NTGS publications in the Musgrave Province*) and a summary of the geology of the Musgrave Province has recently been published (Edgoose *et al* 2004). Recent flying of the 2001 Eromanga and 2004 Simpson airborne surveys have completed high-resolution airborne magnetic coverage of the Musgrave Province at exploreable depths. NTGS is continuing its investigations in the Musgrave Province through collaborative research programs with the University of Adelaide.

Tectonic evolution of the Musgrave Province

The Musgrave Province represents relatively juvenile continental crust that occurs between the older and more evolved crust of the North and South Australian Cratons. The relationship of the Musgrave Province with the surrounding cratons, and its implications for the Proterozoic assembly of Australia, remains a matter of debate. Recent interpretation of the geochemistry of 1600–1540 Ma gneisses from the Musgrave Province within the NT has led to the interpretation that their igneous precursors formed in an island arc environment off the northern margin of the Gawler Craton (Wade *et al* in press). The timing of the amalgamation of the North and South Australian cratons has been interpreted to have occurred either at 1570–1550 Ma (Wade *et al* in press) or during the Musgrave Orogeny at 1200–1160 Ma (eg Myers *et al* 1996).

In the Musgrave Province in the NT, a major north-directed structure, the Woodroffe Thrust, separates granulite to upper amphibolite facies rocks of the Fregon Domain in the south from the amphibolite to greenschist facies Mulga Park Domain in the north. Two major tectonothermal events have affected the region. The 1200–1160 Ma Musgrave Orogeny is a granulite to amphibolite facies tectonic event that forms part of a major late Mesoproterozoic orogenic belt that links with the Albany-Fraser Complex in Western Australia. The 570–530 Ma Petermann Orogeny was a large-scale intraplate transpressional event that resulted in exhumation of rocks from the deep crust as part of a crustal-scale flower structure, cored by a dextral strike-slip zone (Close and Scrimgeour 1999, Camacho and McDougall 2000). Major structures within the Northern Territory, including the Woodroffe Thrust, are largely north-directed. Metamorphic grade during the Petermann Orogeny in the Fregon Domain varies from high-pressure transitional granulite facies in the west to greenschist facies in the east. In the Mulga Park Domain, peak metamorphic conditions during the Petermann Orogeny were middle to upper amphibolite facies, decreasing to lower amphibolite to greenschist facies to the north. The upper crustal expression of the Petermann Orogeny in the western Mulga Park Domain involved northward emplacement of an internally duplexed basement wedge (Petermann Nappe Complex) along a detachment of structurally interleaved basement and basal Amadeus Basin sediments (Dean Quartzite and Pinyinna beds).

Major lithotypes in the Musgrave Province and their metallogenic potential

1600–1540 Ma gneisses – a metamorphosed arc with base metal potential?

The oldest exposed rocks in the Musgrave Province comprise felsic gneiss with both volcanic and intrusive precursors, which is intercalated with less common mafic rocks and metasediments. The felsic gneiss has protolith ages in the range 1600–1540 Ma and reflects a major period of crust formation. These gneisses comprise <10% of outcrop in the western and central Musgrave Province in the NT (Mann Ranges, Petermann Ranges and Olia Chain), but outcrop more extensively in areas east of Kulgera.

LA-ICPMS dating of detrital zircons from a metasediment in the eastern Musgrave Province in SA suggests a maximum deposition age as young as 1400 Ma, suggesting that a previously unknown 1400–1200 Ma metasedimentary succession is present in the Musgrave Province (B Wade, University of Adelaide, pers comm). The metasediments and felsic gneiss underwent deformation and high-grade metamorphism during the Musgrave Orogeny, with metamorphic grade decreasing from medium-pressure granulite facies in the west to low- to medium-pressure upper amphibolite facies in the east. Subeconomic copper and base metal sulfide occurrences, in granulite facies gneisses with possible volcanic precursors in the central Musgrave Province (South Australia), indicate some potential for metamorphosed sediment-hosted or VMS-style mineralisation (Tonkin 1991). Manganiferous sediments associated with amphibolites in the Kelly Hills may reflect a remnant of oceanic crust with possible base metal or nickel potential.

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[3] The name of this province has recently been changed from 'Musgrave Block' to 'Musgrave Province' to allow consistency across state borders.

The Pitjantjatjara Supersuite – extensive granite with untested Cu-Au potential

Granites of the Pitjantjatjara Supersuite (previously referred to as Kulgera Suite or Supersuite) intruded during and immediately after the Musgrave Orogeny at 1190–1120 Ma, and form more than half of the outcropping geology of the province in the Northern Territory. The supersuite includes large-scale clinopyroxene- and hornblende granites in the western Fregon Domain, and biotite- and hornblende granites in the Mulga Park Domain. Pitjantjatjara Supersuite granites have some potential for Fe-oxide Cu-Au deposits, on the basis of being strongly oxidised to oxidised, moderately fractionated, strongly metaluminous, Sr-depleted and Y-undepleted, and having a wide range of compositions (Budd *et al* 2002).

Mafic rocks of the Giles Complex and Alcurra Dolerite – mafic-hosted Ni-Cu-Cr potential

The 1080–1040 Ma Giles Event resulted in bimodal intrusive and extrusive magmatism across much of the Musgrave Province. The mafic to ultramafic Giles Complex outcrops south of the Mann Fault on the SA border, and dykes of the 1078 Ma Alcurra Dolerite are widespread. The Giles Complex has been the focus of considerable exploration interest for magmatic Ni-Cu and Ni laterite mineralisation in South Australia and Western Australia. Subeconomic accumulations of nickel are associated with supergene enrichment of lateritised Giles Complex rocks close to the Northern Territory border in far northwestern South Australia. The most significant of these is associated with palaeodepressions in the Claude Hills peridotite/gabbro intrusion, only 1–3 km south of the border, with an estimated resource of 4.5 Mt at 1.5% Ni (Miller 1966). A sample of lateritised pyroxenite from the only known outcrop of the Giles Complex within the Northern Territory yielded 1.0% Ni, 0.55% Cr and 77 ppm Co. Chrysoprase veins cutting nickeliferous laterite and jasper have been mined less than one kilometre from the Northern Territory border.

The potential for Ni and Cu mineralisation, associated with mafic to ultramafic rocks in the eastern Musgrave Province in the NT, remains untested. There remains a possibility that some of the larger dykes and bodies of Alcurra dolerite, which are seen as potential feeders of the Giles mafic complex, could be sites of entrapment of magmatic Cu-Ni-Cr deposits. Numerous small Ni and Cu prospects occur associated with mafic and ultramafic rocks in ALBERGA (South Australia) immediately adjacent to the NT border, and similar geology is interpreted to extend into the NT. Mithril Resources are currently involved in a joint venture with Gempart Pty Ltd in two exploration leases north of the SA border, west of Kulgera.

Tjauwata Group – polymetallic potential

In the Bloods Range area, a succession of rift-related sediments and bimodal volcanics, the Tjauwata Group, were deposited during the Giles Event and are correlated with the Bentley Supergroup in Western Australia. The Tjauwata Group includes basalt, quartzite, rhyolite, conglomerate, schistose metasediments and red-beds, and is disconformably overlain by the Neoproterozoic basal unit of the Amadeus Basin (Dean Quartzite). The Tjauwata Group contains a number of small copper and base metals occurrences. Secondary copper minerals have been recorded in veins in sheared basalt and schistose sediments of the Tjuninanta Formation. Surface copper grades were up to 26% (Fruzetti and Morlock 1972), but drilling did not detect significant mineralisation at depth. A nearby mineral occurrence in the Tjuninanta Formation has elevated Ag (4.5 ppm) and Cu (1.1%). Secondary lead and copper minerals, galena, silver and gold have been identified in a quartz vein intruding the Mount Harris Basalt, south of Bloods Range (Close *et al* 2003). The vein contains 89 ppm Ag, 1.94% Cu, 2.08% Pb, 220 ppm Bi and 101 ppb Au.

Recent widely spaced (4 km x 0.5 km) reconnaissance sampling of soil and ironstone overlying the Tjauwata Group, by Independence Group NL, has shown several encouraging trends of areas of elevated gold up to 15 ppb Au. (Independence Group 2004a). Check and infill surface geochemical sampling over targets generated from this program confirmed three anomalies including one high-order (104.8 ppb Au total digest) and two low-order (about 5 ppb Au) anomalies, all situated on a north–south trend (Independence Group 2004b). This exploration program is ongoing.

Piltardi Detachment Zone – mineralisation in low- to medium-grade shear zones

The Petermann Nappe Complex in the Petermann and Bloods Range regions involved development of large-scale mid- to upper-crustal shear zones, associated with significant fluid flow. The most important of these is the Piltardi Detachment Zone (PDZ), which comprises greenschist to amphibolite facies mylonites that interleave basement and basal units of the Amadeus Basin in the Petermann Ranges and Olia Chain. A quartz vein within the PDZ near Chirnside Creek yielded 0.19 ppm Au (Scrimgeour *et al* 1999). North of Piltardi waterhole in the Petermann Ranges, malachite-bearing quartz veins occur within Pottoyu Granite, which has been mylonitised in the PDZ. Assay results on these veins yielded 2% Cu. No systematic exploration program has been undertaken to follow-up this promising Au and Cu anomalism. Also within the PDZ, highly strained and ferruginised Pinyinna beds (Amadeus Basin) contain anomalous Co, Cu, Pb, V and Zn. Cenozoic ferruginous caps over the Pinyinna beds in the Olia Chain are also anomalous in lead, zinc and cobalt, but have been interpreted to reflect supergene enrichment (McMahon and Partners 1968).

Summary
The Musgrave Province in the NT is remarkably underexplored, and has potential for economic accumulations of a number of commodities in a variety of settings. Perceptions of difficult land access have contributed to the lack of exploration activity in the area. However, in the past few years a number of exploration titles have been granted on ALRA land in the Bloods Range region. Extensive areas of the eastern Musgrave Province occur on pastoral land, and have current exploration leases. This includes the prospective eastern Fregon Domain in KULGERA and FINKE, where widespread areas of 1600–1540 Ma felsic gneiss and metasediment, with mafic and felsic intrusions, occur both in outcrop and in shallow buried basement. Recent NTGS airborne magnetic data suggests that this terrane extends at exploreable depths for tens of kilometres to the east and northeast of exposed outcrop, beneath shallow Eromanga Basin or Finke Group sediments.

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EAST ARUNTA PROJECT – PRELIMINARY RESULTS AND FUTURE DIRECTIONS

Dorothy Close[1], Ian Scrimgeour, Mark Duffett, Kurt Worden[2] and Ben Goscombe

The East Arunta project commenced in late 2004 and is an integrated multidisciplinary investigation into the geology and prospectivity of the southeastern Arunta Region in central Australia. The area covered by the project incorporates ILLOGWA CREEK, HALE RIVER and HAY RIVER[3], and will focus on the Neoproterozoic to Palaeozoic Irindina Province and the Palaeoproterozoic Aileron Province (**Figure 1**). One of the main aims of the project is to extend the interpretation of the geology of the southeastern Arunta Region under shallow cover of the Mesozoic Eromanga Basin, utilising recently acquired 400 m-spaced airborne datasets (**Figure 2**). It is also designed to develop a well constrained stratigraphic and tectonic framework for the region, building on earlier lithological mapping of BMR (Bureau of Mineral Resources, now Geoscience Australia) in the 1980s.

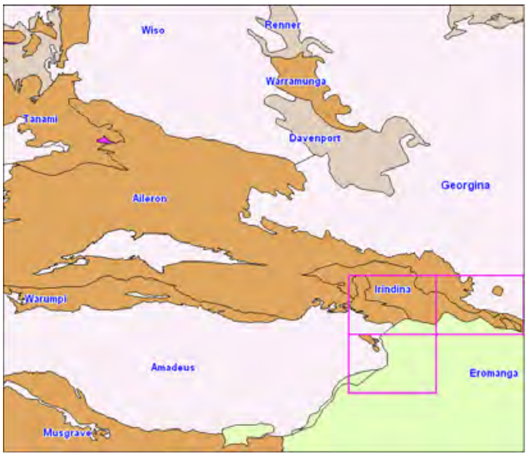

Figure 1. Location of 1:250k mapsheet boundaries within the Arunta Region, NT

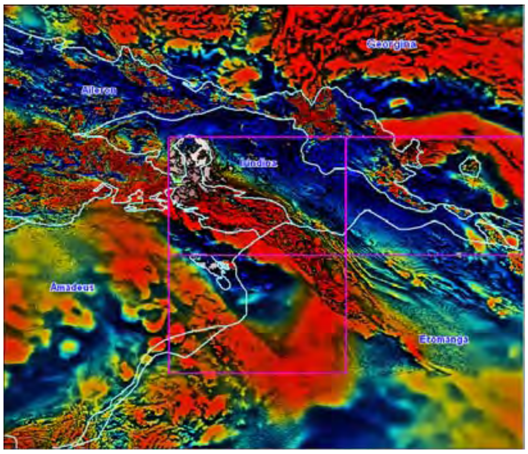

Figure 2. TMI on 1stVD image showing the SW extension of the Irindina Province and Aileron Province under Mesozoic cover

Irindina Province

The recent recognition of a package of rocks within the Arunta (Irindina Province) that represents high-grade equivalents of the adjacent Neoproterozoic to Palaeozoic Amadeus and Georgina basins (Mawby *et al* 1999, Buick *et al* 2001, Maidment *et al* 2004) is a major motivation to update ILLOGWA CREEK. The Irindina Province comprises a Neoproterozoic to Cambrian metasedimentary succession, with voluminous mafic rocks and less common anatectic granites (Harts Range Metamorphic Complex – HRMC). The HRMC has been overprinted by the granulite-grade Ordovician Larapinta Event, a thermal event with no apparent significant effect on the Palaeoproterozoic Aileron Province. Further deformation during the Silurian to Carboniferous may variously be interpreted as discrete phases or continuous deformation during the Alice Springs Orogeny. This project will extend from the PhD work of David Maidment (Maidment *et al* 2004) to correlate the stratigraphy of the HRMC in areas of poor exposure (ie eastern to southeastern ILLOGWA CREEK), unravel the regional deformation during the Palaeozoic, and review the metallogenic potential of this Province in terms of the new interpretation of a Palaeozoic rift succession. The Irindina Province is known to contain Cu-Au prospects (eg Bruce's Cu prospect, *see Wygralak and Mernagh this volume*), and the widespread occurrence of mafic rocks in the province has largely untested Ni, Cu, Cr and PGE potential.

Aileron Province

Southern ILLOGWA CREEK

Outcrop of the Palaeoproterozoic Aileron Province extends onto the eastern and southern sections of ILLOGWA CREEK, and is dominated by the Albarta Metamorphics and the Atneequa Granite Complex. Second Edition mapping of the area by BMR concentrated on lithological mapping, with few absolute constraints on the stratigraphic and tectonic framework. Therefore, a major focus of this project will be to interpret the protoliths and relative ages of the constituent units, and establish regional correlations with other parts in the Aileron Province. An additional focus will be the distribution and timing of metamorphism, deformation and alteration of these units. The genetic and temporal relationship between the Strangways Metamorphic Complex (SMC) in ALICE SPRINGS, and the Albarta Metamorphics remains unclear. Preliminary U-Pb SHRIMP zircon data from an quartz diorite within the Albarta Metamorphics (location 135.45°E, 23.74°S) suggest that it may have a similar age to the 1762 ± 9 Ma Atneequa Granitic Complex (Zhao and Bennett 1995), with isotopic disturbance from a younger thermal event such as the 1730–1690 Ma Strangways Orogeny. Recent interpretations

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of the SMC in ALICE SPRINGS suggest a back arc basin setting (M Cobb, Curtin University, pers comm) with metamorphosed VHMS-style and Fe-oxide Cu-Au mineralisation (Hussey *et al* 2003).

HAY RIVER

The poorly outcropping Mount Smith Metamorphics and Mount Dobbie Granite in HAY RIVER are interpreted to form part of the Aileron Province of the Arunta Region. An integration of geophysical interpretations with revised geochronology, geochemistry, structure and metamorphic studies will determine whether these units are part of the SMC, and are an eastward continuation of the prospective Jervois Mineral Field. The area is also considered prospective for Fe-oxide Cu-Au mineralisation, with oxidised haematite-altered granite being identified under shallow Georgina Basin cover (Elkedra Diamonds 2003).

Casey Inlier, HALE RIVER

A further focus of this project is to investigate the nature of the Arunta Region basement inlier outcropping in northwestern HALE RIVER. There has been no recent regional work in this area and its relationship with adjacent parts of the Aileron Province has remained unclear. Data from preliminary mapping and sample collection, in the eastern section of the inlier in 2004, provide some insights into the similarities and differences between the Casey Inlier and areas to the north. Lithologically, the eastern part of the inlier comprises metapelite and psammite, with small discontinuous quartzite-magnetite horizons, graphitic schist, calcsilicate, marble, massive to layered mafic amphibolite, metapyroxenite, biotite granite and quartzofeldspathic migmatite. These units are transposed by a pervasive WNW–ESE-trending amphibolite facies fabric. Broad lithological similarities exist between this package and the Albarta Metamorphics and Atneequa Granitic Complex that lie immediately to the north of the Casey Inlier; however, early analysis suggests some differences in the proportion and age of the metasediments, the chemistry and age of the intrusives, and the style of deformation. The geochemistry of the mafic units indicates that those within the Casey Inlier are more primitive in nature than those within the Albarta Metamorphics and Atneequa Granitic Complex, and contain anomalous Ni (1300–1600 ppm) and Cr (1150–1900 ppm). Very preliminary U-Pb SHRIMP zircon analysis suggests a conservative maximum deposition age of 1844 ± 6 Ma for the metapsammites (135.45°E, 24.12°S), with a likely approximate magmatic age of 1820–1810 Ma for a biotite granite and migmatite (135.45°E, 24.13°S). The interpretation that the Casey Inlier may represent a different geological domain from the Albarta Metamorphics is also support by modelling of magnetotelluric (MT) data acquired in 2004 by Kate Selway (*Selway et al this volume*). From a N–S traverse across the major geophysical contrasts of the Aileron and Irindina Provinces, Kate has identified a major N-dipping crustal-scale structure that may represent the boundary between the older? metamorphics of the Casey Inlier and the Albarta Metamorphics to the north.

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MINERALISATION OF THE 1690–1610 MA WARUMPI PROVINCE

Max Frater[1]

The Warumpi Province was mapped by NTGS during Second Edition mapping of MOUNT LIEBIG[2] in 1998–2001. The resulting map was published in 2004 and explanatory notes will be published in April 2005. During 2000, NTGS completed an extensive stream sediment survey of the western MacDonnell Ranges that included a large area of the Warumpi Province. A comprehensive statistical analysis of the data and the details was subsequently released in a GIS package (Dunster and Mügge 2001). The age of the Warumpi Province (1690–1610 Ma) is a particularly significant epoch in the evolution of the Australian continent. Stratigraphy of this period hosts the world-class stratabound Pb-Zn-Ag mineralisation in Broken Hill (1690 Ma), the Mount Isa Group (1654 Ma), McArthur River (1640 Ma) and Century (1610 Ma). The Warumpi Province is unexplored.

During 2003, NTGS reviewed the status of mineralisation occurring in three small prospects within the Warumpi Province and in 2004, a reconnaissance appraisal was made of anomalous stream sediments samples from the 2000 Western MacDonnell Ranges stream sediment survey of Dunster and Mügge (2001). This report summarises the results of the 2003–04 review.

Geological setting

The Warumpi Province, located to the west of Alice Springs, is a 1690–1610 Ma terrane, comprising metasedimentary, metavolcanic and metamorphosed plutonic rocks that abut the southern margin of the North Australian Craton (NAC). The Province is divided into two domains, the amphibolite-facies Haast Bluff Domain in the south and the mainly granulite-facies Yaya Domain in the north (Scrimgeour *et al* 2004). The stratigraphic record commences in the Haast Bluff Domain with 1690–1660 Ma felsic intrusive and extrusive magmatism, accompanied by both clastic and chemical sedimentation during the Argilke Event (Scrimgeour *et al* 2004). The Glen Helen Metamorphics (western HERMANNSBURG and eastern MOUNT LIEBIG) and Peculiar Complex (central MOUNT LIEBIG) represent this initial phase of sedimentation and deep- to shallow-level magmatism. The Glen Helen Metamorphics includes migmatitic orthogneiss, abundant biotite granite and less common metapelite, psammite and amphibolite. In central MOUNT LIEBIG, deep-level felsic magmatism is represented by the emplacement of biotite and biotite-hornblende granites (eg Talipata and Udor Granites) and by the formation of the Peculiar Complex, which consists of rhyolitic volcanics, minor chemical sedimentary rocks and amphibolite schist. In the Yaya Domain, two broad stratigraphic units, the Inyalinga Granulite and Alkipi Metamorphics, are recognised, and form part of the Yaya Metamorphic Complex. The Inyalinga Granulite is defined as a heterogeneous metasedimentary facies containing metapelite (including cordierite-granulite), psammite, calc-silicate, quartzite and mafic granulite. The Alkipi Metamorphics is a more homogeneous metasedimentary succession, dominated by pelite and psammite and with mafic rocks usually occurring only as large intrusive bodies. Granitoids are highly strained and felsic migmatites are common in both units. A SHRIMP U-Pb zircon age on cordierite granulite from the Inyalinga Granulite has given a calculated maximum depositional age of 1661 ± 10 Ma for the sedimentary package. SHRIMP zircon ages of two metapelites in the Alkipi Metamorphics returned maximum depositional ages of 1670 Ma and 1650 Ma (Scrimgeour *et al* 2004).

The first orogenic event to effect the Warumpi Province was the 1640–1630 Ma Liebig Orogeny. At this time, the Yaya Domain stratigraphy underwent regional-scale granulite-facies metamorphism as a result of burial to an estimated depth of 30 km (Close *et al* 2004). Large-scale lower crustal melting produced large volumes of magma that intruded the Yaya Metamorphic Complex. These include granite, granodiorite and charnockite of the Illili and Waluwiya suites and less abundant gabbro and pyroxenite (Papunya Igneous Complex). These plutons now form a major component of the Yaya Domain. In the Haast Bluff Domain, only the Glen Helen Metamorphics underwent significant metamorphism, reaching upper amphibolite grade with a pressure estimate of 8–9 kb and temperature of 700°C.

Both the Yaya and Haast Bluff Domains were rapidly exhumed following the Liebig Orogeny. In the Haast Bluff Domain, a succession of variable quartz-feldspar-biotite-muscovite(-garnet) schists, quartzite, calc-silicate, marble and amphibolite (Ikuntji Metamorphics) occurs unconformably on the Glen Helen Metamorphics. The Lizard Schist, dominantly a biotite-muscovite-quartz schist, occurs in the Haast Bluff Domain in central MOUNT LIEBIG at the same stratigraphic level. Both the Ikuntji Metamorphics and Lizard Schist are intruded by tourmaline-bearing pegmatites, with local development of massive tourmalinite.

The 1590–1570 Ma Chewing Orogeny is a major tectonic and thermal event that effected the whole of the Warumpi Province and the bordering NAC. Scrimgeour *et al* (2004) reported kinematic indicators in MOUNT LIEBIG that consistently indicate north-over-south movement during this orogenic event. In the Yaya Domain, the resultant S_2 fabric reaches upper amphibolite facies with estimated P-T conditions of 5.5–6 kbar and 700°C. The earlier S_1 fabric, (a migmatitic layering in the Yaya Domain and gneissic layering in the Glen Helen Metamorphics), is commonly transposed into the more prominent regional S_2 strain fabric. The Ikuntji Metamorphics do not contain an S_1 fabric; they are tightly to isoclinally folded with an axial planar S_2 fabric that has been folded by upright, open to tight F_3 folds.

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[2] Names of 1:250 000 mapsheets are in CAPITALS.

Evidence of retrograde events that either postdated or occurred during the later stages of the Chewing Orogeny have been reported (Scrimgeour *et al* 2004). A greenschist-facies high-strain fabric of Proterozoic age is reported in the Peculiar Complex and coarse muscovite, associated with fluid activity in the Alkipi Metamorphics, has been interpreted as having grown in the period 1570–1150 Ma. An 1150–1130 Ma regional event, the Teapot Event, is a period of elevated crustal temperature that may be related to magmatism associated with the Musgrave Orogeny (Edgoose *et al* 2004). Regionally, temperatures in the Warumpi Province during the Teapot Event are considered to have been in excess of 500°C and locally may have exceeded 650°C.

Historic prospects

Four small base metal prospects occur in the Warumpi Province. These are Stokes Yard in the Glen Helen Metamorphics (HERMANNSBURG), Ulpuruta and Haast Bluff in the Ikuntji Metamorphics, and Mount Larrie in the Alkipi Metamorphics (MOUNT LIEBIG). Mount Larrie is a small copper prospect consisting of malachite staining in metapelites. The mineralisation was not considered significant enough to include in the regional appraisal, but is described in the MOUNT LIEBIG explanatory notes (Scrimgeour *et al* 2005).

The *Stokes Yard Prospect* occurs 6 km north-northwest from Stokes Yard in western HERMANNSBURG. It occurs in a north–south-trending mylonite zone in the Glen Helen Metamorphics. The host rocks are mylonitised leucogranite, amphibolite, calc-silicate and forsterite marble, occurring as breccia and sub-gossanous outcrop approximately 10 m wide and 60 m long. Fruzzetti (1973) reported surface samples averaging 2.83% Pb, 2.81% Zn, 0.27% Cu and 40 g/t Ag. Five inclined diamond drill holes tested the outcrop, but only one hole encountered mineralisation over a narrow interval. The only production is reported to be 1 t of rhodonite for ornamental use (Warren and Shaw 1995).

Detrital zircons from pelitic schists at Stokes Yard suggests a maximum deposition age of about 1640 Ma. Using galena from the prospect and the zircon age as a constraining point in Pb-isotope evolution, Huston *et al* (2003) suggested a primitive lead source for the Warumpi base metal mineralisation, more primitive than in the NAC to the north.

The *Ulpuruta Prospect* (formerly Nickel Hill) consists of two small isolated outcrops, one adjacent to the Haast Bluff–Papunya road and the second 300 m to the north-northwest. This dominantly Pb-Zn mineralisation occurs within the Ikuntji Metamorphics in tightly folded tremolite schist adjacent to marble, amphibolite and meta-arenite (Barraclough 1975). The mineralisation in the outcrop 300 m to the north-northwest is in brecciated actinolite schist, associated with forsterite marble. Ulpuruta was first brought to the attention of the Bureau of Mineral Resources (BMR, now Geoscience Australia) in 1956, when malachite-cuprite-rich samples from the two outcrops returned assays of 11.76% and 9.85% Cu. In 1973, NTGS carried out a magnetometer traverse across the area and noted galena in forsterite marble, as well as Cu mineralisation in amphibolites. Grab samples collected by NTGS from the two outcrops in 1975 returned assays of up to 11.5% Zn, and elevated Pb (6400 ppm) and Cu (5200 ppm Cu). The prospect was pattern auger drilled by NTGS in the same year, but no significant mineralisation was recorded. Drilling generally reached ‘bedrock’ with the two prospects joined by a subsurface ridge (<5 m depth) that was interpreted as representing a folded stratigraphic horizon.

As part of the 2003 review, the outcrop beside the Haast Bluff–Papunya road was mapped and a short surface geochemical traverse of the outcrop (7 samples) was undertaken. Outcrop strikes northeast–southwest and is strongly folded, with the less competent marble squeezed into discordant, highly attenuated isoclinal fold hinges. Bedding dips to the northwest, steepening in that direction from 16–20° in the southeast to 45–62° in the northwest. Mineralisation (galena, cuprite, malachite, azurite and chrysocolla) occurs in a highly deformed and chemically altered rock, consisting of chrysotile, actinolite, epidote, diopside, oxidised mica, quartz, magnetite and opaque hydroxides. The altered host rock occurs within an amphibolite, actinolite-feldspar-mica schist, calc-silicate and marble assemblage. The host is intensely magnesium metasomatised (MgO 12–20%). REE and refractory element chemistry indicates that the most likely protore(?) is a calc-silicate rather than an amphibolite. Two grab samples assayed up to 19.7% Zn, 4.04% Pb and 3.03% Cu. The 7-sample geochemical traverse peaked at 15.5% Zn, 0.77% Pb, 0.04% Cu and 8.5 ppm Ag.

The *Haast Bluff Cu Prospect* is located southwest of Western Bluff, approximately 2.5 km northwest from Ulpuruta. It occurs on the edge of a boulder pediment shedding off the West Bluff Range. In 1971, two samples of the Haast Bluff mineralisation collected by NTGS assayed 1.05% and 5.3% Cu. The mineralisation was auger drilled at the same time as Ulpuruta, but boulder scree interfered with drilling in the north and assays from ‘bedrock’ in the south were not encouraging. Five 1 m-deep costeans were cut by bulldozer across the mineralisation in 1976, but no additional structural information was gained because of their shallow nature. The costeans confirmed that mineralisation was confined to a narrow horizon 0.6–2 m in width, with channel sampling yielding average grades 1–2% Cu. Malachite-azurite mineralisation was reported to occur in oxidised amphibolite, and chalcopyrite and pyrite was recognised in marble and calc-silicate.

In 2003, Haast Bluff was mapped at 1:1000 scale and the mineralised horizon was grab-sampled across four of the 1976 costeans for geochemistry and petrology. Mineralisation is associated with an amphibolite, calc-silicate, calcareous psammite and marble package that occurs in regionally extensive quartz-feldspar-biotite-muscovite schist (Ikuntji Metamorphics). The mineralised package is isoclinally folded, with a steep west-northwest-dipping, north-northeast-trending axial plane S_1 (Chewings Orogeny). A shallow north- and south-dipping mineral lineation defines the F_1 fold axis. Upright, moderately tight to open F_2 folds plunge moderately steeply to the north-northeast, and their interference with F_1 appears to be responsible for a tight, elongate basin and dome pattern in outcrop. Local shear deformation and the ductile nature of the marble horizon has resulted in transposed fold limbs that produce complex and inconsistent stratigraphic relationships. The true width of the amphibolite-calc-silicate package appears to be less than 15 m though, due to deformation, the horizon pinches and swells and in fold hinges may reach an apparent thickness of 30+ m.

Mineralisation occurs in fractured amphibolite, psammite and calc-silicate, with the highest grade appearing in gossanous breccia. The surface breccia consists of matrix-supported fragments of the host horizon, including marble, in a matrix of oxidised biotite, chlorite group minerals, haematite and amorphous Fe-hydroxides. The latter commonly pseudomorphs abundant magnetite or pyrite. The highest assay from the sampled traverses was 11.50% Cu, 0.07% Pb, 0.66% Zn, 0.73 ppm Au and 6.5 ppm Ag.

Regional stream sediment geochemistry

Over 1200 stream sediment samples at an average density of one sample per 5.6 km were collected during the NTGS western MacDonnell Range survey in 2000 (Dunster and Mügge 2001). All major and minor elements and 23 trace elements were analysed under rigorous controls at Genalysis Laboratory Services in Perth. Dunster and Mügge completed a thorough statistical analysis of the collected data, providing threshold values of anomalous populations that could be readily used in the 2003–04 review of Warumpi Province mineralisation. For the purposes of the review, the +2LNSND ($\log_{10}$ transformed two standard deviation) threshold was used to separate anomalous values with a 95-percentile threshold, to recognise second degree anomalism. Nineteen stream sediment collection sites that were anomalous in various elements during the 2000 survey were selected for stream catchment traverses as part of the Warumpi review. Of the 19 stream sediment anomalies followed up in the field, only 6 could be explained by the catchment traverses. Eight of the 19 anomalies could be partially explained by rock assemblages in the catchment, but the sources of anomalous chemistry at the remaining 5 sites were unresolved. In the following discussion, elements that are anomalous at the 95-percentile threshold, but not at the more rigorous LNSND cut-off, are bracketed.

At Mount Larrie, stream sediments anomalous in P-Sn-Y-Mg (-Mn-Ti-Cr-Ni) can be attributed to pegmatite in Illili Suite granite, and gabbro and amphibolites belonging to the Papunya Igneous Complex. However, the source of elevated (Cd-Zn-Sb) is not explained. The source of anomalous Au in stream sediments shedding from the northern slopes of Mount Liebig is also unresolved. At this locality, Yaya Metamorphic Complex migmatites, hornblende-biotite granite and psammites are intruded by quartz veins, pegmatites and amphibolites that have up to 1 m-wide epidote alteration selvages.

A stream sediment sample derived from Talyi Talyi Hills has the most varied anomalous chemistry in the western MacDonnell Range survey. The sample is anomalous in Au-Sn-W-Zn-Nb-Tl-V-Y-Fe-Ti(-Sb-Mo-Mg-Mn). Talyi Talyi Hills consists of weakly porphyritic charnockite of the Waluwiya Suite, which intruded at the time of the Liebig Orogeny. The stratigraphy in the stream catchment is divided between two associations, a hornblende-garnet altered charnockite and a layered calcareous porphyritic rock that may be altered charnockite or an altered metavolcanic. Both assemblages are intruded by prominent pegmatite and the latter may explain some of the anomalous chemistry (Sn, W, Nb and Y). If the calcic porphyry represents an intense alteration of the regional charnockite, it requires an addition of 5–10% CaO and a significant loss of approximately 4.5% K_2O and 6% SiO_2. Calcic-sodic alteration with the removal of potassium is a characteristic of regional ground preparation for Cu-Au mineralisation in the Eastern Mount Isa Fold Belt (Williams *et al* 1995).

Felsic volcanic rocks of the Peculiar Complex in the Haast Bluff Domain are the source of three Au anomalies in the stream sediment survey. Volcanic rocks in the three locations are strongly deformed and in two localities, the rhyolite is intensely albitised at the expense of potassium (Na_2O/K_2O ratio in a range 2.5–30). Carbonate-altered amphibolite sills and dykes are present in all localities and narrow zones of calc-silicate (13.8% CaO) in the rhyolite may represent extreme alteration of amphibolite. Gold anomalies also occur in sediments shedding off the Udor Granite. Oxidation of granite is evident in the stream catchment, with the development of disseminated coarse magnetite grains accompanied by intense epidote alteration.

A quartz-muscovite(-magnetite-biotite) schist at the base of the Heavitree Quartzite (basal Amadeus Basin) may be responsible for elevated As-Sb-Mo-W-Fe-V in sediment samples collected from the south of Mount Palmer. The Bitter Springs Formation appears to be responsible for elevated As-Mo-Sb(-Bi) in stream sediments on the upper catchment of Yaya Creek on the northern side of the MacDonnell Range.

The Ikuntji Metamorphics near Haast Bluff is the source of several Au-Pb-(W-Zn-Bi) stream sediment anomalies. Pervasive calcic alteration associated with deformation is common in the Ikuntji Metamorphics. The highest Au assay (370 ppb) from stream-catchment grab samples is associated with calcic-sodic veining and alteration, involving the depletion of K_2O. In this particular example, a 1.5 cm-wide brecciated Na-feldspar-qtz-epidote-chlorite (-pyrite or magnetite?) vein has cut a highly altered amphibolite that has been strongly oxidised and almost totally replaced by chlorite and epidote. A high proportion of calc-silicate in the area appears to be the result of oxidised fluids having moved along deformation-related channel ways.

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REGIONAL CHARACTERISTICS OF FLUIDS IN THE TANAMI AND ARUNTA REGIONS

Andrew S Wygralak[1] and Terrence P Mernagh[2]

This work commenced in 1999, with a detailed study of the physico-chemical characteristics and age of pre-, syn- and post-mineralisation fluids in major gold deposits of the Tanami Region. The results, describing in details the elements of gold mineral system in the Tanami Region, were recently published in Wygralak *et al* (2005.

In order to understand broader regional changes, this study was extended into Aileron, Irindina and Warumpi provinces of the Arunta Region.

A significant part of this work is based on fluid inclusion microthermometry and Raman microprobe analyses reported earlier elsewhere (eg Wygralak and Mernagh 2003, Mernagh and Wygralak 2004). During the last year, this study was extended to parts of HUCKITTA[3], ILLOGWA CREEK and ALICE SPRINGS. Additional data were obtained on the oxygen isotopes composition of fluids and $^{40}Ar/^{39}Ar$ ages of quartz vein-hosted hydrothermal micas. Results of this work, along with comments on the nature of gold mineral system(s?) located in the Tanami Region, are reported in this presentation.

Calculated $\delta^{18}O$ compositions of fluids indicate the presence of areas dominated by either magmatic/metamorphic fluids ($\delta^{18}O$ values of such fluids overlap), or by meteoric fluids.

The area dominated by magmatic/metamorphic fluid contains practically all known gold occurrences. The fluid has a $\delta^{18}O$ range of +4.0 to +9.8 per mil. $^{40}Ar/^{39}Ar$ ages of most hydrothermal micas associated with ore-stage veining are in the range 1720–1740 Ma. The fluid had a temperature of 250–350ºC, moderate salinity of 3–7% and contained CO_2>CH_4>N_2. Vein quartz is usually grey coloured, with coarse and vitreous, or fine grained, 'sugar-like' textures.

The area dominated by meteoric fluid contains no gold occurrences, but has numerous small copper prospects. Fluid from this area has a $\delta^{18}O$ range of –20.1 to +3.8 per mil. The dominant $^{40}Ar/^{39}Ar$ age of veining is in the range 1590–1430 Ma. Compared with the previous area, the fluid was of lower temperature (180–220ºC), higher salinity (18–23%) and without CO_2 and CH_4. Vein quartz has many high-level (epizonal) features, such as the presence of amethyst, chalcedony, and coliform and blade textures.

Gold mineralisation in the Tanami Region can also be broadly grouped into two zones.

The main mineralised zone (10 Moz Au total resource; includes Dead Bullock Soak, The Granites, Minotaur, Oberon and Coyote in WA) follows the east-southeast-trending 'Trans Tanami Fault Zone'. Ore-stage veining, dated by the $^{40}Ar/^{39}Ar$ method at 1720–1740 Ma, formed at depths of 2.3–9.8 km, from low salinity magmatic/metamorphic, $CO_2 \pm CH_4 \pm N_2$-bearing fluids with a temperature range of 200–400ºC. Ore-stage veining is hosted by metasediments, including siltstone, greywacke and BIF. The main gold precipitation mechanism was reaction with host rocks (reduction by carbonaceous matter or by BIFs).

In contrast, the second mineralised zone, containing the Tanami Goldfield, Crusade Prospect and gold mineralisation in the Birrindudu area trends north-northeast. Ore-stage sericitic alteration, dated by the $^{40}Ar/^{39}Ar$ method, returned a controversial age of 1852 ± 12 Ma. Auriferous quartz veins formed at depths of 1.5–5.6 km, from low temperature (120–220ºC) magmatic/metamorphic fluid, with most CO_2 lost as a result of a drop in P and T. The mineralisation is hosted by igneous rocks and the main mechanism of gold precipitation was a decrease in the P and T conditions. The unusually older age and the fact that this zone terminates against the main mineralisation zone described above raises the question of whether this could be an older mineral system.

An exception in this zone is the Groundrush deposit, which was characterised by high temperatures (260–430ºC), CH_4- and CO_2-rich fluids, which formed at depths of 5.6–11 km. The mineralisation is hosted by dolerite. K/Ar dating of feldspar associated with ore-stage veins returned an age of 1770 Ma, indicating that this deposit could represent a deeper part of the same older system.

During 2004, limited time was spent on a study of quartz veins in the eastern Arunta Region in HUCKITTA. Samples were taken from the Oorabra Reefs, which crosscut the Jinka Granite in the Aileron Province west of Jervois, and east–west-trending quartz veins surrounding Bruces Copper Prospect, within the Neoproterozoic to Cambrian Harts Range Metamorphic Complex (Irindina Province). Elevated gold values were obtained in some samples (**Table 1**, **Figure 1**).

Nearly 50 $^{40}Ar/^{39}Ar$ ages of hydrothermal micas were obtained during this study. The ages vary from 1852 ± 12 Ma in the Tanami goldfield, through 1700–1740 Ma in gold-stage veining in the rest of Tanami Region, to a younger range of 1570–1430 Ma further southeast, to a much younger age range of 230–370 Ma in ALICE SPRINGS, HUCKITTA and ILLOGWA CREEK, which reflects the influence of the Alice Springs Orogeny. A group of older ages, in the range 1670–1580 Ma was obtained from the northeast portion of HUCKITTA. Erratically distributed ages of 1090–920 Ma are associated with a silicification event. In a regional sense, the ages are younging systematically towards the southeast.

Hydrothermal zircons and xenotime were found in ore stage veins at Chapman's Camp (Arltunga goldfield). These will be a subject for future SHRIMP dating.

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Sample	Locality	East	North	Au in ppm
12186	Bruces Prospect	564006	7473821	0.07
12187	Bruces Prospect	563689	7474478	53
12189	Bruces Prospect	563987	7474570	1.9
12194	Bruces Prospect	569727	7475725	0.0027
12206	Oorabra Reefs	583823	7490349	5.7

Table 1. Results of the latest NTGS sampling (WGS84 locations).

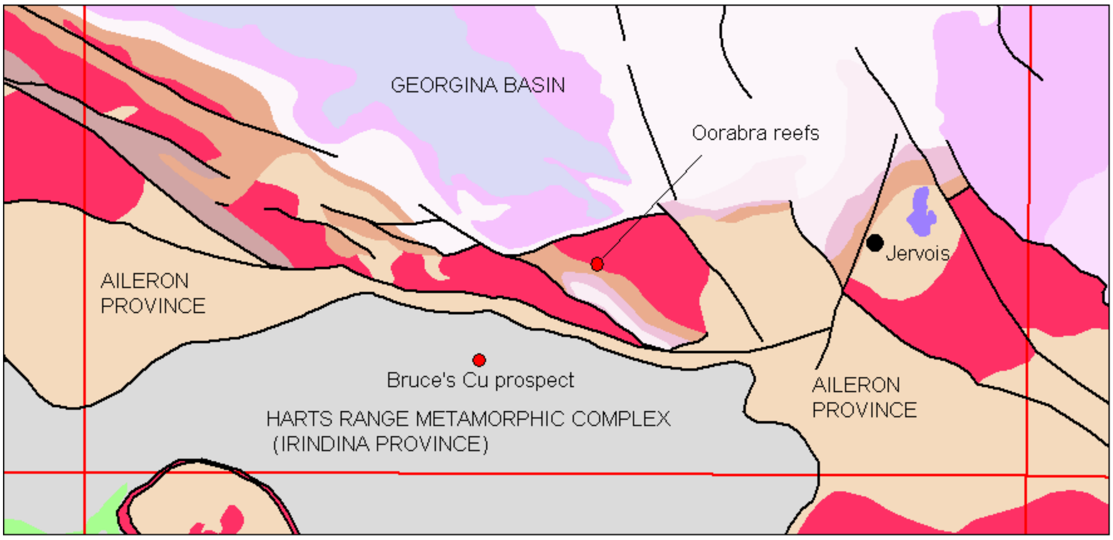

Figure 1. Simplified geology of southern half of HUCKITTA (from 1:2.5M Geological Map of the Northern Territory), showing location of samples.

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MAGNETOTELLURIC SURVEYS IN THE ARUNTA

Kate Selway[1, 2], Martin Hand[1] and Graham Heinson[1]

Imaging lithospheric architecture is vital for tectonic reconstructions of continents and recognising areas of potential mineralisation. Previously in Australia, this structural information has largely been provided by deep seismic reflection surveys. However, magnetotelluric (MT) surveys are increasingly being used as a relatively inexpensive alternative to deep seismic reflection, with projects either completed or active in the Gawler Craton, Arunta Region and Pine Creek Orogen (Broxholme *et al* 2004, Thiel *et al* 2004).

MT is a passive electromagnetic technique. The Earth's time-varying magnetic fields and resultant electric fields are recorded at spaced sites along a traverse. These data are then processed and modelled, giving a cross-section of the resistivity of the Earth. Possible depths of investigation exceed 600 km, but in current Australian studies, they are typically of the order of 50–100 km. Structures such as faults, sedimentary basins, zones of mineralisation and fluid pathways are associated with conductive anomalies and may therefore be imaged with MT. With this in mind, two 150 km-long MT surveys have been carried out in the Arunta Region over the last two years, with the aim of furthering our understanding of the lithospheric architecture of Central Australia (**Figure 1**). This study forms part of a PhD project, which is supported by NTGS.

Redbank Survey

The first survey was carried out along a 140 km north–south traverse, approximately 160 km west of Alice Springs, as shown on **Figure 1**. It extends from the Amadeus Basin in the south to the Arunta Region in the north, crossing the Redbank Thrust Zone (RTZ) in the middle of the line. The RTZ is a thick-skinned fault that was initiated during the Proterozoic Chewings Orogeny (1580 Ma) and reactivated during the mid-Palaeozoic Alice Springs Orogeny. In 1985, a Bureau of Mineral resources (BMR) deep seismic survey was carried out over the RTZ which, combined with gravity data, showed that the fault accommodates some 15–20 km of Moho offset, causing one of the largest continental gravity gradients in the world (Goleby *et al* 1989). At the survey location, the RTZ is also coincident with the inferred Proterozoic boundary between the Aileron Province to the north and the Warumpi Province to the south. This survey location was chosen for two reasons. The first was to verify the applicability of MT in an Australian setting and to the Australian geoscientific community through comparison with pre-existing seismic data. The second was to gain further insight into the RTZ and its relationship to the suture zone between the Warumpi and Aileron provinces.

Data were collected during two field seasons in August–September 2003 and March–April 2004. Twenty-eight sites were collected, with a spacing of 5–10 km. Processing of these data was carried out with the code Robust Remote Reference Magnetotellurics (RRRMT; Chave and Ander 1987). Modelling of the data was carried out using the Non-Linear Conjugate Gradients code (NLCG; Rodi and Mackie 2001).

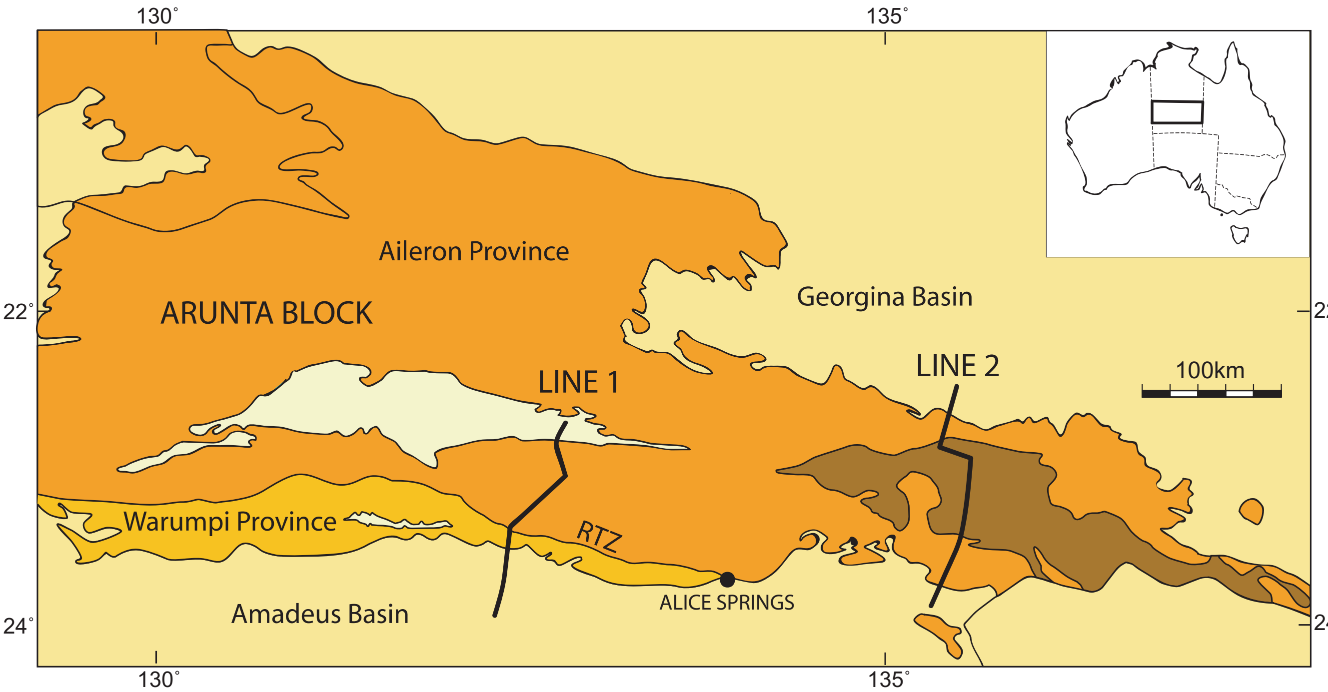

Figure 1. Arunta Region solid geology showing the locations of MT transects. Line 1 is the Redbank Survey and Line 2 is the Eastern Arunta Survey.

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Two main features are evident in the modelled results:

1. A conductive region at the southern end of the line extends from the surface to a depth of 15 km. This is coincident with the known location and depth of the Amadeus Basin, and the conductivity anomaly is therefore interpreted to be caused by the higher porosity and hydration of the basin sediments than the surrounding rock.
2. The northern half of the line is regionally more conductive than the southern half of the line. At the surface, the boundary between the two regions is coincident with the geologically and seismically interpreted outcrop of the RTZ. The conductivity boundary follows the seismically interpreted RTZ to a depth of 5 km. However, the conductivity boundary then becomes sub-vertical, whereas the seismic RTZ continues to dip at 40º. It follows, therefore, that the conductivity boundary is a different structure than the RTZ, that it predated the RTZ and was offset by deformation along the RTZ during the Alice Springs Orogeny. The last major event to have affected this region before the Alice Springs Orogeny was the docking of the Warumpi and Aileron Provinces at 1640 Ma. We therefore tentatively suggest that the conductivity boundary marks the interface between the Warumpi and Aileron provinces, with the contrasting conductivities being pre-existing characteristics of each of the provinces. This boundary was then offset along the RTZ during the Chewings and Alice Springs orogenies. This suggests that, although the RTZ forms a terrane boundary at the surface, it does not represent a major crustal-scale boundary.

Eastern Arunta Survey
The second survey was carried out in the eastern Arunta Region, extending approximately 150 km from the Amadeus Basin in the south to the Georgina Basin in the north, as shown on **Figure 1**. As such, it was the first geophysical survey to cross the entire Arunta Region. There are two key reasons for focusing on the eastern Arunta Region. Firstly, it was hoped that the core of the Alice Springs Orogeny could be imaged into the lower crust. The 450–300 Ma Alice Springs Orogeny was the last major tectonothermal event to affect the Arunta Region and dominates the crustal-scale architecture. The structures that were active during the orogeny are bi-vergent at the surface, with faults on the southern side dipping north and faults on the northern side dipping south. However, the core of the orogen and the relationships between these structures have not been geophysically imaged. Nor has there been any attempt to investigate the depth extent of the regional rehydration that characterises the eastern Alice Springs Orogeny. Secondly, during the Early Ordovician, the eastern Arunta Region was affected by the Larapinta Event. Structural, geochemical and tectonic evidence suggest that this records a high-T extensional regime. Peak metamorphic pressures indicate a burial depth of 30–35 km, which may have been achieved by Cambrian-aged sediment loading, preserved now in the Harts Range Group (HRG; Maidment *et al* 2004).

Thirty sites of data were collected in August 2004, with a site spacing of 5 km. These data were then processed using RRRMT and modelled using NLCG. The main feature of the model is the presence of a crustal-scale low-conductivity domain that is enclosed both laterally and at depth by significantly more conductive regions. This domain correlates with several mapped geological features. At the surface, it corresponds to early-mid Palaeozoic, upper amphibolite- to granulite-grade rocks of the Harts Range Metamorphic Complex. These rocks comprise the highly metamorphosed Cambrian-aged HRG and retrogressed Palaeoproterozoic basement (Entia Gneiss Complex). The southern margin of the low-conductivity domain corresponds to the position of the Illogwa Shear Zone and dips at approximately 45ºN. The northern boundary of the low-conductivity domain corresponds to the location of the Delny-Mt Sainthill Shear Zone and dips at approximately 70ºS. Both the Illogwa and Delny-Mt Sainthill Shear Zones appear to have been imaged to lower crustal depths. The model therefore confirms the bi-vergent nature of the Alice Spring Orogeny.

The origin of the low-conductivity domain is still uncertain, but there are two main possibilities. The first is that it marks the lithological distribution of the Cambrian-aged sequences of the HRG. This possibility presents significant geological problems, the most significant of which is that it suggests that the Cambrian rift sequences extend to a depth of approximately 30 km. While such a thickness may in part reflect the shortening associated with the Alice Spring Orogeny, existing data suggest that the HRG had at least 15–20 km of section, which has now been removed. In total these two sections would suggest a basin of unfeasible thickness.

The second and currently favoured possibility is that the low-conductivity region marks the domain of rocks that have been affected by the regional-scale fluid flow that occurred in the eastern Arunta Region during the early-mid Palaeozoic. This accords with surficial geology. Both the HRG and the Entia Gneiss Complex are characterised by comparatively hydrous metamorphic complexes, in contrast to the anhydrous Palaeoproterozoic regions to the west and south. Additionally, both the HRG and Entia Gneiss Complex underwent extensive fluid-present partial melting during the mid-Palaeozoic. Geological evidence indicates that the Entia Gneiss Complex was derived from anhydrous Proterozoic granulites, which this model shows to be comparatively conductive. Therefore, if this possibility is correct, it follows that fluid flow resulted in a decrease in electrical conductivity in the affected Palaeoproterozoic basement rocks. Although the cause of the high electrical conductivity in the anhydrous granulites is unknown, the crustal scale of the elevated response suggests that graphite films are the current carrier. This would suggest that the crustal-scale fluid flow in the eastern Arunta Region removed graphite.

The second feature of significance in the model is a resistive region that dips at 45º to a depth of approximately 20 km, located 25 km south of the interpreted Illogwa Shear Zone. This region corresponds in location to a geophysically interpreted fault. Recent lithological, geochemical and geochronological data suggest that this structure separates metamorphics of the Casey Inlier to the south and the Albarta Metamorphics to the north (Close *et al* this volume).

Further research

One further MT transect is planned for the current project. This line will extend from the Musgrave Block to the Arunta Region, with the aims of imaging the boundary between these two major Australian Proterozoic regions and of placing further constraints on the nature of the Warumpi Province. Further work will also be carried out, combining MT data with geochemical data to focus and improve geological interpretations of MT results.

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LOW-PROFILE BASEMETAL DEPOSITS IN THE NORTHERN TERRITORY

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The Northern Territory hosts some significant base metal (Cu-Zn-Pb-Ag) ore deposits including the high-profile world-class McArthur River Mine (227 Mt @ 9.2% Zn, 4.1% Pb, 41 g/t Ag and 0.2% Cu) and Browns Prospect (70.5 Mt @ 3.1% Pb, 0.85% Cu, 0.12% Co and 12 g/t Ag). Several low-profile base metal deposits are located across the Northern Territory and there is scope for the substantial upgrading of currently estimated mineral resources. Some of these deposits can be classed as MVT (eg Sandy Creek, Coxco and Cooley II), or carbonate replacement style (Bulman, ?Home of Bullion and Jervois).

Outcropping Zn-Pb-Ag mineralisation at the **Sandy Creek** deposit was discovered by Aquitaine Australia Ltd in 1972. The deposit is hosted within the Carboniferous Burt Range Formation along the eastern margin of the Bonaparte Basin. Discontinuous Zn-Pb-Ag mineralisation is present over a 15 km strike length. The *Sorby Hills* deposit (16.25 Mt @ 5.3% Pb, 0.6% Zn and 56 g/t Ag), located 24 km to the southwest (in WA), is also hosted by carbonate lithologies of the Burt Range Formation.

Following the completion of 19 diamond and 50 percussion drillholes in 1984, an “inferred” resource of 3.2 Mt @ 4.4% Pb, 2.5% Zn and 15 g/t Ag (3% Pb + Zn cut-off) was outlined by the Sandy Creek JV (Ingebritsen and Shelley 1984). Two distinct styles of mineralisation are present at Sandy Creek:

1 High-grade (eg 16 m @ 9.5% Pb and 2% Zn) breccia zones, within and proximal to north-trending, near-vertical basement-related faults.
2 Lower-grade (eg 5 m @ 1.6% Pb and 1.4% Zn) stratabound sedimentary carbonate breccia and porous dolomitic sandstone.

A recent review of the exploration data over Sandy Creek and adjacent areas indicates that previous drilling encountered poor sample recovery in the mineralised zones and in many cases, failed to intersect the host unit or geophysical targets (P Kastellorizos, Exploration Manager, Tennant Creek Gold Ltd pers comm). The main mineralised zone at Sandy Creek has the potential to host an open pit resource of 10–20 Mt @ 6–8% Pb and 2% Zn (Tennant Creek Gold 2004).

Outcropping Zn-Pb-Ag mineralisation at the **Bulman** deposit was discovered and briefly worked by prospectors in 1910. The deposit is hosted within gently dipping, laminated stromatolitic dolostone and chert of the Mesoproterozoic Dook Creek Formation (McArthur Basin). These sediments have been intruded by dolerite sills and dykes assigned to the Derim Derim Dolerite (1324 ±°4 Ma), which varies from 20 to 100 m in thickness (Sweet *et al* 1999). Contact metamorphic effects in carbonate country rocks include pervasive silicification and recrystallisation, to produce marble and serpentine ± talc-bearing calc-silicate hornfels.

The Zn-Pb-Ag mineralisation at Bulman is found in ten separate deposits scattered over a 40 km^2 area, in close proximity to the dolerite intrusives. A combined resource of 1.2 Mt @ 6.5% Pb and 0.93 Mt @ 11% Zn was estimated for seven of the deposits (Nasca 1979). This estimate was based on data obtained from 20 drillholes, surface mapping and rock chip sampling.

Three styles of mineralisation were described by Patterson (1965) at Bulman:

1 High-grade (20% Zn and 3% Pb) surface crusts (0.3–0.6 m thick) comprising cerrusite, galena, hydrozincite, smithsonite and willemite.
2 Small high-grade pods in karstic cavities and various fractures.
3 Stratabound Zn-Pb ± Ag (10% Zn, 3% Pb, 10 g/t Ag) massive sulfides in bedding-parallel lenses up to 125 m long and 24 m thick.

The Bulman deposits remain relatively untested and potential exists for the discovery of significant sub-surface deposits, using modern geophysical techniques with follow-up grid drilling.

Sub-surface copper mineralisation at **Cooley II** was discovered during a ground IP survey by MIM Exploration Ltd in 1964. The deposit is hosted within brittle, deformed, massive to laminated stromatolitic dololutite and dolarenite (Mara Dolostone Member within the Emmerugga Dolostone) adjacent to the Emu Fault Zone (McArthur Basin). A crude mineral resource of 5 Mt @ 1.1% Cu was estimated by MIM Exploration Ltd following the drilling of 23 diamond drillholes (Kneale *et al* 1979).

The Cu-bearing mineralisation at Cooley II consists of veins (a few millimetres to several centimetres in width) and disseminations to massive patches of coarse pyrite, chalcopyrite and bornite. Minor sphalerite and galena infill brittle dilatant fractures and open spaces in breccia zones (Williams 1978). A metal zonation using variations in the Cu/(Pb+Zn) ratio was mapped by Williams (1978) and this indicates a progressive, southwest-trending decrease in Cu relative to Pb-Zn, away from the Emu Fault Zone.

Recent structural studies (Hinman 1995) on drillcore, surface and sub-surface exposures across the HYC-Cooley area suggest that the Western Fault Block (area between the HYC deposit and Emu Fault Zone) is the product of reverse faulting

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and thrusting during the "Cooley Inversion" transpressional event (1635 Ma). The Western Fault block (containing the Teena and Emmerugga Dolostone units) has been thrusted against and over much of the Barney Creek Formation.

The Cooley Breccia Zn-Pb and Ridge II concordant Zn-Pb mineralisation appears synchronous with this tectonic event. The Cooley II Cu and HYC North Cu-Pb mineralisation is later, and probably coincides with reactivation of the Emu Fault Zone during a regional north–south deformation event at 1590 Ma (Hinman 1995). Significant potential exists for repetitions of this style of mineralisation along the Emu Fault Zone and other similar structures across the McArthur Basin.

Outcropping Zn-Pb mineralisation at the **Coxco** deposit was discovered and worked by prospectors in the late nineteenth century. The deposit is hosted within a sedimentary breccia assigned to the lower Barney Creek Formation and a brittle-deformed algal-laminated, stromatolitic dolostone (Teena Dolostone) adjacent to the Emu Fault Zone. Intermittent exploratory and resource drilling was conducted by MIM Exploration Ltd between 1966–1996 and a more recent (2000–2001) drilling program was completed by North Mining Ltd (Carey 2001). A mineral resource of 7.8 Mt @ 4.2% Zn and 1.1% Pb was estimated by Rothery (1996).

Three styles of mineralisation are described by Carey (2001) at Coxco:

1 Stratabound, early diagenetic Zn-Pb sulfides (sphalerite-galena-pyrite) within partly silicified sedimentary breccia (Barney Creek Formation), lying at the unconformable contact between the underlying Teena Dolostone and overlying Lynott Formation. The mineralisation is typically 2–10 m in thickness and grading 2–5% Zn, but drillhole intersections of 21 m @ 7.4% Zn (Coxco 7) are possible. Mineralisation is highly erratic, with the widest grade intercepts being closest to the Emu Fault.
2 Epigenetic Zn-Pb sulfides (sphalerite-galena-pyrite-marcasite) within brittle dilatant fractures and chaotic breccia zones in dolostones (Teena Dolostone). Higher grades (eg 5 m @ 7% Zn) are commonly intersected close to the upper dolostone–shale interface. Mineralisation typically decreases to the east, away from the Emu Fault and is commonly developed in the footwall of moderate to steeply angled, west-northwest-dipping reverse faults.
3 Palaeokarstic related mineralisation.

Significant potential exists at depth for tectonically fractured and breccia-controlled, coarse-grained sphalerite-galena-pyrite-marcasite mineralisation of the Teena Dolostone on the western limb of the north-plunging Coxco Anticline. In addition, there is potential for near-surface sedimentary breccia containing high-grade Zn-Pb oxide mineralisation along strike. Drillhole comparison results suggest that RC drilling may be an unreliable sampling technique through these thick, base-metal oxide-sulfide horizons Carey (2001). High-quality, core drilling may provide the most reliable sampling method, if an accurate oxide resource is required for feasibility studies.

Cu-Pb-Zn-Ag mineralisation at **Home of Bullion** outcrops over a strike length of 240 m and was mined intermittently between 1923 and 1957, producing about 1370 t of Cu (grading 20% Cu) from 7115 t of ore. Only five exploratory holes have been drilled into this high-grade mineral system that is open at depth and along strike in both directions. A crude mineral resource of 130 000 t @ 7.1% Cu, 4–6% Zn and 1–2% Pb to a depth of 107 m was estimated by Bell (1953). More recent (1993–1998) exploration work in the vicinity by Aberfoyle Resources Ltd focused on the epigenetic gold potential outside the "Mining Leases".

The deposit consists of four shear? zone-hosted massive sulfide lenses, within quartz-muscovite schists of the Bullion Schist (northern Aileron Province). Interbedded mafic volcanics and intrusive amphibolites are common within the pelitic succession, and thin calc-silicate interbeds have been located along strike from the mineralisation (Drown 1993). A spotted, quartz-muscovite-tourmaline schist unit with retrogressed andalusite or cordierite porphyroblasts is also present. A small porphyritic granite stock outcrops 3 km to the west.

The "Main Lode" strikes west-northwest and dips steeply (55–65°) to the north, parallel to bedding and a pervasive cleavage. The oxide ore (goethite-copper carbonates-cerrusite) typically grades 2–12% Cu, 1–5% Pb, <2% Zn and 30–60 g/t Ag. The supergene ore (30–60 m depth) typically grades 12–25% Cu, 2–3% Pb, 1% Zn and 1.5 g/t Au and contains significant amounts of chalcocite and tennantite. Primary ore (pyrite-sphalerite-bornite-chalcopyrite-galena), intersected in drillholes, exhibits grades of 3–5% Cu, 1–6% Pb and 5% Zn (Sullivan 1953).

Drown (1993) reports a pre-deformational chlorite alteration present in the footwall schist, metamorphic recrystallisation textures in the sulfide ore, some primary ore metal zonation, banded ore textures and a chert unit (exhalite? cap) in the hangingwall succession as possible evidence for a syngenetic (VHMS) origin for the deposit. Limited Pb-isotope data suggests an epigenetic model is more likely (Warren *et al* 1995). Further studies on primary sulfide ore will be necessary to determine if a syngenetic origin for the deposit is correct; the results may have significant implications on mine resource potential and regional exploration strategies.

Discontinuous outcrops of Cu-Pb-Zn-Ag mineralisation over a 7 km strike length at **Jervois** were discovered in 1929 and intermittently mined until 1961. The Green Parrot deposit was mined by the Plenty River Mining Company using opencut methods between 1982–1983, producing 44 000 t @ 1.5% Cu, 8.5% Pb, 2.5% Zn and 160 g/t Ag. In 1997, Britannia Gold NL estimated 1.83 Mt @ 2.4% Cu at the Marshall-Reward deposit, 300 000 t @ 2% Cu at Bellbird and 500 000 t @ 8% Pb, 3% Zn, 1.5% Cu and150 g/t Ag at Green Parrot. Reward Minerals Ltd (current project operators) have estimated a global copper resource of 6.2 Mt @ 2.1% Cu at Jervois.

The base metal mineralisation at Jervois is stratabound and hosted within steeply dipping lenses of calc-silicates, garnet-chlorite-magnetite rock and garnet-magnetite quartzite, within a thick succession of spotted andalusite-cordierite schist and quartz-sericite-feldspar schist, assigned to the Palaeoproterozoic Bonya Schist (eastern Aileron Province). Pb-Zn-Cu-Ag mineralisation (eg Green Parrot deposit) is typically hosted in the calc-silicate rock types, whereas the copper mineralisation (eg Bellbird deposit) is best developed in the garnet-chlorite-magnetite quartzite (BIF) unit.

Ypma (1990) interpreted the quartz-sericite-feldspar schist, felsic gneisses and cordierite-muscovite schist units as having been formed from felsic and intermediate volcanic rocks. However, there is a distinct possibility that some of these igneous protoliths are intrusive. The presence of stratiform banded iron formation, Mn-bearing calc-silicates and tourmalinites, all of which are closely associated with Cu-Pb-Zn-Ag mineralisation, suggests a original chemical sediment.

The Pb-Zn-Ag mineralisation at Jervois has many geological features in common with Broken Hill-type (BHT) Pb-Zn-Ag mineralisation, including the close association of disseminated scheelite in the stratabound calc-silicates (Ypma 1990). Alternative genetic models include carbonate replacement by Pb-Zn-Cu sulfides during intrusion of pre-deformational felsic and/or mafic sills, and syn-tectonic Cobar-style (Cu-Ag-Pb-Zn-Au). Reward Minerals Ltd are currently conducting drilling programs to establish ore resources in the JORC measured category at the Bellbird and Marshall-Reward deposits. A high percentage of holes drilled last year returned ore grade intersections including 7 m @ 1.8% Cu, 14.2% Pb, 7.6% Zn and 415 g/t Ag from 16 m depth (Green Parrot RJ 26) and 9 m @ 4.6% Cu and 28 g/t Ag from 84 m depth (Bellbird RJ 19). The structural setting at Jervois is favourable to repetitions of high-grade Cu-Pb-Zn-Ag lenses, so more targeted drilling is required to elucidate the full resource potential of this large mineral system.

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INDUSTRY INFORMATION SERVICES

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The Minerals and Energy Information Centre (MEIC) is your first port of call for products and services of the Geological Survey. Services include product distribution, access to, and distribution of open file company reports, reference queries and data delivery via the web.

In the past 12 months, several information projects have been completed. These include: geochemistry data capture in the Pine Creek Orogen; upgrades to the core library database records; scanning of all NTGS technical reports; onshore petroleum well geological data capture; and the completion of the first implementation of the web mapping interface for geoscientific GIS data, now known as STRIKE. The first of the new comprehensive 1:250k GIS datasets, TOBERMOREY[2], was released in June 2004. SANDOVER RIVER has also been released and MOUNT EVELYN is due in the very near future.

The Pine Creek Orogen open file geochemistry data capture project, including the purchase of AngloGold data, resulted in the addition of approximately 43 000 new sample points and drill collars to the database. These data have been included in an updated Digital Information Package (DIP 005), released in January 2005, and is also included on the geochemistry layers delivered through STRIKE.

The core library database, COREDAT, had 1562 records without coordinates in January 2004 and a project to locate these drillholes and update the database has been completed. During this process, duplicate records were removed, other information updated and some core identified for disposal. As at October 2004, only 199 records remained without coordinates. These records have been checked, but drillhole locations cannot be determined at present. After a further period of checking, a decision will be made whether to store the core for a further period of time, while other databases that may contain relevant information are upgraded.

Geoscientific data from 112 onshore Northern Territory petroleum exploration and stratigraphic wells have now been captured. The data are available online through Geoscience Australia databases at http://www.ga.gov.au/oracle/apcrc/. Over 23 000 rows of data are available and include: header information; summary and objective remarks; reservoir properties; hydrocarbon shows; depositional environments; biostratigraphy; stratigraphy; and directional survey information. The Internet site facilitates easy discovery of the data through text- and map-based searching, allows downloading, and provides leading-edge on-line graphing functionality. Data entered in this project complements data already captured by GA from offshore Northern Territory petroleum wells.

As mentioned last year, the IRMS minerals database has many incomplete or inconsistent records as a result of poorly designed legacy systems. A project to upgrade database content commenced in January 2004 and will continue until the worst of the records are updated. Of the estimated 7000 records with no information in key fields, 1200 reports have been reindexed as at the end of February 2005. The first focus of the project continues to be those with no subject keywords. A further 4700 records have had some improvement using batch modification techniques. Updated records are available via the IRMS searching interface on the website, which is updated monthly.

New Minerals and Energy Group and NTGS websites were designed, updated and launched in 2004. The NTGS website has been redesigned to provide access to geological information and projects related to geological terranes from the home page, through menu tabs such as Proterozoic Orogens and Palaeozoic Basins. The Territory Geoscience tab provides access to all projects, geophysical surveys, and geochemical and geochronological information at a Territory level, rather than by project. Minerals and Energy Information Centre services, product downloads and information are accessed through the Information Centre tab; all databases and applications are accessed directly via the Online Systems tab and the Exploration tab provides direct access to titles information, IRMS, the new Exploration News database, mineral and petroleum opportunities, commodity information and reporting guidelines. The Exploration News database is updated every Monday, and includes brief references and abstracts of information relating to the NT exploration industry, covering areas such as indigenous liaison, land access, environmental issues, commodities, company information, statistics, mine safety, research and government policies.

Another major project completed in the last year is the development of the NTGS Information Management Strategic Plan (IMSP). Although this document is primarily for internal use, it describes our information management vision, and sets out the major goals and projects for the four years starting in July 2004. Our vision is to professionally collaborate and manage geoscientific data of the Northern Territory, and be recognised for providing accurate and high-quality geological resources to the Government, mining industry and public. The information resource is valued as a strategic asset and is managed to ensure it is:

1. readily and flexibly accessible
2. easily discoverable
3. assured to a quality that matches stakeholder requirements
4. generated and managed for the long term
5. consistently reviewed and updated to ensure currency.

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AN OVERVIEW OF THE HYDROCARBON POTENTIAL OF THE NORTHERN TERRITORY'S ONSHORE SEDIMENTARY BASINS

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The petroleum prospectivity of the Northern Territory's sedimentary basins remains largely untested, as initial exploration programs undertaken in the 1960s to early 1990s were far too sparse to adequately gauge the region's potential. Difficulties in negotiating access to prospective land have also impeded exploration in the last decade, but the recent grant of several new exploration titles indicate an increase in exploration activity. It is pertinent that in the last four years in the Northern Territory, twenty-two new petroleum exploration licence applications have been made by nine new operators and three new permits have been granted in the last year.

Several basins contain important oil-prone Palaeozoic petroleum systems including the Pedirka Basin (Permian Purni Formation), Amadeus Basin (Ordovician Horn Valley Shale), Georgina Basin (Middle Cambrian Arthur Creek Formation, Thorntonia Limestone) and also the southeast Bonaparte Basin (Carboniferous). The Beetaloo Sub-basin has a well documented Mesoproterozoic petroleum system. Over the last 5–10 years, studies of these petroleum systems by the NTGS petroleum group has led to an enhanced understanding of their potential, leading to increased exploration activity targeting these basins.

In the ***Georgina Basin***, extremely rich, oil-prone microbial source rocks in the Middle Cambrian Arthur Creek Formation/Thorntonia Limestone section are pivotal to the exploration effort and there is evidence of widespread oil migration. The facies architecture of the overlying Steamboat Sandstone comprises recently recognised tidal channel and deltaic facies, well-represented on seismic, but lacking well control. Potential reservoirs are up to 150 m thick. The basin has been unroofed to some degree, leading to shallow target depths of 300–1000 m, and stratigraphic/structural entrapment could reach hundreds of millions of barrels of oil. Other large stratigraphic plays include Arthur Creek Formation shoals and sandy debris flows, and Hagen Member (of the Late Cambrian Arrinthrunga Formation) shoreline plays, all of which have potential in the tens of millions of barrels.

The ***Wiso Basin*** has many analogies with the Georgina Basin, but a basinal stratigraphic test is required to assess available petroleum systems. Any success in the Georgina Basin will stimulate exploration in this western counterpart.

Recent studies by NTGS and others show that the Neoproterozoic in the ***Amadeus Basin*** is an attractive gas target, particularly in the southern portion of the basin, where large structural and combination plays could provide major gas resources via fractured reservoirs (Heavitree Quartzite). Exploration is in its infancy, but there is potential for large reserves. There is also an impetus for gas exploration, given that the current gas supply contracts for Darwin expire in early 2009 and additional supply for other resource/industrial projects could arise in the next 5–10 years.

In the ***Pedirka Basin/Eromanga Basin***, recent studies by NTGS have highlighted the Early Permian Purni Formation as an important oil source rock. This unit and a glaciogene sandstone at its base correlate with the Patchawarra Formation and Tirrawarra Sandstone, respectively, a petroleum system which is important in the Cooper Basin. Additional Triassic and basal Jurassic petroleum systems exist in what is a very sparsely explored basin, and the oil potential of these is believed to be in many ways analogous to the Cooper Basin.

The Mesoproterozoic ***Beetaloo Sub-basin*** includes rich petroleum systems, based on source rocks in the Kyalla and Velkerri formations, and reservoirs in the Bessie Creek, Moroak and Jamison Sandstones. The main hindrance to exploration is the long geological time spans required for hydrocarbon preservation, but maturation/expulsion studies are ongoing and unconventional play types such as fractured shale reservoirs and basinal gas plays are being investigated.

The ***Southeast Bonaparte Basin*** hosts several small gas fields onshore, and the Turtle and Barnett Oil fields offshore. Source rocks for the latter were originally attributed to the Carboniferous Milligans Formation, but Gorter *et al* (2004) illustrate that the source is in fact shale in the Langford Group, which is separated from the overlying Milligans Formation by a major unconformity. This is an important advance in the understanding of this portion of the basin and presents a number of new exploration opportunities.

In summary, with the exception of the northern Amadeus Basin, all of the Northern Territory basins mentioned above are largely underexplored by international standards. This can be attributed initially to a lack of early success in what are complex basins and subsequently, to land access problems. It is only over the last decade that modern geological and geophysical concepts, including interpretations of recently acquired airborne aeromagnetic data, have been applied to basin studies, but land access has remained difficult.

Many of these new concepts will be discussed at the up-coming Central Australian Basins Symposium (CABS), which will include 55 technical papers, to be held in Alice Springs on August 16–18. With the persistence of high oil prices and easing of land access constraints, the NT's onshore basins appear to be on the verge of a new era of exploration and discovery.

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SALT TECTONICS AND RELATED EFFECTS ON BASIN MORPHOLOGY

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Previous investigations on the Amadeus Basin and its development, have largely involved either strict sedimentological models, or basement models. These two end-members are not taking advantage of the cross-fertilisation and two investigative methods. However, some previous workers (eg McNaughton *et al* 1968), have noted that the presence of salt in the Amadeus Basin is an important mechanism in basin formation, both from morphological and prospectivity points of view.

Salt flow is an important mechanism in controlling the formation of complex traps for hydrocarbons and metals. Evaporites and associated flowage are responsible for trapping more than 60% of the hydrocarbon reserves of the Middle East (Edgell 1996).

Salt tectonics (synonym halotectonics) is a general term that encompasses the notion of salt flow, trans-stratal salt movement, salt pillowing and diapirism. It refers to tectonic deformation involving halite or other evaporites as a substratum or source layer. Halokinesis is a form of salt tectonics, in which flow of salt is powered by gravity, that is, by the release of gravity potential without significant lateral tectonic forces (upwelling and withdrawal; Trusheim 1960).

Because the weight of overlying sediments tends to expel salt upward, salt tectonics is largely confined to shallow crust above the ductile-brittle transition zone, some 8–15 km deep (Jackson *et al* 1994). In this brittle domain, the overburden deforms not by creep flow, but by frictional slip along faults of penetrative slip surfaces (Jackson *et al* 1994). In contrast, salt deforms as a viscous or power-law fluid, with viscosity typically in the range 1017–1019 Pa s, depending mainly on grain size and water content (van Keken *et al* 1993).

Salt structures generally evolve from concordant low-amplitude structures to discordant high-amplitude intrusions, and then to extrusions, but they can stop growing at any state. Gentle immature salt structures, concordant with their cover, include salt anticlines, salt rollers and salt pillows. Salt anticlines (salt rides, salt waves) have approximately symmetrical cross-sections, with a planar base and arched roof. Salt rollers (Bally 1981) are also ridge-like, but are asymmetrical in cross-section; a long gentle dip slope is in stratigraphic contact with the cover, whereas a short steep scarp slope is in normal fault contact with the cover. Salt pillows are periclinal subsurface domes; plan views are circular to moderately elliptical and their bases are generally subplanar.

In the case of diapirs, those features that have discordant contacts with overlying strata (as opposed to concordant structures such as salt pillows and salt cored anticlines), they face a 'lack-of-room problem'. Three modes of piercement solve this problem; active, passive and reactive diapirism.

Within the Amadeus Basin, all these features are present and are indicative of different levels of (salt) structural maturity. The regional deposition of a salt unit, at the very bottom of the basin succession, is the perfect precursor to decoupling and the onset of salt tectonics. Reconstruction reveals a series of **'**structural' sub-domains that characterise the development of the basin, which in turn affects exploration models and therefore prospectivity. The variation is pronounced from east to west, and north to south. For instance contained within the Carmichael Sub-basin (northern Amadeus) is a large thickness of Pertnjara Group, shed off the Arunta Region during the Alice Springs Orogeny (ASO). This has effectively capped salt movement, and thus there are not any diapirs at the surface in this area. In the eastern Amadeus Basin, thinner initial depositional thicknesses of Bitter Springs Formation salt have withdrawn very early in the basin history, causing rafting and megablocks to form.

A salt layer decouples the stratigraphy above and below, which has implications for the mechanical deformation of both. Faults do not form in salt layers unless there is extreme seismic activity (Weijermars *et al* 1993). This implies that distinct morphological differences exist, which has flow-on effects for prospectivity of various stratigraphic packages. The complete detachment of most of the Amadeus stratigraphy by a mobile viscous layer that preferentially absorbs strain, at a level just above the basement, needs to be understood to better refine exploration models.

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GEOCHRONOLOGY OF THE LITCHFIELD PROVINCE: NEW RESULTS AND PRELIMINARY INTERPRETATIONS

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The Palaeoproterozoic Pine Creek Orogen (PCO) is located on the northern periphery of the North Australian Craton (NAC). On the western margins of the orogen, between the north-trending Giants Reef Fault system and the onlapping Mesozoic Bonaparte Basin, the Litchfield Province (LP) forms a longitudinal domain of metasediments and syn- to post-tectonic felsic and mafic intrusives (eg Pietsch and Edgoose, 1988). Lithostratigraphic relationships, both within the LP and with the low-grade central PCO succession immediately to the east, are unclear and ambiguous due to poor exposure. This contribution is part of an ongoing NTGS program to review and reassess the lithostratigraphic correlations and the timing of structural, metamorphic and mineralisation events across the PCO. It will introduce new SHRIMP zircon and *in situ* monazite geochronology relevant to understanding the geological evolution of the Litchfield Province, and the lithostratigraphic and tectono-metamorphic relationships with other adjacent terranes of the NAC. Current regional interpretations suggest that the LP represents a plausible and intuitive geological link between the central PCO and the Palaeoproterozoic Halls Creek Orogen in Western Australia, both notably diverse and productive metallogenic provinces. An improved understanding of the geological relationships within the LP and with adjacent metalliferous provinces may help stimulate mineral exploration in the LP.

Existing lithological relationships

The Litchfield Province contains three medium- to high-grade metamorphic units, namely the Hermit Creek, Welltree and Fog Bay metamorphics. Lithological correlations between the Litchfield Province metamorphic units and their broader relationship with the central Pine Creek region to the east, and the Hall Creek Orogen to the southwest, are problematic and conjectural. Lateral facies equivalence is inferred between the turbiditic Burrell Creek Formation (Finniss River Group; upper Pine Creek succession) and metasediments of the Welltree Metamorphics (Pietsch 1986). The Hermit Creek Metamorphics have been correlated with both the lower and the upper Palaeoproterozoic Pine Creek succession (Berkman 1980, Needham and Stuart-Smith 1984, Pietsch and Edgoose 1988, Needham and De Ross 1990). Little is known of the Fog Bay Metamorphics and most information is based on drillcore stored at the NTGS core library (Darwin). The Fog Bay Metamorphics are inferred to be faulted against the Welltree Metamorphics along the north-trending Tom Turner fault and have been tentatively correlated with the Hermit Creek Metamorphics (Edgoose *et al* 1989). Rb-Sr whole rock isochrons (2002 ± 42 Ma, Hickey 1985) provide some evidence for a Palaeoproterozoic history for the Fog Bay Metamorphics, but the regional lithostratigraphic and tectono-metamorphic implications of this age are obscure.

Objectives and preliminary results

In order to address these regional lithostratigraphic uncertainties, the Fog Bay, Welltree and Hermit Creek metamorphics were sampled in 2003 by J Lally (NTGS), K Worden (GA) and I Scrimgeour (NTGS) for detrital zircon U-Pb SHRIMP analysis. The primary objective was to constrain maximum deposition ages (MaxDep ages) and obtain provenance information for the sedimentary precursors. Unfortunately, the Fog Bay Metamorphics failed to yield zircons; this unit has been re-sampled recently and results are pending (2005). In addition to the detrital investigation, reconnaissance electron microprobe (EMP) *in situ* monazite geochronology from all three metamorphic units was conducted to explore the timing of metamorphic events affecting the LP.

SHRIMP detrital U-Pb zircon data

The Welltree and Hermit Creek metamorphics detrital zircon populations (**Figure 1**) yield maximum deposition ages (based on the weighted mean age of the youngest 6 analyses) of 1845 ± 10 Ma and 1846 ± 7 Ma respectively (2σ errors). Alternative MaxDep ages based on the youngest analysis from each sample give 1825 ± 32 Ma and 1841 ± 20 Ma, respectively. The general chronological spectrum of the zircon detritus indicates that the sedimentary precursors for these metamorphic units were likely derived from the same (or very similar) source region(s). Prominent peaks at about 1861 Ma (Hermit Creek Metamorphics) and about 1865 Ma (Welltree Metamorphics) are clearly evident in the spectra (**Figure 1**).

Recent unpublished SHRIMP zircon U-Pb ages from interbedded, conformable felsic volcanic lenses (Warrs Volcanic Member), from within the Burrell Creek Formation (Finniss River Group, central PCO), indicate extrusion and(or) eruption at about 1862 Ma, placing a robust constraint on the depositional age of that formation. The MaxDep ages for the Hermit Creek and Welltree metamorphics (about 1841–1825 Ma) suggest that deposition of their sedimentary precursors commenced *after* deposition of the Burrell Creek Formation (1862 Ma). Furthermore, the predominant peak at about 1860–1865 Ma, in the zircon detritus in both metamorphic units, correlates well with crystallisation ages for volcanics in the Burrell Creek Formation and the South Alligator River Group (eg Gerowie Tuff, about 1863 Ma), within the central PCO. This observation suggests that the upper successions of the central PCO (Finniss River and South Alligator groups) are likely source material for the Hermit Creek and Welltree Metamorphics. These results indicate that the sedimentary precursors for

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the Hermit Creek and Welltree metamorphics are *younger* than, and possibly *derived* from the low-grade upper successions of the central regions of the PCO.

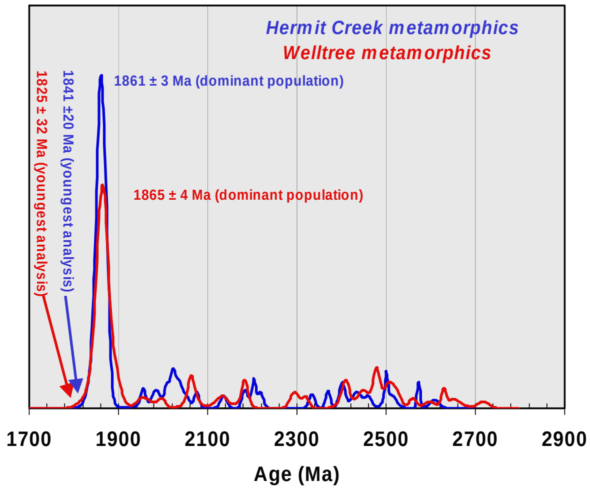

Figure 1. Detrital zircon population from the Welltree Metamorphics (red, n = 80) and the Hermit Creek Metamorphics (blue, n = 71). Note the dominant peak in both samples at 1861–1865 Ma and the *broad* similarity of the Archaean to Palaeoproterozoic zircon detritus.

In situ EMP monazite data

In situ EMP analysis on monazite (conducted on polished thin sections at the University of Adelaide, Jan 2005) from the Hermit Creek, Welltree and Fog Bay metamorphics were conducted, to provide a preliminary insight into the timing of significant geological events from the Litchfield Province. Monazites from two principle textural locations were targeted; grains within garnet porphyroblasts and those located in the quartzo-feldspathic (± biotite) matrix.

Due to the low precision of the EMP analytical technique (about 2% at the 1σ level), it not possible to resolve internal complexity within the acquired dataset. The results (presented as a weighted mean for an individual sample with the MSWD ~1) for the Hermit Creek, Welltree and Fog Bay metamorphics are 1788 ± 13 Ma, 1754 ± 11 Ma and 1801 ± 12 Ma, respectively. Based on textural observations and comparisons with individual spot analyses, there is some indication that garnet porphyroblasts are shielding inclusions of older monazite against a 1750 Ma event that is affecting or growing monazite in the matrix. The spread of weighted mean ages from about 1800 Ma to about 1750 Ma, as presented here, are considered to reflect the superimposed presence of peak metamorphic ages (1840 Ma?) within the EMP data, the precise age of which is not possible to statistically resolve, due to the low precision of the EMP method.

Although further chronological work is planned to better resolve the chronological complexity implied within the EMP data (via SHRIMP dating of selected *in situ* monazites), a preliminary interpretation is proposed here. Page *et al* (1985) determined Rb-Sr whole rock ages of about 1770 Ma from deformed felsic granitoids. However, these show a marked internal scatter, indicating that isotopic systems in the Litchfield Province have been disturbed. Şener (2004) reported vein-style Au-mineralisation texturally associated with monazite dated at about 1750 Ma from the Goodall Au deposit in the central PCO. It seems clear that the western PCO experienced a significant event at 1770–1750 Ma. We tentatively suggest that an episode of post metamorphic peak regional-scale fluid movement through the PCO occurred at this time. Fluid influx resulted in some Au mineralisation in the central PCO (Şener 2004) and probably facilitated retrogression affecting peak metamorphic assemblages in the Fog Bay, Welltree and Hermit Creek metamorphics. The source of fluids, the circulatory mechanism and the prevailing tectonic environment for the regional-scale hydration is unclear at this preliminary stage.

Conclusions

1. The Welltree and Hermit Creek metamorphics within the Litchfield Province are younger than the Burrell Creek Formation (Finniss River Group), in contrast to current stratigraphic interpretations. Maximum deposition ages for these units are 1845 ± 10 Ma and 1846 ± 7 Ma, respectively (based on youngest 6 analyses). The chronological distributions of zircon detritus from both units suggest derivation from the same (or similar) source region(s). Probable candidates for sources are the upper successions of the central PCO.
2. Electron microprobe monazite chronology of the Hermit Creek, Welltree and Fog Bay Metamorphics provide ages in the range 1800–1750 Ma. These ages are complicated by an inferred, older irresolvable population of monazite ages. Previously published studies reveal the presence of a 1770–1750 Ma isotopic event in the LP (including Au-mineralisation in the adjacent central PCO). Based on these previous reports and the interpretation of our data presented here, we infer an episode of regional-scale fluid ingress at this time (1770–1750 Ma), which affected the Litchfield Province, and which may be related to Au mineralisation.

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TOWARDS A CORRELATION OF THE EARLIEST PROTEROZOIC EVOLUTION IN CENTRAL AUSTRALIA

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At AGES 2003 and 2004, Geoscience Australia and NTGS have introduced progressive updates on the rapidly evolving big-picture understanding of the Arunta and regions to its north. Primary outcomes, based on extensive new mapping accompanied by coverage of new U-Pb and Ar/Ar geochronology, have included:

- a revised chronology of correlated, isotopically-dated events (Claoué-Long 2003)
- formalisation of this event framework and the major regional lithological packages (Scrimgeour 2003)
- recognition of distinct geological provinces (Warumpi and Irindina) that have separate evolutionary histories (Scrimgeour 2003)
- progressive refinement of the operation of key events, such as the Strangways Orogeny (Scrimgeour 2004)
- expansion of the 'footprint' of regional thermal events into the Tanami and Davenport regions, from study of the low to medium temperature Ar isotopic record (Fraser 2003, 2004)
- an emerging realisation that the Arunta Region 'mobile belt' and the 'North Australian Craton' to its north, rather than having developed separately, may share elements in common.

This update outlines new evidence for the last of these themes – the correlation of major Proterozoic packages over very wide geographic regions – focusing especially on the earliest evidence preserved in the rock record.

The earliest extant rocks over most of the Arunta Region are widespread clastic sediments, known as the Lander Package in the west and north, and as the Ongeva Package in the east Arunta (Scrimgeour 2003). Confident correlation of these two packages has been difficult because of their very different metamorphic expressions. The Lander Package comprises shallow marine and turbiditic sediments, much of it still at low metamorphic grade. The Ongeva Package includes the protoliths of much of the Strangways Metamorphic Complex and other metamorphic units such as the Bonya Schist and the Kanandra Granulite; it is more difficult to study because much of it is at higher metamorphic grade (granulites). It also includes prominent mafic and felsic igneous precursor rocks, which appear to be largely absent from the Lander Package.

Claoué-Long (2003) showed that the Lander Package can be divided stratigraphically into two units, based on detrital zircon age patterns in the provenance. Over large areas of the western and northern Arunta, the youngest detrital zircons in the sandstones have ages of 1830–1840 Ma, together with other provenance components at 2100–2200 Ma and 2500 Ma. This provenance pattern matches with that found in the Killi Killi Formation in the Tanami Region, indicating a linked sedimentary origin. Locally, in the Reynolds Range, there are sandstones containing the same detrital populations, but with the addition of some younger zircons in the age range 1800–1820 Ma, indicating derivation from a provenance that included younger components; this provenance has also been identified in the Tanami Region Ware Group sediments.

Protolith ages within the Ongeva Package in the east Arunta now indicate a correlation with both of the Lander units. At Edwards Creek, Harry Creek and the Phlogopite Mine, all part of the Erontonga Metamorphics, which is assigned as the basal stratigraphic unit to the Strangways Metamorphic Complex, granulite-grade units have yielded simple single-age protolith zircon ages as follows:

Harry Creek	1801 ± 3 Ma
Edwards Creek	1803 ± 5 Ma
Phlogopite Mine	1810 ± 4 Ma

The fact that each has a single crystallisation age indicates that the protoliths were probably volcaniclastic rather than detrital sediments, and their ages constrain stratigraphy over the short period 1810–1800 Ma. The rare 1800–1820 Ma zircons in the younger Lander units to the west are consistent with derivation from a source that included volcanism at this time, supporting stratigraphic correlation. Dating of prominent metamorphic zircon overgrowths in these rocks indicates that the Strangways metamorphism terminated at 1690 Ma, 30–40 million years later than suggested in previous compilations (Collins and Shaw 1995).

Correlation of other Ongeva Package units with the earlier Lander sediment unit is found 100 km to the northeast in the Kanandra Granulite, which largely comprises mafic and subordinate felsic granulites. A felsic granulite contains zircons with thick overgrowths, whose age confirms that the Strangways thermal event was responsible for the granulite-grade metamorphism. Prominent cores within these zircons contrast with those further south (eg Edwards Creek) in not having one

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crystallisation age; instead, they have an inherited age pattern spanning from the late Archaean to 1840 Ma, identical to the provenance found elsewhere in Lander Package sediments of low metamorphic grade. This identifies the protolith of at least some Kanandra felsic granulite as Lander Package sediment.

In the last year, attempts to extend these correlations northward have tested the suggestion, originally made by Donnellan and Johnstone (2003) on the grounds of geophysical mapping under cover, that stratigraphic continuity might exist between the Tennant and Arunta regions. The Tennant, Davenport and Barrow Creek areas have the advantages of low metamorphic grade (greenschist grade or below), and intercalation within the stratigraphy of prominent felsic volcanic horizons amenable to dating. There is the opportunity to calibrate the stratigraphic and structural development to precise isotopic ages, without the complication of high-grade metamorphic disturbance of isotopic systems. Work is still in progress, but early highlights include stratigraphic ages for four regionally important volcanic horizons, and detrital zircon spectra for different horizons of clastic sediments:

Strzlecki Volcanics (Barrow Creek)	1807 ± 3 Ma
Arabulja Volcanics (Davenports)	1814 ± 3 Ma
Treasure Volcanics (Davenports)	1815 ± 3 Ma
Epenarra Volcanics (Davenports)	1840 ± 4 Ma

Sediments intercalated with these dated volcanics contain the following detrital zircon age spectra:

- Unimbra Sandstone (Davenport Province) and undivided Ooradidgie Group (Barrow Creek) have the same zircon content as found in Arunta Region Lander Package sandstones, ie dominated by 1880–1840 Ma detritus, with some older Proterozoic populations and an Archaean (2500 Ma) component; the youngest detrital zircons constrain deposition to after 1830–1840 Ma.
- Coulters and Erorolla Sandstones (above the Arabulja level in the Davenport Province) have the same provenance spectrum, with the addition of younger grains at 1800–1810 Ma.

It is important to note that this dataset is incomplete, with the ages of several other units between, above and below these horizons still to measured. However, it is already evident that the two Lander Package provenance signatures observed in the Arunta Region, and found also in the Tanami Region, are identifiable in the Davenport Province, where they can be placed directly within dated stratigraphy. The provenance with an 1840–1830 Ma maximum deposition age (Unimbra, Ooradidgie) is associated with Epinarra volcanism at 1840 Ma. Younger detrital zircons in the higher sandstone units (Coulters, Erorolla) are consistent with the younger phase of felsic volcanism at 1820–1800 Ma. Within this progression, there are likely to be disconformities and other complications yet to be established, but so far, the time progression and its wide geographic correlation are consistent.

There are emerging indications that this correlation may be extended much further across northern Australia. A new dataset of detrital zircon ages in the Hermit Creek Metamorphics at Pine Creek, once regarded as a basement unit, has yielded a Lander Package provenance spectrum with the same maximum deposition age of 1840 Ma (*see Carson et al this volume*), suggesting that it, too, is likely to correlate with sedimentation in the Arunta, Tanami and Davenport regions.

The correlations emerging from this work are surprising, but also quite simple. Evidently, the major early basin successions of the west and north Arunta (Lander Package and equivalents), east Arunta (Ongeva Package), Tanami Region (Tanami and Ware Group), parts of the Davenport Province (Hatches Creek Group), and perhaps elements at Pine Creek, are not disconnected evolutions. They comprise a correlatable basin system, linked by a common evolution of sediment provenance and, where it can be measured, stratigraphic timing. The evolution measured by these data commenced after about 1840 Ma. Units in the east Arunta were transformed into a granulite terrane during the Strangways event that terminated at 1690 Ma; elements further to the west and north largely escaped this metamorphism, although structural and lower-grade thermal effects of this event may be traced into the more distal regions.

The detail of this timing and correlation framework has two major purposes. At a practical level, direct correlation of basement inliers now separated by later cover lends substance to exploration for mineral deposits under that cover, where it is sufficiently shallow. The wide area of covered basement between the richly mineralised Tanami and Tennant/Davenport regions is of particular interest in this regard, with both geophysical (Donnellan and Johnstone 2003) and geochronological evidence converging as a basis for extrapolating stratigraphy and structures. Second, these regionally applicable correlations and timings are constraints on geodynamic models for Proterozoic northern Australia, and they, in turn, link mineralisation to process and place.

Future work is likely to focus on the Tennant and Davenport areas. Application of modern dating techniques offers the potential to calibrate the stratigraphic and structural development of this little-metamorphosed inlier (*see Donnellan this volume*) with attractive precision (better than ± 5 Ma). This may then be used as a template to correlate into other regions which are metamorphically or structurally complex (Arunta Region), or poorly exposed (Tanami Region), or to the very large covered areas between them.

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A FRAMEWORK FOR THE PALEOPROTEROZOIC GEOLOGY OF THE TENNANT REGION

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The Tennant Region comprises the central Warramunga Province (original Tennant Creek Block), the Davenport Province to the south and southeast, and the Tomkinson Creek Province to the north. The Tomkinson Creek Province (Blake 1987) has previously inappropriately been called the Ashburton Province by Donnellan *et al* (1995). The framework presented here is based on First Edition 1:100 000 and Second Edition 1:250 000 mapping, undertaken: (1) collaboratively by BMR[2] and NTGS in the Davenport Province and southernmost Warramunga Province (1981–1983); (2) by NTGS in TENNANT CREEK[3] (1989–1993) and HELEN SPRINGS (1995–1997); and (3) by NTGS in BARROW CREEK (1981–1988). It is further based on the interpretation of semi-regional airborne magnetic (and BMR regional gravity) data (Johnstone and Donnellan 2001, and Donnellan and Johnstone 2004). These magnetic data were collected over TENNANT CREEK by AGSO in 1998 and over BONNEY WELL, FREW RIVER and ELKEDRA by NTGS in 1999. The data were stitched with those of a 1981 survey over BARROW CREEK and a 1993 survey of HELEN SPRINGS to complete coverage of the Tennant Region. The lithostratigraphic framework outlined below is summarised in **Figure 1**.

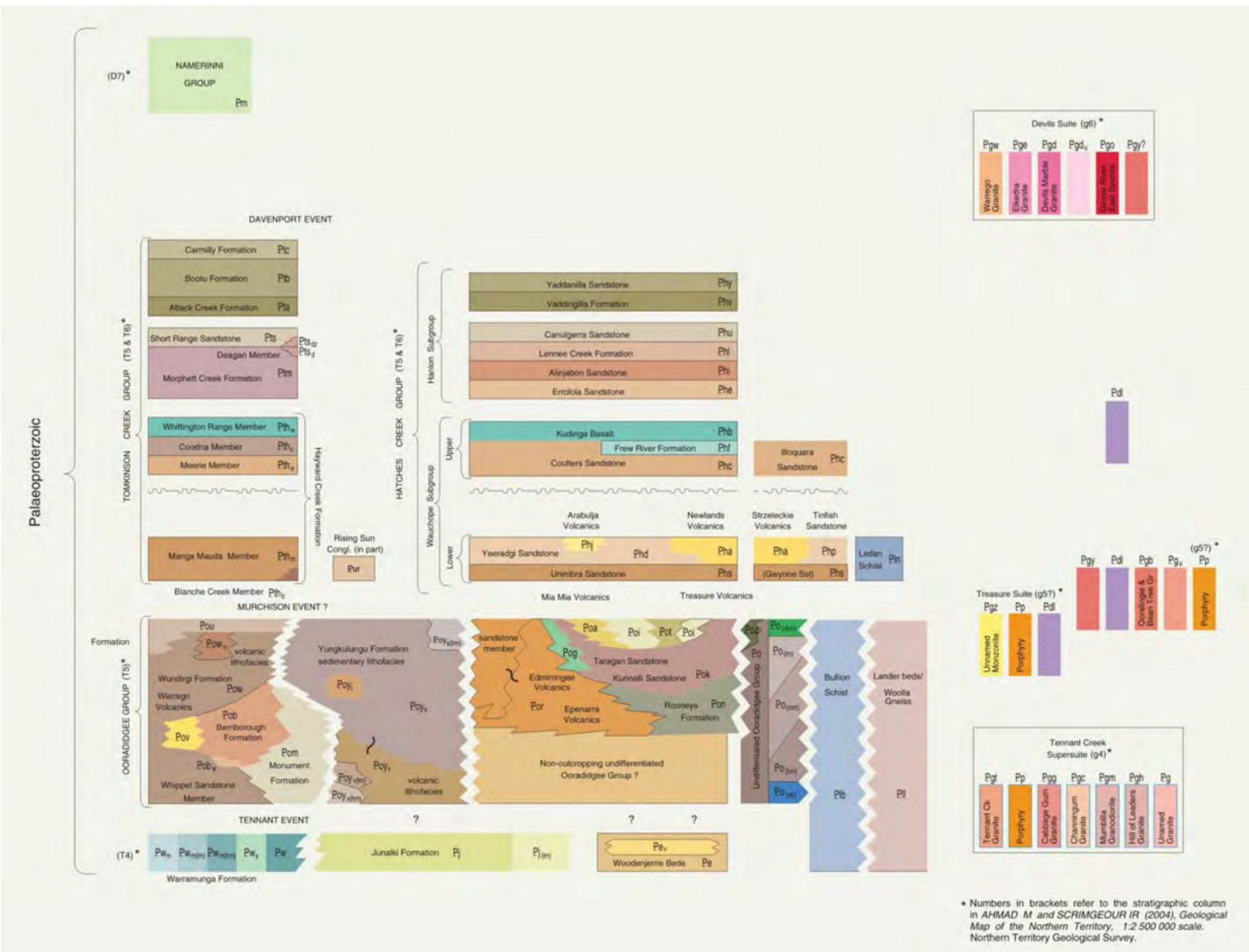

Figure 1. Lithostratigraphic framework of the Tennant Region (from Donnellan and Johnstone 2004).

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[3] Names of 1:250 000 mapsheets are in CAPITALS.

Lithostratigraphic framework

Mapping in the Davenport Province in the 1980s resulted in formalisation of the Hatches Creek Group, and defined three constituent subgroups (Ooradidgee, Wauchope and Hanlon), twenty formations and two members (Blake *et al* 1984, 1987 and 1988). This work confirmed that differences in folding between Warramunga Group and Hatches Creek Group rocks in the north of the Davenport Province were associated with a major angular unconformity. Blake *et al* (1987) recognised that the Epenarra Volcanics, the basal unit of the Ooradidgee Group in the north of the Davenport Province, overlay an irregular topography on folded and eroded Warramunga Group rocks in the Murchison Ranges. Donnellan and Johnstone (2004) later called this early folding the Tennant Event. Hatches Creek Group rocks show concentric northwest-trending, and superimposed northeast-trending folding (Stewart in Blake *et al* 1987). Both of these phases of folding are attributed to a second major deformation that is now called the Davenport Event.

First Edition mapping in TENNANT CREEK concluded that the Tomkinson Creek beds (correlatives of the Wauchope and Hanlon subgroups of the Hatches Creek Group) overlay Warramunga Group rocks with a local unconformity (see Dodson and Gardener 1978). Blake (1984) recognised an erosional unconformity between folded greywackes, and overlying volcanic rocks in the vicinity of Rising Sun Ridge to the southeast of Nobles Nob mine. Furthermore, Blake (1984) correlated rocks outcropping in the vicinity of the Last Hope mine in northwest TENNANT CREEK with the Ooradidgee Subgroup. These rocks were subsequently assigned to the Brumbreu Formation by Donnellan *et al* (1991, 1995).

In determining a stratigraphy for TENNANT CREEK, Donnellan *et al* (1991, 1995) reasoned that:

1. rocks included in the Warramunga Group should show evidence of deformation in both the Tennant and Davenport events
2. rocks that could be demonstrated to be conformable (or disconformable) with respect to the Tomkinson Creek beds were part of that succession.

Greywackes and siltstones, underlying the unconformity recognised by Blake (1984) near Nobles Nob, were mapped as part of a widespread, at least in part tuffaceous (turbiditic), succession throughout the Tennant Creek goldfield and defined as the Warramunga Formation (Donnellan *et al* 1991, 1995). This unit also includes argillaceous banded ironstone that is known locally as 'haematite shale.' The old group name Warramunga was retained for this lithostratigraphic unit in TENNANT CREEK for historical reasons. It hosts the important Tennant Creek-style, massive ironstone-associated, Cu-Au deposits of the Tennant Creek goldfield.

Rocks of the Warramunga Formation show open to close folding about east–west-orientated fold axes, and have a well developed axial planar slaty cleavage. This phase of folding and associated foliation is attributed to the Tennant Event. There are two overprinting crenulation cleavages, and associated meso- to macro-scale kink bands, in the Warramunga Formation that are interpreted to be an expression of the Davenport Event.

Rocks overlying the unconformity were similarly mapped as part of a widespread thick succession of volcanic rocks, and overlying and intercalated sedimentary rocks that were defined as the Yungkulungu Formation. The Yungkulungu Formation shows more open folding and is interpreted to unconformably overlie more tightly folded Warramunga Formation sedimentary rocks throughout the area to the east of Rising Sun Ridge, in the vicinity of the Yungkulungu Ridge, Gosse River and Golden Mile. The Yungkulungu Formation was therefore excluded from the Warramunga Group.

In northwestern TENNANT CREEK, the Brumbreu Formation has a conformable and apparently transitional relationship with the Wundirgi Formation, which in turn is conformable with the Warrego Volcanics. All of these lithostratigraphic units were therefore excluded from the Warramunga Group.

A conformable succession of rocks in central TENNANT CREEK, comprising the Monument and Bernborough formations (including the Whippet Sandstone Member), have no outcropping relationships that definitively indicate their stratigraphic affinities. However, a predominantly subaerial volcanic succession in the Bernborough Formation is correlated with the Warrego Volcanics and the volcanic lithofacies of the Wundirgi Formation. The entire succession (ie Monument and Bernborough formations) can be correlated with the Yungkulungu Formation. Both of these successions include volcaniclastic sedimentary rocks that were deposited in generally shallow water environments. Subaqueous volcanic rocks occur in the lower part of the Yungkulungu Formation, and somewhat deeper water sediments occur in the lower part of the Monument Formation.

Donnellan *et al* (1991, 1995) excluded all the above volcano-sedimentary units (ie Yungkulungu, Monument, Bernborough, Wundirgi and Brumbreu formations together with the Warrego Volcanics) from the Warramunga Group and defined them as the Flynn Subgroup. The Flynn and Ooradidgee subgroups were broadly correlated. The Tomkinson Creek beds were formalised as the Tomkinson Creek Subgroup and combined with the Flynn Subgroup in the (now defunct) Churchills Head Group. Mapping of the Tomkinson Creek Subgroup in TENNANT CREEK and HELEN SPRINGS confirmed its lithostratigraphic parallels with the Wauchope and Hanlon Subgroups.

The Junalki Formation outcrops in central-southern TENNANT CREEK. It was originally tentatively correlated with the Yungkulungu Formation (Donnellan *et al* 1995), but was subsequently re-interpreted to be part of a more extensive succession of rocks in BONNEY WELL and FREW RIVER (Johnstone and Donnellan 2001) and correlated with the Warramunga Formation.

Included in the former Warramunga Group are the Junalki Formation and the Woodenjerrie beds, in the Murchison Ranges and immediately to the north of the Davenport Ranges in BONNEY WELL and FREW RIVER. These two units have different total magnetic intensities that are probably, in part, a consequence of the relative proportion of volcanics intercalated with sedimentary rocks. These rock units are broadly correlated with the Warramunga Formation in TENNANT CREEK, but are assigned different names because they generally lack the discrete magnetic anomalies associated with the Warramunga Formation. They do contain argillaceous banded ironstone. These lithostratigraphic units (Warramunga and Junalki formations, and Woodenjerrie beds) have not yet been combined in a group.

The Flynn and Ooradidgee subgroups were subsequently combined in the Ooradidgee *Group* (Donnellan *et al* 2001). This volcano-sedimentary succession is characterised (in outcrop) by lateral variations, interdigitation and partial correlation between constituent formations around localised volcanic centres. This is in contrast with the layer cake stratigraphy of the overlying Wauchope and Hanlon subgroups (ie the redefined Hatches Creek Group), and the similarly redefined Tomkinson Creek *Group* in the Davenport and Tomkinson Creek provinces, respectively. A lithostratigraphic correlation between the Tomkinson Creek and Hatches Creek groups is well founded. Contemporary airborne magnetic data (see below) indicate probable continuity of the two groups under cover to the east and west of TENNANT CREEK. However, pending geochronological corroboration, the two groups have not yet been combined.

Magmatism

Magmatism that is broadly syn-, to post-tectonic with respect to the Tennant Event has been assigned to the Tennant Creek Supersuite (eg Tennant Creek Granite, Mumbilla Granodiorite and Hill of Leeders Granite) by Wyborn *et al* (1998). These authors further assigned the Elkedra, Devils Marbles and Warrego granites to the ~1720 Ma Devils Suite, and felsic volcanics (eg Treasure, Arabulja and Newlands Volcanics), unnamed porphyry, granophyre, and monzodiorite-diorite to the Treasure Suite.

Tennant Event

This event resulted in predominantly east–west, open to close folding in the Warramunga and Junalki formations, and the Woodenjerrie beds, with development of an axial planar slaty cleavage. Unconformable relationships indicate this episode of folding probably predates deposition of the Ooradidgee Group.

Davenport Event

Northwest-, and overprinting northeast-trending folding (Davenport Event), classically expressed in the Davenport Province, apparently predates intrusion of the Elkedra Granite of the 1720 Ma Devils Suite (Blake *et al* 1987). Folding, interpreted to be contemporaneous, trends northwest and more northerly in the Tomkinson Creek Province. Stewart (1987) concluded that the Hatches Creek Group was folded concentrically about three competent units, the Unimbra, Coulters and Errolola sandstones. Less competent units above the Errolola Sandstone (Alinjabon Sandstone and Lennee Creek Formation) and below the Unimbra Sandstone (Kurinelli Sandstone) folded disharmonically with respect to the succession bounded by these two sandstones. Similar disharmonic relationships probably explain shorter wavelength folding in the Wundirgi Formation, and in the upper Morphett Creek Formation (above the lowermost sandstone interval which is correlated with the Errolola Sandstone) of the Tomkinson Creek Group.

Murchison Event

The relationship between Ooradidgee Group rocks and those of the Wauchope Subgroup and Tomkinson Creek Group is variable and may be: conformable and apparently transitional; disconformable; unconformable; or an angular unconformity with localised (synsedimentary) folding of the Ooradidgee Groups rocks. Locally, there is a foliation that is probably contemporaneous with this folding.

The Murchison Event is interpreted to correspond with the change to a layer-cake stratigraphy, at the base of the Unimbra Sandstone in the outcropping Davenport Province and at the base of the correlative Manga Mauda Member of the Hayward Creek Formation in the Tomkinson Creek Province. The Unimbra Sandstone in the Davenport Province has been interpreted to record a marine transgression (and subsequent regression) from the east (Sweet in Blake *et al* 1987). It variably overlies the Treasure, Edmirringie and Epenarra Volcanics, Taragan Sandstone, Woodenjerrie beds and Junalki Formation. The correlative Manga Mauda Member of the Tomkinson Creek Province is interpreted to be predominantly fluviatile. Whereas the Unimbra Sandstone locally interfingers with the Treasure Volcanics, there may be a more pronounced hiatus recorded to the north beneath the Manga Mauda Member, and reflected in the conglomeratic Blanche Creek Member. Fluviatile sedimentation and reworking of Warramunga Formation (and Ooradidgee Group) rocks in the Tomkinson Creek Province at this time contrast with apparently continuous sedimentation between the Treasure Volcanics and Unimbra Sandstone in the southeastern Davenport Province. These relationships probably reflect uplift in the northwest and subsidence in the southeast, and/or regional tilting.

There are apparently no correlatives of the Treasure and Newlands/Arabulja/Strzelecki volcanics of the Davenport Province in the Tomkinson Creek Province. This can be explained by:

1. the localised distribution of the Arabulja Volcanics in the vicinity of the Murray Downs Dome
2. both the Treasure and Newlands Volcanics are thicker in the central and eastern Davenport Province and absent to the northwest in the Murchison Range area. The Strzelecki Volcanics are confined to the Taylor and Crawford ranges, but are correlated with the Newlands Volcanics. Thus, volcanic activity at this time is apparently localised more to the south of the Davenport Province.

The Yeeradgi Sandstone is thickest in the Kurundi Region[4], and unconformably overlain by the Coulters Sandstone in the west of this region (Stewart and Blake 1986). Haines *et al* (1991) identified a disconformity at the base of the Illoquara Sandstone, and possibly also at the base of the correlative Coulters Sandstone, in BARROW CREEK. Thus, a second hiatus, a disconformity, can be interpreted in the lower Wauchope Subgroup throughout much of the Davenport Province, but is possibly of longer duration in the northwestern Davenport Province, and probably longer again in the Tomkinson Creek Province. Ahmad and Scrimgeour (2004) indicated that this is a major time break on their geological map of the Northern Territory.

Younger successions

In the northern Tomkinson Creek Province, the Namerinni Group overlies the Tomkinson Creek Group with an angular unconformity, and is correlated with the McArthur and McNamara groups (Hussey *et al* 2001). The Namerinni Group is not discussed further here. Locally in outcrop, late Neoproterozoic/Palaeozoic rocks of the Georgina and Wiso basins unconformably overlie Palaeoproterozoic rocks of the Tennant Region.

The Rising Sun Conglomerate is of limited contemporary geographical distribution, and apparently confined to a largely fault-bounded block, south and southeast of Nobles Nob mine in TENNANT CREEK. It mainly comprises a succession of polymictic conglomerate, sandstone, and (probable tuffaceous) siltstone in the vicinity of Rising Sun Ridge. It has been variously correlated with: the Blanche Creek Member (Crohn and Oldershaw 1965); sedimentary rocks of the Epenarra Volcanics and Unimbra Sandstone, together with the unconformably overlying Ediacaran Andagerra Formation (Blake 1984); and the Andagerra Formation and Helen Springs Volcanics (Donnellan *et al* 1995). Crohn and Oldershaw (1965) identified an intrusive lamprophyre sill in the upper part of the Rising Sun Conglomerate succession. This would suggest a pre-1690 Ma age for this whole succession and indicates that a correlation with the Tomkinson Creek and/or Hatches Creek groups is probable. Unfortunately, Crohn and Oldershaw (1965) did not give a grid reference for the lamprophyre and subsequent workers have not yet corroborated their observation. However, many of the pebbles and boulders in the Rising Sun Conglomerate suggest a Tomkinson Creek/Hatches Creek group provenance, in contrast with the likely Warramunga Formation/Ooradidgee Group provenance of clasts in the Blanche Creek Member. The Rising Sun Conglomerate also includes reworked conglomeratic clasts (Ivanac 1954, Crohn and Oldershaw 1965). It is possible that the conglomerate could reflect tectonic rejuvenation during Hatches/Tomkinson creek group times, with reworking of earlier parts of the succession. Correlation with conglomeratic units in the Jeromah or Gleeson formations, respectively, at the base of the Namerinni and Renner groups, are possible, but not considered very probable.

Interpreted geological framework, extending the lithostratigraphy under cover

High-quality, semi-regional (200 m line-spaced) airborne magnetic (and radiometric) data were collected over TENNANT CREEK by AGSO in 1998. An interpretation of these data together with the 11 km-spaced BMR gravity data was integrated with the mapped geology, resulting in an interpreted 1:250 000 scale map of the Palaeoproterozoic geology of TENNANT CREEK (Johnstone 2001, Johnstone and Donnellan 2001).

Airborne magnetic coverage was extended over BONNEY WELL, FREW RIVER and ELKEDRA (200–400 m line-spaced coverage) in 1999. These data were stitched with those of a 1981 survey over BARROW CREEK and a 1993 survey of HELEN SPRINGS. An interpretation of these airborne magnetic data and 11-km spaced BMR gravity data was integrated with mapped geology to produce a 1:500 000-scale interpreted Palaeoproterozoic geology map of the Tennant Region (Donnellan and Johnstone 2004).

Hone (in Blake *et al* 1987) had previously recognised that magnetic units, mafic and felsic volcanics, and mafic sills alternate with non-magnetic (sedimentary) rock units in the Hatches Creek Group. He consequently concluded that:

1 mapped stratigraphy can be extended under cover
2 anomalies parallel the strike of bedding, enabling major structures to be recognised
3 the Hatches Creek and Tomkinson Creek groups have similar magnetic character and can be linked subsurface to the west of TENNANT CREEK in GREEN SWAMP WELL.

These characteristics greatly facilitated the interpretation of the new generation of high-quality airborne magnetic data.

[4] 100 000-scale special geological map.

‘Late’ granites, ie Devils Suite, are generally readily recognisable in the geophysical data. These granites form discrete, sub-circular non-magnetic features associated with marked gravity lows. Granites of the Tennant Creek and Treasure suites are more difficult to assign using semi-regional geophysical data. Both have magnetic characters apparently attributable to rafts or screens of non-assimilated country rock. In general, the Tennant Creek Supersuite granites are apparently localised in the Warramunga Province.

Hone (in Blake *et al* 1987) reported that Tucker *et al* (1979) recognised that Hatches Creek Group geology may extend for up to 300 km to the east of the Davenport Ranges under the Georgina Basin. A Northern Territory-wide stitch of airborne magnetic data (Clifton 2004) indicates that continuity between the Hatches Creek and Tomkinson Creek groups is likely to the east (as well as to the west) of TENNANT CREEK. In the airborne magnetic data, the strike of these two groups, to the east and west of TENNANT CREEK, is apparently close to parallel. To the west of TENNANT CREEK, the strike is approximately northwest (in GREEN SWAMP WELL) and to the east (in ALROY and BRUNETTE DOWNS), it is approximately northeast. These airborne magnetic data have not yet been interpreted in detail and, therefore, these relationships have yet to be substantiated.

Conclusions

Mapped lithostratigraphy and lithostratigraphic correlations within the Tennant Region allow a reasonably coherent, geological framework for the region to be deduced. This has been extrapolated under cover using geophysical data. In addition, it can be reasonably concluded that in the Tennant Region:

1. The Tennant Event predates deposition of the Ooradidgee Group and resulted in approximately easterly oriented folding in the Warramunga and Junalki formations and Woodenjerrie beds, and in an axial planar slaty cleavage. Syn to post-tectonic magmatism (eg the deformed Tennant Creek Granite of the Tennant Creek Supersuite) is associated with this event.
2. The Murchison Event is a regionally widespread event resulting in tilting and/or uplift in the north, and subsidence in the south and southeast of the Tennant Region. Bimodal magmatism (Treasure Suite) pre- and postdated the Murchison event.
3. The Davenport Event resulted in concentric folding about northwest- and northeast-oriented fold axes in the Davenport province, and northwest- and more northerly-oriented axes in the outcropping Tomkinson Creek Province. This deformation is expressed in the Warramunga Province as two crenulations and associated macro-scale kink bands in the Warramunga Formation; and as open concentric folding, and disharmonic folding, in overlying Ooradidgee Group rocks. The Devils Suite (1720 Ma) probably postdates the Davenport Event. Future work will focus on providing SHRIMP U-Pb chronological constraints on the lithostratigraphic framework presented above (*see Claoué-Long et al, this volume*).

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COMMON THREADS IN THE PINE CREEK, TANAMI AND TENNANT CREEK AU-MINERAL SYSTEMS: CAN WE SEW UP NEW EXPLORATION STRATEGIES?

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Overview

A spatial link between granitic intrusions and significant gold deposits has long been recognised in the Pine Creek, Tanami and Tennant Creek areas. However, both locally in these areas and globally in similar systems, there have been protracted debates as to whether or not the spatially-related granitic intrusions are an essential ingredient in the formation of adjacent gold deposits. Nonetheless, it is increasingly being accepted that granite intrusions can play an important role and a new class of granite-related conceptual exploration models are now emerging. The two best known are Thermal Aureole Gold (TAG, Wall and Taylor 1990) and Intrusion-Related Gold (IRG, Sillitoe and Thompson 1998).

Key ingredients in the TAG or IRG models are ilmenite- to magnetite-stable granitic intrusions and fluids to transport the metals from these granites to the sites of deposition. The depositional sites are commonly not within the intrusion itself, and deposits can occur up to 5 km from the granite boundary. Wall (in press) noted that this style of deposit is commonly located in the tops and roof zones above plutons, frequently occurring in anticlinorial zones. Globally significant gold deposits that have been assessed as TAG or IRG types include Muruntau (>3000 t), Fort Knox (>175 t), Pogo (177 t) Obuasi (>1500 t) and Campbell-Red Lake (>770 t) (Thompson and Newberry 2000, Wall in press).

It is the aim of this paper to benchmark the district- to regional-scale parameters of gold mineralisation in the Pine Creek, Tanami and Tennant Creek areas against these conceptual models and note any implications for exploration strategies. This review will consider some other NT provinces, but not the Arunta Region, as insufficient details on the granites and sedimentary/metamorphic successions are currently available to confidently predict the location of potential TAG or IRG environments.

Regional-scale patterns in granite types and common threads

In a review of Australian Proterozoic granites, nine fundamental associations were identified. With two of these associations, the Cullen and the Hiltaba, significant hydrothermal Au, Cu, Zn, Pb, Sn, W and Mo mineralisation occurs within 5 km of the boundaries of plutons (Wyborn 2003). Both of these associations comprise high-temperature granite melts that formed at <30 km in the crust. However, the Cullen Association is characterised by Au ± Sn, W, Bi, Cu, and U, whereas the Hiltaba Association is spatially related to Cu + Au ± Ag ± U mineralisation. The Hiltaba Association, regarded as having formed at higher temperatures than the Cullen Association, will not be considered further in this paper.

In the NT, the Cullen Association was identified in the Pine Creek (Cullen Supersuite), Tanami (Granites Supersuite) and Tennant Creek-Davenport areas (Treasure Suite). In these areas, the granites can range from mafic diorites and granodiorites to highly fractionated Rb-rich leucogranites. As is typical of TAG or IRG models, granites in the Pine Creek and Tanami have low Fe_2O_3/FeO ratios, with Pine Creek having the lowest ratio. In contrast, granites of the Tennant Creek area are all magnetite-stable. Cullen Association granites have not been identified in the Litchfield area, eastern Pine Creek Orogen, Arnhem Block, or McArthur Basin. None of these areas have significant Au mineralisation.

Regional-scale patterns in fluid types and common threads

The fluids associated with Au mineralisation in the Pine Creek, Tanami and Tennant Creek areas are compatible with a magmatic origin, although it is noted that in all areas, the $\delta^{18}O$ of the fluids also overlap with fluids of a metamorphic origin. There are some regional variations in the ore-fluid compositions.

In the Pine Creek Orogen, Wygralak and Ahmad (1990) reported fluid inclusion homogenisation temperatures of 200–300ºC. The fluids had moderate salinities of 7–14 wt% NaCl eq, were weakly acidic and contained mostly CO_2 with minor CH_4. However, Matthai *et al* (1995) reported that the formation of the Cosmopolitan Howley deposit was associated with a weakly acidic, oxidised magmatic brine at temperatures in the range 550–620ºC. This may represent the high temperature end-member of the system at Pine Creek.

There were two important stages of fluid flow at Tennant Creek. The first involved precipitation of the barren magnetite-rich ironstones. A wide range of homogenisation temperatures have been reported from fluid inclusions in the ironstones (150–350ºC, Zaw *et al* 1994) and reported salinities vary from 10–26 wt% NaCl eq. No gases have been reported in these fluids. Their high salinities and log fO_2-pH plots indicate moderately acidic fluids capable of transporting high concentrations of iron. The composition of the later mineralising fluids seems more variable and several authors (eg Huston *et al* 1993, Skirrow and Walshe 2002) have invoked fluid mixing between oxidised (hematite-stable) and reduced (pyrrhotite-stable) end-member fluids. The reduced fluids are weakly acidic, have salinities of 20–36 wt% NaCl eq and contain N_2 with minor CH_4. The oxidised fluids are thought to be associated with the Au-rich deposits. They are also weakly acidic, with lower salinities (0–10 wt% NaCl eq) and contain N_2 with minor CO_2. Reported homogenisation temperatures for these deposits vary widely, but the majority lie in the range 250–350ºC.

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In the Tanami Region, the fluid inclusions associated with mineralisation homogenise over the range 200–430ºC. The fluids are weakly acidic and salinities typically range from 0–14 wt% NaCl eq, although salinities up to 21 wt% NaCl eq have been reported from the Tanami goldfield (Mernagh and Wygralak 2005). The gas composition of the fluids appears to vary with the depth of the deposit. Deeper deposits contain $CH_4 \pm CO_2$, whereas intermediate deposits contain $CO_2 \pm N_2 \pm CH_4$ and high-level deposits contain little or no gases.

In summary, the fluids are generally weakly acidic, but vary from moderately oxidised to moderately reduced. Higher salinities have been recorded at Tennant Creek where N_2 is more common. Mineralisation temperatures in the Tanami generally overlap with those of Tennant Creek, but salinities are typically lower (<14 wt% NaCl eq) and higher amounts of CO_2 and CH_4 occur in the fluids. With the exception of the Cosmopolitan Howley deposit, the lowest temperatures occur at Pine Creek, where the fluids have similar salinities to those in the Tanami, but are mainly enriched in CO_2.

Interaction of these fluids with iron-rich rocks (eg ironstone, Banded Iron Formation (BIF), mafic igneous rocks (basalt, dolerite, gabbro), or carbon-rich rocks (eg carbonaceous siltstone and shale) will enhance Au deposition. Alternative mechanisms for deposition are pressure release leading to phase separation and/or fluid mixing with meteoric fluids at higher levels. This style of deposit would occur in more competent rock types (eg turbidites, mafic intrusive rocks) due to their more brittle nature.

Regional scale patterns in host rocks types and common threads

Ahmad *et al* (1999) reported on the time-space distribution of gold deposits in the NT. They noted that with the exception of the White Range Goldfield in the Arunta Region (hosted within the Neoproterozoic Heavitree Quartzite), most gold production has been from the Palaeoproterozoic orogenic domains. They proposed that the separate Palaeoproterozoic provinces may have been formed in a single superbasin. The oldest sedimentary cycle in this superbasin can be divided into three phases of differing tectono-stratigraphic character:

- An early rift phase comprising fluviatile sediments and some minor mafic volcanics. This phase is only recognised in the Pine Creek Orogen (Namoona and Mount Partridge Groups).
- An overlying sag phase, which includes pyritic carbonaceous shale, chert, siltstone, tuff, carbonate and Banded Iron Formation (BIF). This sag phase is found in the Pine Creek Orogen (South Alligator Group) and the Tanami Region (Dead Bullock Formation).
- An upper flysch phase, which is found in all gold-bearing Palaeoproterozoic provinces. In Pine Creek, this comprises the Finniss River Group; in the Tanami Region, the Killi Killi Formation; and in the Tennant Creek area, the Warramunga Formation.

Significant mineralisation is found in the sag and flysch phases. The sag phase contains the greatest abundance of rocks with reactive minerals that can enhance Au deposition. Across the three areas, the sag phase shows the greatest variability. In the Tanami Region, the sag phase comprises deeper-water chert, carbonaceous shale and iron formations; carbonate rocks are virtually unknown. In the Pine Creek Orogen, the sag phase was deposited in shallower water; banded iron formation is more common and carbonate-rich rocks are also present. In the Tennant Creek area, Ahmad *et al* (1999) suggested that the sag phase could be represented by haematitic shale which occurs within the Warramunga Formation.

The older Palaeoproterozoic sedimentary cycle was deformed and intruded by granites, and in places, unconformably overlain by a second sedimentary cycle, which comprises thick successions of felsic volcanic rocks, clastic sediments and minor mafic volcanic rocks. Some mineralisation is hosted in these overlying successions (eg the Tanami goldfield in the Mount Charles Formation).

All successions are intruded by dolerite and in some areas, these dolerites host mineralisation. Some reactive host rocks are also created by deformation and in Tennant Creek, most deposits are hosted in magnetite bodies that were formed during an earlier deformation.

Many of these reactive host rocks occur elsewhere in the NT and also in the Halls Creek Orogen of Western Australia. However, significant gold mineralisation seems only to occur where these successions are intruded by granites of the Cullen Association.

The composition of the sediments themselves also appears to influence the redox of the granites, and in turn, the related metallogeny of the provinces. Many of the granites in the Pine Creek and Tanami areas are more reduced than those of the Tennant Region, particularly in areas where the country rocks contain carbonaceous sediments. In contrast, in the Tennant Region, where there are no carbonaceous sediments, all granites are oxidised and magnetite stable.

Regional-scale patterns in ore grades, tonnages and metals, and common threads

A compilation of production and reserves in each of the three areas shows that there are fundamental differences in the various metals present. Pine Creek has the widest diversity of metals related to granite intrusions and includes Sn, Ta, W, Pb, Zn, Ag, Cu and iron ore. Tennant Creek has Cu, Bi, W, Ag and iron ore, whereas the Tanami region only has Au.

We suggest that although the type of granite in these three provinces is a common thread, the combination of both different host rock types and fluid compositions is controlling these metal associations. The host rock types are most varied in the Pine Creek Orogen. The presence of carbonates permits the development of skarn-style deposits and possibly controls the distribution of base-metals. In Tennant Creek, where the sediment hosts are more oxidised and the fluid salinities are higher, Fe, Cu and Bi are more common; carbonaceous sediments have not been recorded. The Tanami Region has more carbonaceous shales and the area is Au dominant. Significant carbonate has not been recorded in either Tennant Creek or Tanami.

The style, grade and tonnages of the individual deposits also varies with host rock stratigraphy. As noted by Ahmad *et al* (1999), gold-quartz veins, lodes, sheeted veins, stockworks and saddle reefs are usually contained within turbidites, but there are also a few occurrences in intermediate to basic volcanic and intrusive rocks. The grade in this style is low (<3 g/t), but tonnages can be high (0.5–50 Mt). In contrast, gold deposits hosted in ironstone bodies, the predominant style in the Tennant Creek area, have much higher grades (~20 g/t), but the tonnages are lower. Gold deposits that occur in iron-rich hosts in the sag phase have grades and tonnages intermediate between the other two types.

Exploration implications

Historically, Au deposits in Pine Creek, Tennant Creek and Tanami were not considered to be world class and, hence, not major exploration targets. The discovery of Callie, which contains 30 Mt at a grade of 5.5 g/t (165 t contained Au), showed that at least the Tanami area is prospective for world-class deposits. Given some similarities between Pine Creek and Tanami, we suggest that both of these provinces make very prospective targets for further discoveries of IRG or TAG deposit types.

Current exploration in the Tanami is focusing on sediments that host Callie, ie the sag-phase sediments. Coyote is the only significant deposit in the overlying turbidites. In contrast, in Pine Creek, a greater tonnage of gold has been found in the turbidites (Ahmad *et al* 1999) and recent exploration has not been as focused on the more iron-rich rocks of the sag phase. We suggest that exploration in both areas should consider both sedimentary phases, with specific focus being on the structurally attractive roof zones above flat plutons, particularly in anticlinorial zones. We also note that given the low pH of the fluids in these terranes, the presence of carbonate rocks in the Pine Creek Orogen could enhance permeability and porosity.

In the Tennant Region, if lateral facies equivalents of the more reactive iron-rich or carbonaceous rock types that occur in Tanami and Pine Creek can be located, then this would greatly improve the prospectivity of this province for TAG- or IRG-style mineralisation. Some quartz vein mineralisation does occur in the Tennant Region (eg Last Hope and Bull Pup), but as the geophysical expression of this style would be vastly different from the more common ironstone-hosted deposits, exploration strategies would have to be adjusted.

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NEW CONSTRAINTS ON THE TIMING OF DEPOSITION AND MINERALISATION IN THE TANAMI GROUP

Andrew J Cross[1, 2], Ian R Fletcher[3], Andrew J Crispe, David L Huston[2] and Nick Williams[2]

Recent years have seen a sustained commitment by the Northern Territory Geological Survey and Geoscience Australia to isotopically date the event history of the Tanami Region. These studies have primarily used SHRIMP U–Pb zircon and, to a lesser extent, $^{40}Ar/^{39}Ar$ techniques (see Cross *et al* 2003, Smith *et al* 2001, Fraser 2002). Here, we report our ongoing results and the tectonic significance of recent SHRIMP U–Pb zircon studies of two sediments and a tuffaceous unit within the Dead Bullock Formation. We also report the results of recent SHRIMP U–Pb *in situ* dating of ore-related hydrothermal xenotime from the Callie deposit that challenges the approximately 1720 Ma age of mineralisation suggested by Fraser (2002).

New stratigraphic constraints and **tectonic interpretations**

The basal Tanami Group consists of two units, the Dead Bullock Formation and conformably overlying turbidites of the Killi Killi Formation. The Dead Bullock Formation is host to the giant Callie lode Au deposit. This unit is a thick package of siltstone, carbonaceous siltstone, iron formation and minor sandstone that is divided into the Ferdies Member (older) and Callie Member (younger).

The Killi Killi Formation is a part of a widespread northern Australian turbidite package. Four samples from this unit have remarkably similar detrital zircon age patterns. Each is dominated by an 1865 Ma age mode and has a subordinate late Archaean mode at 2.5 Ga (see Cross *et al* 2003). The 1865 Ma age mode coincides with peak magmatism associated with the Hooper Orogeny. The youngest zircons in the Killi Killi Formation consistently indicate a maximum depositional age of 1.84 Ga.

Recent SHRIMP U–Pb detrital zircon studies from two Ferdies Member samples from the Dead Bullock Formation show them to be markedly different to those from the overlying Killi Killi Formation. One sample is dominated by zircon 2.56–2.44 Ga old, and the other contains Archaean components with ages of 3.22 Ga, 2.77 Ga and 2.45 Ga. These detrital zircon age components suggest derivation from either the Pilbara Craton in Western Australia and/or the Rum Jungle region in northern Australia. The youngest zircons from the Ferdies Member imply that this unit was deposited after 2.44 Ga and possibly after 2.11 Ga. However, these detrital zircon ages may be poor estimates of the depositional age. A depositional age of 1.91–1.88 Ga is suggested by a possible correlation with the Saunders Creek Formation in the nearby Halls Creek Province.

The oldest well constrained age for the Tanami Group comes from a tuff intercalated with the Callie Member. This tuff gives an age of 1838 ± 6 Ma (95% conf), which constrains the age of the Callie Member and provides a minimum age for the underlying Ferdies Member. This age is similar to the Inspiration Peak Monzogranite (1844 ± 4 Ma) in the Tanami Region and bimodal volcanics of the Koongie Park Formation (1843 ± 2 Ma, Page *et al* 1994), in the central zone of the Halls Creek Orogen.

Given the similarities to the Halls Creek Orogen, it is possible that the Palaeoproterozoic Tanami basin developed in response to uplift associated with the beginning of the 1.88 Ga Hooper-Nimbuwah Orogeny. Initial uplift and erosion of Archaean basement rocks produced sediments now represented by the Ferdies Member of the Dead Bullock Formation. However, it was up to 40 my later before the plutonic products of that magmatism were exposed, eroded and transported to form the Killi Killi Formation. A similar significant age contrast in detrital zircon between basal and overlying sediments shed from an orogen has been observed by McLennan *et al* (2001), in lower Palaeozoic rocks in the New England region of North America. These researchers also reported that the oldest sedimentary successions do not record contemporaneous orogenic activity, but rather reflected older recycled continental margin rocks. Detrital zircon studies thus suggest that the first sediments shed from an emerging orogen might not record contemporaneous magmatism, but rather represent the eroded products of uplifted basement rocks.

***In situ* SHRIMP U–Pb dating of ore-related hydrothermal xenotime from the Callie deposit**

SHRIMP U–Pb dating of ore-related hydrothermal xenotime (YPO_4) has in recent years gained credibility as a robust technique that can be used to constrain evolutionary and exploration models (Şener *et al* 2003, Vielreicher *et al* 2003 and references therein). The success of this technique is underpinned by the high spatial resolution and precision achievable by SHRIMP and the unique properties of xenotime which make it a good geochronometer. Advantages in using xenotime as a geochronometer include low initial Pb contents, the ability to self anneal radiation damage (Harrison *et al* 2002, Fletcher *et al* 2000) and a closure temperature greater than 750°C (Dahl 1997). Hydrothermal xenotime commonly occurs as small (<100 µm and commonly <10 µm) crystals (Vielreicher *et al* 2003). The high spatial resolution of SHRIMP can target these tiny grains in polished thin sections and thus maintain the textural integrity of the analysed material.

Gold at the Callie deposit occurs within quartz veins that form sheeted sets within a D_5 structural zone, where it cuts the D_1 Dead Bullock Soak anticlinorium. In addition to gold, these veins also contain pyrite, pyrrhotite, and arsenopyrite, as well as biotite, chlorite and minor carbonate gangue.

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A thin section of a gold-xenotime-bearing quartz vein sampled from Callie Mine drillcore was cut and mounted in the surface of an epoxy disc. Following reflected- and transmitted light photography and cathodoluminescence imaging, xenotime grains were analysed for U–Pb isotopes using SHRIMP B, which is housed at the Curtin University of Technology in Western Australia. The data were processed following the methods of Fletcher *et al* (2000). Pb/U ratios were normalised to the MG1 xenotime standard, which has a $^{206}Pb/^{238}U$ ratio of 0.07897, equivalent to an age of 490 Ma, and $^{207}Pb/^{206}Pb$ ratios were monitored using the Xeno1 standard, which has a $^{207}Pb/^{206}Pb$ age of 997 Ma (Fletcher *et al* 2004).

Hydrothermal xenotime occurs in the quartz vein as small (5–20 µm) equant, euhedral to anhedral, pale yellow-green crystals. No xenotime was observed outside of the quartz vein. A SHRIMP spot of 8 µm was used to wholly sample the xenotime grains, without overlapping onto adjacent minerals.

Seventeen SHRIMP analyses were carried out on xenotimes from within the quartz vein. Eight analyses have high common Pb contents and/or are greater than 10% discordant. These xenotimes have ambiguous compositions and the data are excluded from the pooled age calculation. The remaining concordant and near-concordant analyses combine to give a weighted mean $^{207}Pb/^{206}Pb$ age 1803 ± 19 Ma (95% confidence, MSWD = 0.57). This age is considered to closely represent the age of the host Au-bearing quartz vein and, by inference, the age of mineralisation at Callie.

This age is in contrast to the approximately 1720 Ma age of mineralisation, interpreted from $^{40}Ar/^{39}Ar$ studies of hydrothermal biotite from Callie and reported by Fraser (2002). Because of the inferred robustness of the U–Pb system in xenotime, we prefer an age of about 1800 Ma for gold mineralisation, although the results of Fraser (2002) are at present unexplained. Our 1800 Ma age is toward the younger end of the age range (1825–1790 Ma) recorded for Tanami granites. This is consistent with a genetic link between gold and granites, as has been suggested elsewhere in the Tanami Region by Tunks and Marsh (1998) and G Morrison (in Smith *et al* 1998).

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A REVISED LITHOSTRATIGRAPHIC FRAMEWORK FOR THE NORTHERN TANAMI

Andrew Crispe[1], Leon Vandenberg and Karin Orth[2]

In 2004, NTGS geologists continued fieldwork on the BIRRINDUDU[3] 1:250 000 basement mapping project in the northern Tanami Region. Field observations confirm that this area is economically prospective, as correlations with the better-documented stratigraphy from the southern and central Tanami have been made. Mapping is concentrating on Palaeoproterozoic low-grade metasediments and volcanics of the Tanami and Ware Groups, extending our existing knowledge of the Tanami stratigraphy to the north.

Fieldwork was conducted on an area in the central south of the mapsheet that incorporates rocks originally mapped by the Bureau of Mineral Resources (now Geoscience Australia) as Nongra beds. The various lithologies of this unit have now been separated into four stratigraphic units: the Dead Bullock and Killi Killi formations, an as-yet unnamed sandstone and an unnamed volcanic package.

Southern exposures of the Dead Bullock Formation in BIRRINDUDU consist of ferruginous silt and nodular chert that flank wide, ferricrete-capped rises, reminiscent of the outcrop at Dead Bullock Soak. Outcrop to the north consists of thickly bedded, contorted ferruginous chert and BIF, an intervening siltstone, and thinly bedded chert and siltstone. It is possible that this outcrop may be an equivalent of the jasper chert member within the Killi Killi Formation. Outcrop in the 'Nongra beds' area is predominantly cleaved and crenulated Killi Killi Formation greenschist-facies greywacke and siltstone. Geophysical interpretation indicates that granite is widely distributed in the subsurface.

The unnamed sandstone in the Nongra area forms thin graded beds of grey quartzose sandstone with fluted sole-marks and red siltstone interbeds. It has experienced two phases of folding and appears to conformably overlie the Killi Killi Formation. This rock type indicates a change in sedimentary environment, from a deep-water turbidite to a shallow, winnowed environment. This implies that the available accommodation space was nearly filled, a phenomenon that is not often observed in other North Australian Craton turbidite facies.

Karin Orth was employed on contract to study the felsic volcanic rocks and interbedded sandstones of the Winnecke Range and the newly recognised, poorly outcropping volcanic succession, 50 km to the west. Both of these units are interpreted to belong to the Ware Group. The Mount Winnecke Formation in the Winnecke Range is folded into two north-trending synclines, with a complicated intervening anticline. Two major intervals of quartz- to lithic sandstone dominate outcrop; these were probably deposited in a fluvial, braided stream to shallow-marine environment. They contain granule conglomerate and mudstone, and are overlain by a fining-upward succession of sandstone and mudstone. Feldspar-rich dacite of the Mount Winnecke Formation was observed at two main intervals. The upper interval, outcropping extensively to the south of the ranges, is calculated to consist of 900 km^3 of dacite. These are probably subaerial fissure-fed lavas with steep flow-fronts and toe breccias. Less common ignimbrite and porphyry have also been noted. The volcanic rocks to the west (previously included within Nongra beds) consist of amygdaloidal rhyolite (probably a lava), overlain by water-lain fine-grained vitriclastic sediment, followed by channelised volcaniclastic conglomerate. The fine-grained unit overlying the rhyolite contains fiamme-like alteration patches indicative of sub-seafloor alteration in high geothermal gradients. The environment of deposition and diagenesis, coupled with slightly elevated Cu, Pb and Zn in these rocks, increase the prospectivity of this unit for VHMS-style base metal mineralisation.

The Helena Creek area contains siltstone and coarse sandstone that is deformed into north-trending folds in a similar fashion to those at Winnecke Range. Preliminary detrital zircon geochronology data yielded an 1820 Ma maximum depositional age for this deeper marine sediment, indicating that it belongs to the Ware Group and is likely to be a basin-ward equivalent of the Mount Winnecke Formation. The coarser sediments are pervasively tourmalinised, indicating that a large amount of fluid derived from the surrounding granophyre has permeated the area. Small occurrences of gold, in quartz veins in granophyre, are located south of the area.

In summary, NTGS mapping has highlighted a number of interesting stratigraphic and mineralisation-related issues for further evaluation. We consider the area to be highly prospective for Tanami-style gold mineralisation in the Dead Bullock and Killi Killi Formations. Winnecke Range high-level felsic intrusive and associated volcanic rocks may have generated epizonal deposits such as porphyry-related Cu-Au or, more distally, VHMS base metal deposits. NTGS is planning to drill selected areas in BIRRINDUDU to test models, with a view to expanding the mineral prospectivity of the region.

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3D INVERSION OF GRAVITY AND MAGNETIC DATA FOR THE TANAMI REGION

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Cover obscures much of the highly prospective basement rocks of the Tanami Region of the Northern Territory. The cover varies from a thin veneer of Cenozoic sand and gravel, to platform successions more than a kilometre thick. The challenge for the mineral exploration industry is to identify potential targets beneath the cover, guided only by a limited number of direct geological observations.

One of the goals of the joint Geoscience Australia and Northern Territory Geological Survey Tanami Project is to produce a 3D geological map of the region which integrates, and is consistent with the known geology and geophysical datasets. The 3D map will aid explorers by providing a model of the architecture that will assist with the identification of the important elements of gold minerals systems, including pathways for fluids carrying gold in solution and traps where gold might be deposited.

A 3D map of several important surfaces was constructed for the Tanami Region using manual interpolation between 19 geological sections (Meixner *et al* 2004, Vandenberg *et al* 2004a). These sections were based on surface lithological and structural observations. Gravity and magnetic potential field data are sensitive to the 3D geometry of lithological units and to their physical properties, hence can be used as an independent test of the likelihood of a proposed 3D geological map. Prior to construction of the 3D surfaces, each of the cross-sections underpinning the Tanami 3D map was evaluated using the 2D potential field modelling approach implemented in ModelVision software. Subject to constraints in the form of surface geological observations and measurements of physical properties, manual adjustments to the geometry and/or the physical property values were made until the predicted potential field data were judged to be consistent with the observed data. The 3D map and the associated datasets can be viewed at: www.ga.gov.au/map/web3d/tanami/index.jsp.

The 2D potential field data modelling method leaves some questions unanswered: Is the assumption of constant geometry along strike justified? Are there structural inconsistencies in the geometrical arrangement of units from one section to the next? To investigate these issues, 3D potential field inversion modelling was carried out for the Tanami Region using programs developed by the University of British Columbia – Geophysical Inversion Facility (UBC-GIF; Li and Oldenburg 1996, 1998a).

Geophysical potential field inverse modelling

Iterative geophysical potential field inverse modelling is a process whereby adjustments are made to an initial physical property model until there is an acceptable fit between the predicted response of the model and the observed geophysical data. The parametisation of the model can vary from one procedure to another, as can the method used to make adjustments to the model. In the 2D modelling procedure that was used in the initial generation of the Tanami 3D map, the model was composed of a number of horizontal prisms with constant cross-section, adjustments to the shape and/or physical properties were determined by the interpreter, and profiles of gravity and magnetic data were considered simultaneously. In the case of the UBC-GIF 3D inversion programs, the model is in the form of a mesh of rectangular prisms, with adjustments automatically made by the software to the physical properties, leaving the geometry of the mesh constant throughout the process. Inversions for 2D grids of gravity and magnetic data were carried out in completely separate sessions.

A characteristic of potential fields, referred to as “non-uniqueness”, is that there are an infinite number of models that will generate the exact same response. The degree of non-uniqueness is compounded by finite errors in any observed dataset. A further complication for the interpretation of potential field data is that these data do not inherently have any depth resolution. A set of rules or “constraints” is thus required to produce a single model when an iterative inversion procedure is applied. Whether the inversion is carried out manually or automatically, the most common constraint is that the extent of the adjustments made to the initial model must be minimised. When used in this fashion, the initial model is referred to as a “reference model”. This constraint is tantamount to saying that the true model is close to the reference model. The UBC-GIF programs also include a constraint that the adjustments made with respect to the reference model are as smooth as possible, so that the minimum amount of additional structure is introduced.

The terms “unconstrained” and “constrained”, as applied to potential field inversions, can be misleading. In both cases, they are mathematically constrained. It might be better to refer to these as employing generic and specific constraints, respectively. In the case of the UBC-GIF potential field inversion programs, the unconstrained or generic approach uses a reference model that has zero magnetic susceptibility or density contrast everywhere. When nothing is known about a region, this is probably the best guess that could be made for the distribution of these properties. Potential field data do not possess any inherent depth-to-source information; therefore, “unconstrained” UBC-GIF potential field inversions utilise a default depth weighting factor, derived in empirical fashion by Li and Oldenberg (1996, 1998a), as the best compromise value to force the inversion to replicate the depth and shape of the source bodies used in their synthetic test cases.

When even a small number of geological and physical property observations are available, or when certain geological principles are known to apply to the region under consideration, it is possible to make a more specific reference model that will include geologically sensible variations in the physical properties. The inversion can be forced to honour the supplied

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property values at specific points within the model, or to utilise property values between specified upper and lower bounds if the values are less well known. The depth weight parameters can also be varied to suit the specific characteristics of the study area. When these more specific conditions are used, the inversion is worthy of the term “constrained”.

The UBC-GIF inversion programs can take several days to execute on a single PC. Under certain conditions, a single large inversion can be broken up into a series of smaller overlapping inversions termed “tiles”. A distributed computing environment has been set up at Geoscience Australia, using the existing network of desktop PC’s. This allows multiple tiles to be processed concurrently on different PCs, thereby substantially reducing the elapsed time for each inversion.

However, the major obstacle to routine application of constrained potential field inversion methods lies in the generation of realistic reference models. The most common method for producing a reference model begins with the construction of a 3D geological map with very specific properties, namely that the map must be composed of surfaces that bound closed regions. Very specialised software, training and experience in the operation of this software, and copious amounts of time are required to generate such maps. Given a map satisfying this requirement, a mesh can be produced such that the cells within each region are attributed with the supplied representative physical properties for each particular geological unit.

Unconstrained inversions

Unconstrained density and magnetic susceptibility inversion models were produced for the Tanami Region. Each model consists of a mesh with approximately 250 km east–west extent, 350 km north–south extent and 15 km vertical extent. The models cover the TANAMI[3], THE GRANITES and portions of surrounding 1:250 000 mapsheet areas. The density mesh has cubic cells with sides of 2 km length, whereas the magnetic susceptibility mesh has cubic cells with sides of 1 km length. The resolution that can be achieved through inversion is ultimately dependent on the spacing and accuracy of the input gravity and magnetic data. Given an average spacing between gravity observations of 2–4 km, it is unlikely that the use of cells smaller than 2 km would produce any additional information. However, given a line spacing of 500 m or less for the magnetic data, slightly greater detail could be achieved by reducing the dimensions of the cells used in the inversion of magnetic data to 500 or 250 m. There would be a considerable increase in computation time associated with such a reduction in cell size, and this effort was not considered to be warranted at this stage of the investigation.

The response of material beyond the limits of the inversion mesh was removed using the method described by Li and Oldenburg (1998b). A very coarse preliminary inversion was performed using a mesh much larger in extent than that used in the final series of inversions. The response of material outside the final mesh was isolated by forward modelling the response of the coarse inversion models, after substituting zero physical property values within the region occupied by the final mesh. Although there are many ways to estimate the so-called “regional response”, and there is no definitive answer, this method has the desirable characteristics of removing a spatially consistent component of the response and of leaving a residual that is a valid potential field response, at least to the accuracy of the input data.

In many instances, geological boundaries correspond to distinct discontinuities in physical property distributions. Although the models produced through unconstrained inversion have smooth variations in physical properties, discrete boundaries can be constructed by producing 3D contour surfaces, termed *iso-surfaces*, or by identifying surfaces joining local maxima in the gradients of the properties. In this instance, iso-surfaces were generated to identify regions with anomalous low density and high magnetic susceptibility values. The values for these surfaces were chosen so that the surfaces acted as a proxy for specific geological boundaries. This was achieved by comparing the position of these surfaces at shallow depths with the position of the geological boundaries at the interface between basement and cover, as published on the 2D geological maps. The low density regions mostly correspond with either outcropping or interpreted sub-cropping granites of the Grimwade Suite (Slater 2000, Vandenberg *et al* 2004b). The exception is an elongate body in the south of the study area, which coincides with a region that is entirely undercover and which has been interpreted as a mixture of metasediments and granite. The majority of the regions, defined by high magnetic susceptibility values, coincides with outcropping or interpreted sub-cropping mafic and BIF units within the Dead Bullock Formation, or mafic units within the Mount Charles Formation. There are regions of coincident high magnetic susceptibility and low density values in the western part of the model that correspond to outcropping or interpreted magnetic granites of the Frederick Suite.

Conclusions and future work

Despite the generic nature of the controls utilised in the unconstrained inversions carried out to date, these inversions have shown promise for suggesting a possible 3D geometry for geological features having anomalous density and magnetic susceptibility values. The majority of the high magnetic susceptibility regions of the model appear as deformed and folded sheets, and map to the surface locations of outcropping mafic and BIF units of the mineralised Dead Bullock Formation. A similar sheet of high magnetic susceptibility material within the model corresponds in location to highly mineralised mafic units of the MacFarlane Peak Formation. The inversion models, therefore, may be used as a regional-scale guide for determining where these units might appear at depth, as well as suggesting where these units might sub-crop beneath younger cover. This is an important outcome since these units are considered to be potential traps for gold mineralisation. This result is complementary to the information gained from the previous 2D modelling work which focused primarily on modelling the location and orientation of the major structures that may have acted as pathways for mineralised fluids.

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[3] Names of 1:250 000 mapsheets are in CAPITALS.

Future inversions will be constrained through the use of a reference model that represents a regional-scale 3D geometrical hypothesis for the geological units of the Tanami. These geometries will be based on surface and shallow drillhole lithological and structural observations. Acquisition of crustal seismic data is planned. Interpretation of these data will provide valuable additional geometrical constraints at depths far below those that will ever be sampled by drillholes. Specific knowledge of the physical properties obtained from samples collected in this region will be utilised by setting upper and lower bounds on the values that can be generated in the inversion models. Discrepancies between the final inversion model and the reference model will provide an indication that either the supplied geometry or the physical property values, or both, need to be re-examined. This method will allow geological, rock property, seismic and potential field information to be integrated producing one or more hypotheses for the geology of the region that are consistent with all of the available input data.

The application of two different potential field modelling methods, namely a manual 2D modelling method and a 3D automated inversion method, has highlighted certain characteristics of the particular programs. Significant geometrical simplifications had to be accepted when using the 2D program. In contrast, the 3D program was able to utilise models that reproduced every essential detail in the gravity and magnetic grids for the study area. By using a litho-model approach, the 2D program used in this study was able to associate both density and magnetic susceptibility values with each object, and thus allowed simultaneous investigation of both the gravity and magnetic response. In contrast, the 3D program utilised a physical property approach. This meant that an additional interpretation stage had to be applied following inversion, to extract geological boundaries from the physical property distributions. It also meant that the density and magnetic susceptibility models were derived through separate processes, and that important relationships between these properties for different geological units were ignored. The input of the interpreter during the 2D modelling process ensured that complex geological information such as folding and faulting style, observed in surface maps, was honoured at depth. It is difficult to transfer this information to the 3D inversion through the reference model and virtually impossible to maintain the styles as changes are made by the inversion program.

Substantial further work is required to investigate the significance of some general issues that apply to all regional potential field investigations. These issues include:

- Should the modelling be carried out using a spherical or flat Earth?
- What constraints related to the Curie depth can be applied when working with crustal magnetic susceptibility models, and are the impacts at upper crustal levels (ie, 0–5 km depth) significant?
- What isostatic constraints can be applied, and will these significantly affect the density model at upper crustal levels?

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SEISMIC REFLECTION SURVEY OF THE TANAMI REGION (NT–WA): 2005 UPDATE

Leon Vandenberg[1], Bruce Goleby[2] and Leon Bagas[3]

The project

The Tanami Seismic Project is a collaborative research project between Geoscience Australia (GA), Geological Survey of Western Australia (GSWA) and the Northern Territory Geological Survey (NTGS). This project also involves (through cash and/or in-kind contributions) the mining companies, Newmont Australia and Tanami Gold, which have an interest in furthering research into the geological controls on Palaeoproterozoic gold systems in the poorly exposed Tanami Region of central-northern Australia.

The project aims to collect seismic reflection data in the Tanami Region to improve our understanding of the regional 3D crustal architecture and mineral systems.

The survey consists of four regional seismic traverses; the location of the traverses is shown in **Figure 1**.

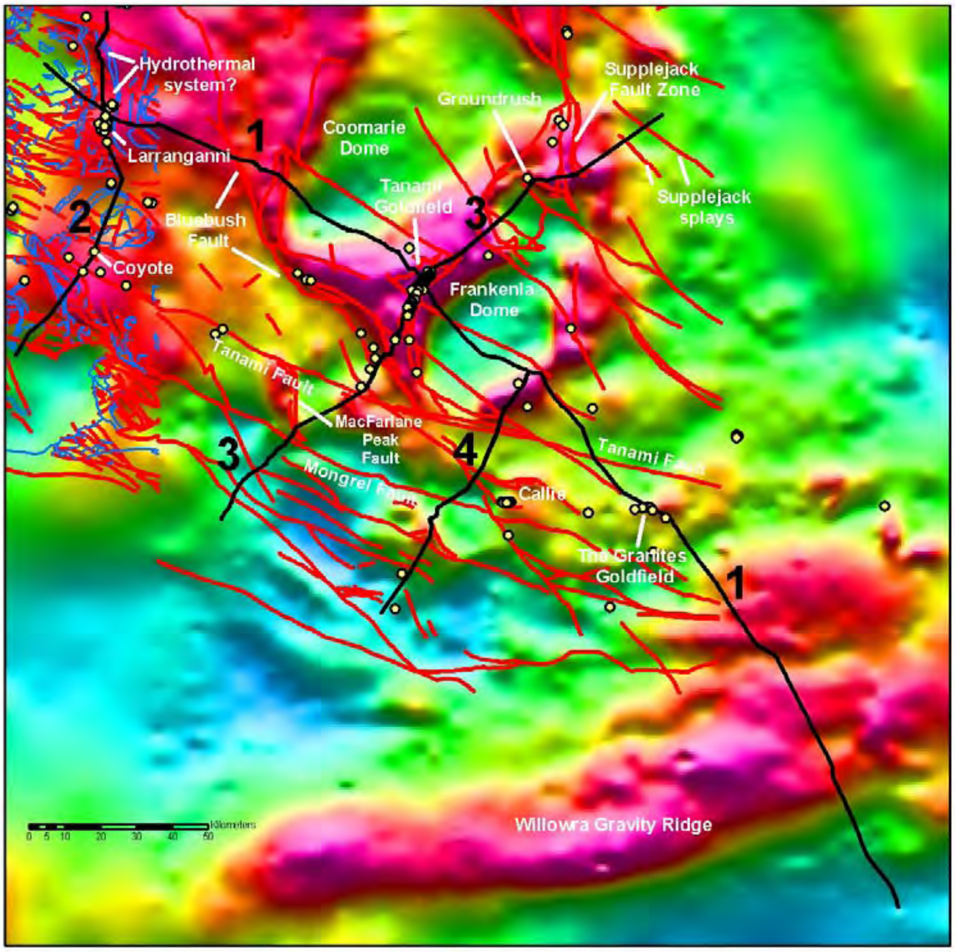

Figure 1. Location of the Tanami Seismic traverses (black traverses with number) on regional gravity image. Also shown are the main faults (red) and main mineral deposits (yellow dots). Key faults, geological features and mines are named.

The key objectives of the seismic survey are to:

- image the geometry of the main faults
- determine a deformation sequence to these fault structures
- identify through-going crustal structures
- determine stratigraphic thicknesses of the Tanami Group and granite body geometries
- determine relationships of the various stratigraphic packages to controlling structures
- investigate the relationship of mineralised domains to crustal-scale structures
- identify Archaean basement and its relationship to the overlying Tanami Group stratigraphy
- investigate the character of the Tanami–Arunta boundary.

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Timetable:

Scope Project	December 2003
Initial Reconnaissance	June 2004
Begin obtaining access approvals	June 2004
Complete approvals	April 2005
Begin line clearing and track cleanup	April 2005
Begin data acquisition	May 2005
Begin field QC processing	May 2005
Complete data acquisition	July 2005
Complete field QC processing	July 2005
Begin restoration	July 2005
Complete restoration	July 2005
Complete report on field operations	November 2005
Complete archival of field tapes	December 2005
Begin Processing	June 2005
Begin Interpretation	August 2005
Complete Main Processing	January 2006
Complete Interpretation	February 2006
Complete draft of report on data interpretation	April 2006
Seismic workshop	May–June 2006
Publish record on Tanami Seismic Research Project	July–August 2006

Operational permits and specifications

This survey will follow a minimal cultural and environmental impact approach, where disturbance of sites of cultural significance is avoided, and removal of topsoil, changes to water flow along drainage or wash areas, and disturbance to larger vegetation are minimised in accordance with state government statutes and guidelines. For both the Northern Territory and Western Australia, details of operational permits and specifications are still under negotiation.

The seismic survey will be undertaken on behalf of the consortium by ANSIR (Australian National Seismic Imaging Resource), a Commonwealth government Major National Resource Facility (MNRF). ANSIR is a partnership between Geoscience Australia and the Research School of Earth Sciences, Australian National University. ANSIR uses a facility manager, TEREX Seismic Ltd, to run the seismic equipment and manage the seismic personnel during the seismic operations.

Seismic reflection data will be acquired with the following equipment:

- ARAM24 seismic reflection recording system with 24 bit Delta-Sigma technology
- 10 Hz geophones
- 3 x IVI 60 000 lb Vibrators, operating at all times
- 1 x IVI 60 000 lb Vibrator spare.

Seismic reflection data will be acquired with the following parameters (note that the final parameters will be determined prior to, and during initial field experiments and regularly monitored for suitability):

- 240 active channels
- 2 msec sample rate
- 40 m group interval, and 80 m Vib interval, giving a sub-surface coverage of 60 fold seismic data and CDP interval of 20 m
- ~18 second record length
- 3 sweeps of 12 seconds sweep length.

Finances

Total project budget is currently $850 000 plus industry in-kind contributions.

Project representatives

Geoscience Australia: Bruce Goleby (Project Leader; 02 6249 9404)
Northern Territory Geological Survey: Leon Vandenberg (08 8951 8180)

Geological Survey of Western Australia: Leon Bagas (08 9222 3221)
Industry Participants: Newmont Australia, Tanami Gold.

Traverse 1 – northwest to southeast transect across Tanami Region (04GA-T1)
Traverse 1 forms the backbone to the proposed seismic array and transects the Tanami Region from northwest to southeast (**Figure 1**). Starting in WA, the traverse crosses over an interpreted granitic body, before crossing a north-trending magnetic anomaly that may be associated with an early layer-parallel (thrust) fault. The traverse continues east across the north-trending Larranganni gold prospect area and the southern end of a north-trending magnetic anomaly. There, the traverse will test the hypothesis that the mineral occurrences and magnetic anomaly are associated with a fault-controlled hydrothermal alteration system. After passing the WA/NT border, Traverse 1 crosses the northerly trending Bluebush Fault and the Coomarie and Frankenia granitic domes. The seismic profiles from this location are anticipated to define the geometry of both the fault and the granitic bodies. The traverse then crosses the Tanami mine district between the granitic bodies, allowing the testing of relationships between mineralization and northeast-trending structures. Further southeast, the traverse crosses The Granites mine sequence and may help determine the relationship between mineralization and the northwest-trending structures in the area. The most southerly section of the traverse crosses the prominent east–west-trending Willowra Gravity Ridge which may represent the Tanami–Arunta boundary. The traverse may resolve the geometries of major crustal structures, interpreted to be associated with the gravity ridge. The traverse will also test the hypothesis that the gravity ridge is offset by several regional-scale, mineralized easterly and northerly trending faults.

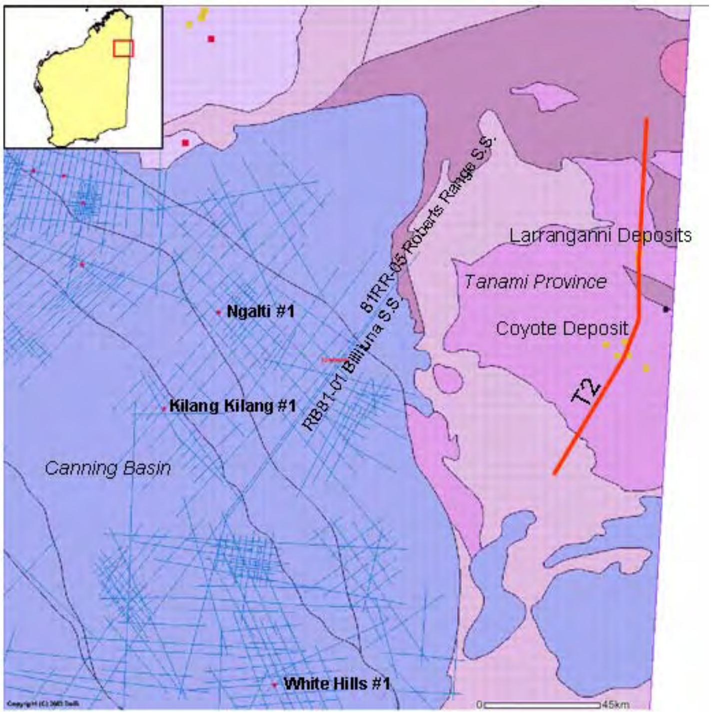

Figure 2. Tanami region of Western Australia. Approximate location of Traverse T2 is shown as red line. Background is tectonic units with overlying Phanerozoic units, with the Tanami in purples and pinks. Yellow dots are gold deposits. Blue lines are 2D seismic lines. Small red dots are petroleum wells. Two regional seismic lines have been labeled. Map courtesy of GSWA and created online using http://www.doir.wa.gov.au/aboutus/geoview_launch.asp**.**

Traverse 2 – northerly trending traverse passing through the Larranganni and Coyote gold occurrences (04GA-T2)
Starting from the north, Traverse 2 crosses a series of northwest-trending structures before crossing the northern end of an interpreted hydrothermal-alteration zone. It is anticipated that this traverse will help resolve the geometries of the northwest-trending structures, and any structure related to the proposed alteration zone. South of the Larranganni group of occurrences, the traverse traverses a series of westerly trending structures, before crossing what is interpreted as a contact metamorphic aureole. To the south of the Coyote gold deposit, the traverse first crosses the Tanami Fault and then a magnetic granite that is elongated in a northwesterly direction (**Figures 1** and **2**). The traverse is thus ideally located to determine the fault and granite geometries. A number of moderately magnetic and folded rock bodies are located immediately to the southwest of the granite. These rocks are thought to be early dolerite sills, and appear to be terminated in a zone that is parallel to, and west of the granite. This section of the traverse may determine fold orientations and the nature of the termination of the dolerite sills. There is some suggestion that this termination represents is an early fault that has been folded and refolded before the emplacement of the granite (interpretation by Leon Bagas, GSWA). The traverse then crosses a number of west-northwest-trending structures before terminating in a subdued magnetic zone, interpreted to represent granite. It is

anticipated that the traverse will help determine the geometries of these structures and whether they are a continuation of the Mongrel Fault.

Traverse 3 – Northeast-trending traverse beginning at the Tanami goldfield (04GA-T3)

Traverse 3 starts in the northeast near Lake Buck. It crosses the north–south-trending Suplejack Fault Zone, a structure hosting significant concentrations of gold mineralisation, before crossing a number of northeasterly-trending structures, interpreted to be splays off the Suplejack Fault Zone. The traverse is ideally located to resolve whether these structures are splays and would significantly enhance the exploration potential of this region. Traverse 3 then follows the haulage road west from the Groundrush deposit to the Tanami goldfield (**Figure 1**). This segment of the line is oriented perpendicular to a major structure and some lessor structures. The traverse then crosses a gravity low attributed to the northerly extension of the Frankenia Granite. The location of the traverse may resolve the geometries and relationship of the fault as well as the geometry of the granite contact. This 30 km section of the traverse is parallel to the geological grain and the seismic will image some of the along-strike variations in the Tanami Group stratigraphy. It is possible that the geological grain is a relatively shallow feature and this will be tested by the traverse, which will provide information about geometries at depth. Heading south, Traverse 3 then crosses a series of structures, including the Tanami, Mongrel, and older Bluebush and MacFarlane Peak faults (**Figure 1**). Some of these faults are related to gold mineralisation and the traverse is ideally located to determine their geometries. The traverse also crosses a number of granitic bodies and may resolve the geometries of the granites within the surrounding Tanami Group sediments.

Traverse 4 – Southwest-trending traverse passing near Callie (04GA-T4)

Traverse 4 crosses a series of structures including the Tanami, Mongrel and older Bluebush faults (**Figure 1**). Some of these faults are related to gold mineralisation and the traverse is ideally located to determine fault geometries. The traverse also crosses a number of granitic bodies and may resolve the geometries of the granites within the surrounding Tanami Group sediments.

Acknowledgments

The development of this project has only been made possible by the positive spirit of cooperation shown by a large number of people and agencies (Central Land Council, Department of Infrastructure Planning and Environment, Transport and Works, Kimberly Land Council). In particular, we would like to thank Brett Anderson-Steele (CLC) and Neil Price (Indigenous Business and Industry Services). The continued support in the development of this proposal by Newmont Australia, Tanami Gold and Barrick Gold of Australia is gratefully acknowledged.