Accessing Australia’s Final Exploration Frontier

NORTHERN TERRITORY GEOLOGICAL SURVEY

Annual Geoscience Exploration Seminar
incorporating the 2007 Mining Services Expo

Organised by the NT Geological Survey,
Department of Primary Industry, Fisheries and Mines
Supported by Mining and Petroleum Services,
Department of Business, Economic and Regional Development

RECORD OF ABSTRACTS

AGES 2007

20–21 March, Alice Springs Convention Centre
Minister’s foreword

Welcome to the Northern Territory, and to our eighth Annual Geoscience Exploration Seminar, which will showcase the rich mineral potential of the Territory.

This year’s AGES is being held during an exciting period for the Northern Territory exploration and mining industry, with rapidly increasing levels of private sector investment in exploration and development. The Northern Territory currently has the fastest growing economy in the nation, with annual growth of 7.5% in 2005-06. This is driven mainly by the mining and petroleum sector, which contributed 56% of the Territory’s economic growth in the past year. Mining’s share of the Territory’s GSP is now 26%, making it clearly the largest industry in the Territory. This underscores the fact that the continued growth of a sustainable resources sector is a critical element in the long-term economic development of the Territory.

We are now into the final year of the Northern Territory Government’s four-year, $15.2 million exploration investment attraction strategy, Building the Territory’s Resource Base. This program has focused on attracting exploration investment through a combined approach involving accelerated acquisition and delivery of pre-competitive geoscience data, improved land access and promotion. During the four years of the program, there has been a dramatic increase in the uptake of geoscience data and products, along with a reversal in the recent decline in the Territory’s share of Australian exploration expenditure.

AGES is used by my Department of Primary Industry, Fisheries and Mines as a key platform to communicate the results and significance of its targeted geoscience programs, as well as collaborative geoscience undertaken by partner organisations. It also acts as the premier networking forum for the Territory’s exploration industry. I am pleased to say that for the second year, through co-operation with the Department of Business, Economic and Regional Development, a Mining Services Expo is being held concurrently with AGES, to showcase central Australian businesses and their capability to support the exploration and mining industry.

In this current resources boom, there is a highly competitive environment for attracting exploration investment, both nationally and globally. I believe that the Northern Territory, with its vast areas of relatively under-explored prospective land, still holds tremendous potential for new world-class discoveries. AGES remains a critical element of our strategy to spread this message and to grow and develop the Territory’s exploration and mining industry.

I trust that you will find AGES both enjoyable and stimulating, and that it will assist you in your future exploration and investment decisions.
AGES and Mining Services Expo, Alice Springs Convention Centre

Booth No. Exhibitor Name
1 & 2. Dept of Primary Industry, Fisheries & Mines (DPIFM)
3. Fleetwood
4. Arafura Resources
5. Fluid Power NT
6. CTE Pty Ltd
7. Dave Douglas Tyre City
8. Indigenous Business and Industry Services (DBERD)
9. Newmont
10. Thrifty
11. R & R Enterprise
12. R & R Enterprise
13, 14 & 15. Blackwoods
16. Dept of Business, Economic & Regional Development
17. Central Comms
18. Central Comms
19. Opposite Lock Alice Springs
20. Central Petroleum
21. The Alice Springs Watershed
22. ALS Chemex
23. GHD
24. Ausfuel
25. Thor Mining
26. PRS Power Steering, MinMap
27. Prime Industrial Rental
28. Alice Hosetech
29. Alice Hosetech
30. Alice Tanks
31. Olympia Resources Limited
32. Hirex Services
33. Australian National Helicopters
34 & 38. Murray Neck Homeworld
35. Work Wear Alice Springs
37. Klohn Crippen Burger P/L
38 & 34. Murray Neck Homeworld
39. Geminex
40. Geminex
41. Toll Priority
42. Hella Australia
43. Australasian Jet
44. Manufacturer’s Council – Chamber of Commerce NT
45. NHP Electrical Engineering
46. QB Hire Earthmoving Machinery
47. TBA
48. BusyBee Promotions and Workwear
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Tony Meixner (GA)
# Annual Geoscience Exploration Seminar

## Accessing Australia’s Final Exploration Frontier

### AGES 2007

**20–21 March**, Alice Springs Convention Centre

### Program

#### MONDAY 19 MARCH

5:00-6:30pm  Registration and Ice Breaker - Sponsored by Newmont Tanami Pty Ltd

#### TUESDAY 20 MARCH

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:00-8:30</td>
<td>Registration</td>
</tr>
</tbody>
</table>
| 8:30-8:40 | The Hon Chris Natt  
Minister for Mines and Energy  
AGES Opening Address |
|          | **Session 1**                                                           |
| 8:40-9:00 | Ian Scrimgeour  
Opening remarks |
| 9:00-9:20 | John Dunster  
NT exploration overview 2006 |
| 9:20-9:40 | Graeme Beardsmore  
(Hot Dry Rocks)  
Geothermal energy potential of the NT |
| 9:40-10:00 | Sjoukje de Vries  
(FrOGTech)  
OZ SEEBASE™ Proterozoic Basins |

**Morning tea 10:00-10:30**

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
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| 10:30-10:50 | Westgold Resources  
Overview of NT exploration projects |
| 10:50-11:10 | Roger Clifton  
Making the most out of NTGS geophysical data |
| 11:10-11:30 | Clarke Petrick  
New and upcoming geophysical surveys |
| 11:30-11:50 | Tracey Rogers  
All you want to know about accessing NTGS information |
| 11:50-12:10 | Matilda Minerals  
Overview of NT exploration projects |

**Lunch 12:10-1:00**

<table>
<thead>
<tr>
<th>Time</th>
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| 1:00-1:20 | Dorothy Close  
Diverse terranes and mineral potential of the Casey Inlier, Arunta Region |
| 1:20-1:40 | Mithril Resources  
Overview of NT exploration projects |
| 1:40-2:00 | Kate Selway (Adelaide Uni)  
Magnetotelluric imaging of the central Australian lithosphere |
| 2:00-2:20 | Tennant Creek Gold  
Overview of NT exploration projects |
| 2:20-2:40 | Ollie Raymond (GA)  
A new digital geology of the Northern Territory, and delivery of geological data via the Internet and international standards |

**Afternoon tea 2:40-3:15**
Annual Geoscience Exploration Seminar

Accessing Australia’s Final Exploration Frontier

Session 4
3:15-5:00  Session on ALRA amendments, amendments to Mining Act, land access
3:15-3:35pm  Gary Taylor  Exploration & the Mining Management Act
3:35-3:55pm  Alan Holland  Mining Act Review - update
3:55-4:15pm  John Litchfield (OIPC)  Amendments to the ALRA Act
4:15-4:35pm  Jerry Whitfield  ALRA amendments from a NT perspective
4:35-5:00  Rodger Barnes (CLC)  Howard Smith (NLC)  John Litchfield (OIPC)  Member of the Titles Division  Discussion panel on presentations

7:00 - late  AGES Official Dinner  Dinner Speaker - Dr Dick Henley

WEDNESDAY 21 MARCH

Session 1
9:00-9:20  Masood Ahmad  Why is the Pine Creek Orogen so mineralised?
9:20-9:40  Linda Glass  Mafic rocks of the Litchfield Province, western Pine Creek Orogen: Evidence for a Palaeoproterozoic arc-related setting and links to the Halls Creek Orogen
9:40-10:00  Peter Schaubs (CSIRO)  Alligator Rivers uranium field numerical modeling project
10:00-10:20  GBS Gold  Overview of NT exploration projects

Morning tea 10:20-10:40

Session 2
10:40-11:00  Lisa Worrall (CRC-LEME)  Targeting Callie-style gold mineralisation through the regolith in the Tanami
11:00-11:20  Leon Vandenberg  Overview of new seismic data from the Tanami Seismic Collaborative Research Project.
11:40-11:50  Ian Scrimgeour  Closing remarks

12:00 Lunch & Close
NT mineral exploration overview 2006

*John Dunster*

**Commodity review**

The current mineral commodities boom, driven partly by unprecedented demand from China, began with a steady climb in commodity prices until mid-2005, followed by an increase in momentum in fiscal 2005–06 and the most rapid rise in mid calendar 2006. Precious metal prices peaked in May. Gold is the preferred target of the majority of Northern Territory exploration companies surveyed during 2006. Gold is probably unique in being a de facto international currency and it can experience a “flight to quality” when other economic indicators go down. Gold hedging has been a problem. Despite the increase in the gold price, production in Australia is falling, as the country loses ground to South America, Asia and Africa, and about 70% of Australia’s gold production is now in foreign hands. The Northern Territory’s production in 2004/05 was 6% of the Australian total. GBS, Tanami, Newman and Renison are the main players. Silver and platinum group elements prices generally track gold. Copper, zinc, lead, cobalt and nickel are the main base metals of interest in the NT, with about 16 companies actively exploring. Molybdenum, tin and tungsten are another suite that has attracted several specialist exploration companies, and iron and manganese are also targets in the Northern Territory. Base metals have increased dramatically in price during 2006. Copper peaked at over 3.5 times its 2003 price, but prices started to decline as the copper inventory increased. Some analysts see copper as a bell ringer for other base metals. Lead prices increased significantly from July 2006, as its inventory fell. The zinc price has increased markedly since July 2005, as demand increased and stockpiles dwindled. As at the end of 2006, the equivalent of another Century ore body needs to be found each year, just to meet demand. Nickel has been the standout performer, increasing in price more than five fold from 2002 to 2006, and is now pushing into the realms of a precious metal. Its warehouse levels are notoriously difficult to predict, due to a highly fluctuating demand and substitution in stainless steel manufacture. Uranium is of special interest to the Northern Territory, as it has, arguably, some of the most prospective provinces in the world. As of the end of 2006, there were in excess of 56 companies active in uranium exploration in the Northern Territory. Uranium is sold by contract. Its quoted price has gone up seven fold in five years and even modest uranium deposits are now valued in the billions of dollars. Diamonds are another commodity strongly associated with the Northern Territory. Analysts predict that diamonds will relatively out-perform gold as a commodity in years to come. There are seven main companies exploring for diamonds.

**Tenement situation**

At the end of 2006, 37% of the Northern Territory landmass was covered by 2821 granted titles and 22% was under 2047 applications for exploration. There were 603 granted mineral claims and 838 mining leases. Only 0.13% of the Northern Territory is under actual mining title. The number of applications and grants per year is now at record levels. This is a result of momentum building steadily since large tracts of land, particularly to search under cover, were granted in 2002/03. 2005/06 was highlighted by an increased turnover in ground, a situation the Department is now actively encouraging, and this is being monitored, based on geological province. The Pine Creek Orogen, for example, needs more ground turned over to improve the effectiveness of exploration.

**Exploration expenditure**

By virtue of its size and its endowment in geologically prospective provinces, Western Australia has traditionally attracted the largest proportion, by far, of the total exploration expenditure in Australia. Recent years have seen the Northern Territory on a par with New South Wales and Victoria, all of which were understandably ahead of Tasmanian. The standout for 2005/06 has been South Australia, which has captured an increased market share. The Northern Territory needs to take steps to redress this and to claw back to its previous best of 10% in 1990, from its present 6% Australian market share.

**Exploration highlights by geological province**

The McArthur Basin is one of the Territory’s largest and most prospective, yet underrated provinces. It is ‘elephant country’ and, on average, has quite large titles. It has a 20+ year history of world-class mining, worth >$3B, and is prospective for base metals, uranium and diamonds. In 2006, there were major exploration or mining developments in all of these commodities. Highlights included X-Strata receiving approval for its new open cut operation at the McArthur River Mine, Redbank Mine’s good drilling results and copper production, and North Australian Diamonds’ successful diamond recovery activities at Merlin. Gravity Diamonds continued to evaluate the Abner pipe and explored regionally for diamonds. Sandfire Resources got some encouragement at Gordon’s copper prospect.
The **Tanami Region** is a mature gold and uranium province with proven gold production. It is one of the Territory’s smallest geological provinces and is covered by a relatively low number of titles, but has a good record of turnover of ground. It is the only province where the average size of applications is larger than the granted ELs. The big two explorers (Newmont Australia and Tanami Gold) were quiet in the NT during 2006, focusing instead on the Western Australian portion of the province. Of the juniors, Ord River Resources had some good intercepts at their prospects.

The **Arunta Region** is a highly complex metamorphic province and NTGS has done much in recent years to unravel that complexity. It is truly a multi-commodity province, with targets that include base and precious metals through to garnet and vermiculite. Highlights for 2006 include Tanami Gold’s gold and copper intercepts at Tekapo, Arafura Resources’s ongoing work at the Nolan’s Bore rare earth-phosphate-uranium deposit, Thor Mining’s feasibility study at Molyhil, Cazaly Resources’ work on the Quartz Hill rare earth-uranium prospect, Reward Minerals’ drilling at the Jervois base metals deposit, the continuing exploration at the Hammer Hill JV nickel-cobalt-chromium prospect and the Barrow Creek JV nickel-copper prospect. The tenement situation in the Arunta Region has improved and it now has the highest five-year average turnover of any major NT province.

The **Pine Creek Orogen** (PCO) has over 1000 documented mineral occurrences and is one of the Northern Territory’s most mature provinces in terms of exploration. It is renowned for gold and high-grade uranium. It contains 20% of the World’s low-cost uranium and this alone makes it currently some of the most desirable real estate anywhere. The average size of a granted EL is 142 km², the smallest of all the major provinces. NT Mines and Energy recognises that land is not being turned over quickly enough in the PCO, with too many stagnant titles, and is working to remedy that. Exploration and mining highlights for 2006 include GBS Gold’s activities at Cosmo Deeps, Brocks Creek underground, Rising Tide, Princess Louise and Fountainhead, Compass Resources’ work at the Browns base metals and Mount Fitch uranium deposits, Territory Iron’s activities at Frances Creek, Valencia Ventures’ activities at Mount Bundy gold, and Vista Gold’s proposed redevelopment of Mount Todd. Renison Consolidated also commenced gold production from their Toms Gully mine in 2006. ERA continued mining at the Ranger mine, increasing reserves and announcing the building of a laterite treatment plant.

The **Tennant Region** is another highly prospective multi-commodity province at a moderately mature state of exploration. The traditional target of Warramunga Formation iron-oxide gold±copper has been the mainstay of exploration for over 100 years and the high-grade gold has been a company-maker. New exploration methods and new target commodities will see exploration activity increase. Considerable potential exists for targets in extensions to the province under cover. In 2006, Westgold Resources and Adelaide Resources have separately reinvigorated the Rover field and surrounds with some good base metal±gold intercepts. OM Holdings has continued development work at the Bootu Creek manganese mine.

The **Musgrave Province** extends over Western Australia, South Australia and the Northern Territory. It is a relatively complex metamorphic region that contains nickel, PGE, gold, uranium and lead-zinc-silver targets. Despite a high level of activity in the adjacent states and recent work by NTGS, much of the Northern Territory portion is yet to be explored. At the end of 2006, there were only seven granted exploration licences and 48 applications. The average size of a title exceeds 455 km²; a testament to the greenfields nature of the province in the Northern Territory.

The onshore **Bonaparte Basin** contains Mississippi Valley-type base metal deposits. Tennant Creek Gold has resurrected the Sandy Creek (or Legune) lead-zinc deposit as part of their Manbarrum project. The basin’s potential for other similar deposits and for other commodities, such as uranium and coal, is almost untested. Several junior companies have recognised this and, at the end of 2006, there were seven granted ELs and 18 applications in the basin.

The uranium exploration boom has led to a massive resurgence in interest in central Australian basins. The **Ngalia Basin**, home to several known uranium prospects, including Bigryli, has gone from being almost entirely vacant to almost entirely pegged. Similarly, the **Amadeus Basin**, mostly thought of as a petroleum province, was previously only being explored for evaporites, copper and gold. There are now over 100 uranium applications. The Amadeus Basin contains the Angela/Pamela deposit, which previously was under an RO. When this was recently revoked, the Angela/Pamela deposit generated worldwide interest and received 37 tenement applications. The central Australian basins should not be seen as just being prospective for uranium. They warrant more systematic exploration for other metals using modern techniques.
The final frontier is perhaps something that’s all too often ignored – the **Mesozoic and Cenozoic basins**. These register with most explorers as “overburden” and “dirt”. The Territory’s Mesozoic Arafura, Daly, Dunmarra and Eromanga basins, and the almost unknown Cenozoic basins have historically been explored for a wide range of placer deposits, industrial minerals and bulk commodities. Bauxite should still be a viable exploration target in NT in these settings. Other possible commodities include kaolin clay as in Cape York, coal and oil shale. Cenozoic sediments are currently the bread and butter of Matilda Minerals (mineral sands), Olympia Resources (garnet) and others in the Territory. These may not be world-class deposits perhaps, but uranium could be a very different story. At today’s prices, one modest sized, Mesozoic-hosted, Cenozoic palaeo-channel or calcrete uranium deposit could easily be a company-maker. Potentially, such deposits could be worth more than all the gold ever produced in the Northern Territory!

**Conclusion**

The minerals commodity boom continued during 2006. Uranium and nickel were the stand-outs. Although there were signs that gold and copper, in particular, were past their peaks, the year closed with analysts bullish. Inventories of important base metals, especially zinc and nickel, are perilously low. Driven by the boom, exploration activity is probably at an all-time high in the Northern Territory. Despite the record numbers of exploration titles, the NT still has a way to go to get back it’s rightful share of Australian expenditure. There have been significant discoveries and mining developments in most of the proven provinces and uranium has seen a resurgence in exploration in basins previously not being worked. However, there has not been a grass-roots world-class discovery in the Northern Territory for a generation. The major explorers in the Tanami have been quiet and activity in the Arunta has focused on less-conventional target commodities. Perhaps the next “big thing” will come from basins that, to date, have been largely ignored.

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**Geothermal energy potential of the Northern Territory**

**Graeme Beardsmore**

**Geothermal energy, geothermal systems and exploration**

Where high temperatures occur in rocks close to the Earth’s surface, the heat can be harnessed to provide useful power for the benefit of mankind. The general term for this resource is “geothermal energy”. Globally, geothermal energy currently provides more than 8900 MW of electrical power (Bertani 2005), as well as direct heat for applications such as space heating and aquaculture. Almost all electrical power is generated in regions where naturally occurring hot water and steam is found in permeable rocks close to the Earth’s surface. This is sometimes referred to as “conventional” geothermal energy.

“Hot fractured rock” (HFR) geothermal energy differs from conventional geothermal energy in that it does not rely on the rock’s natural permeability. Rather, a permeable reservoir, or underground heat exchanger, is artificially created by fracturing hot rocks deep underground (eg Tester et al 2006). Heat can then be recovered from the hot rocks by passing water through the underground heat exchanger from one borehole to another. The water heats up as it permeates through the hot rocks, and flows to the surface through a production bore as super-heated water. At the surface, the super-heated water is passed through a heat exchanger to vaporise a secondary fluid to drive a turbine. The spent geothermal water is reinjected into the underground heat exchanger to extract more heat, making a closed loop.

The conditions necessary for the extraction of geothermal energy can be described using the concept of geothermal systems. A geothermal system has three components: a heat source, a reservoir and a fluid. The heat source can be thought of as a volume of rock at a particular temperature, at a drillable depth. The reservoir is a volume within the heat source, through which a fluid can flow to extract heat. In HFR operations, the reservoir is artificially created within the heat source, and the fluid artificially introduced into the reservoir.

Temperatures suitable for HFR electricity generation exist beneath every point on the Earth’s surface. However, the cost of drilling to access the heat will typically be lowest at locations where a high geothermal gradient exists. High geothermal gradients are found in regions with high heat flow and low thermal conductivity.
Surface heat flow is the sum of heat from the mantle and heat generated within the crust. A one-kilometre thickness of rock generating heat at a rate of 1 µW/m² within the crust contributes 1 mW/m² to surface heat flow. McLaren et al. (2003) demonstrated that heat flow from the deep crust and mantle beneath the Northern Territory is about 40 mW/m² and that extra heat is generated in the upper 13 km of crust (on average).

Table 1 summarises heat generation data, derived from geochemical analyses of basement rocks in a number of Northern Territory Proterozoic and Archaean terranes. Many of these rocks generate heat at rates greater than 5µW/m³, sufficient to generate surface heat flow of over 100 mW/m² within the Northern Territory, equivalent to the heat flow in the vicinity of Geodynamics Limited’s Habanero HFR development (Beardsmore 2005). It is likely that heat flow in much of the Northern Territory is of sufficient magnitude to generate attractive geothermal targets, where insulating sedimentary layers exist.

Table 1. Summary of heat generation data from Northern Territory basement rocks.

<table>
<thead>
<tr>
<th>Region name</th>
<th>Heat generation (µW/m²)</th>
<th>#data</th>
<th>Mean</th>
<th>Median</th>
<th>Max.</th>
<th>Min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aileron Province (Arunta Region)</td>
<td>136</td>
<td>4.52</td>
<td>3.39</td>
<td>18.7</td>
<td>0.23</td>
<td></td>
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<tr>
<td>Warumpi Province (Arunta Region)</td>
<td>10</td>
<td>3.67</td>
<td>3.41</td>
<td>7.49</td>
<td>0.82</td>
<td></td>
</tr>
<tr>
<td>Warramunga Province (Tennant Region)</td>
<td>15</td>
<td>4.10</td>
<td>3.24</td>
<td>14.8</td>
<td>2.94</td>
<td></td>
</tr>
<tr>
<td>Pine Creek Orogen</td>
<td>423</td>
<td>61.1</td>
<td>3.01</td>
<td>5110</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>Archaen basement</td>
<td>22</td>
<td>2.12</td>
<td>1.93</td>
<td>6.70</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>Davenport Province (Tennant Region)</td>
<td>91</td>
<td>3.29</td>
<td>3.42</td>
<td>6.01</td>
<td>0.70</td>
<td></td>
</tr>
<tr>
<td>Murphy Irirr</td>
<td>34</td>
<td>4.09</td>
<td>3.44</td>
<td>10.6</td>
<td>2.11</td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>731</strong></td>
<td><strong>37.0</strong></td>
<td><strong>3.21</strong></td>
<td><strong>5110</strong></td>
<td><strong>0.23</strong></td>
<td></td>
</tr>
</tbody>
</table>

Different types of rocks have different thermal conductivities (Beardsmore and Cull 2001). Coal has a very low thermal conductivity compared to most other rocks; it is an excellent thermal insulator. Fine-grained porous or mafic rocks, such as basalt, shale and mudstone, are also good insulators. Rocks such as quartzite and dolostone, on the other hand, are typically poor insulators. The ratio of coaly/shaly layers to sandy/dolomitic layers in a sedimentary column gives an indication of the column’s insulating properties.

From the point of view of energy extraction, the optimum orientation for a geothermal reservoir is horizontal. To hydraulically enhance the permeability of horizontal fractures, the minimum compressive stress direction in the crust must be close to vertical. This can only be achieved in regions under tectonic compression. Hills and Reynolds (2000) showed that the whole of the Northern Territory is currently in a compressive stress regime, implying that hydraulic stimulation of basement rocks at about 5 km depth should enhance the permeability of horizontal fracture systems.

Assessment of individual basins

A number of individual basins in the Northern Territory were assessed for prima facie evidence that they may hold economic geothermal systems. The Amadeus Basin has localised areas of basement with exceptionally high heat-generating properties that could elevate surface heat flow to levels that counteract the negative impact of a generally conductive cover succession. The thick basement sections required for this scenario are most likely to be found in the shallower portions of the basin near its flanks. This would have the added advantage of placing the hot basement within drillable depths.

Basement beneath the Georgina Basin is at an appropriate depth to access through drilling and there are good reasons to expect high heat flow in parts. The challenge is exporting power from a geothermal discovery, given the generally remote location.

The nested McArthur Basin / Beetaloo Sub-basin / Dunmarra Basin region has a high probability of good geothermal systems. Heat flow is likely to be high in places and there are significant shale beds in the Beetaloo Sub-basin and Dunmarra Basin. There is a low probability of finding basement at drillable depths beneath the thick insulating layers, but potential exists for finding in situ permeable sedimentary layers, or layers that can be artificially fractured. Parts of the broader McArthur Basin are close to the electricity line that extends to Katherine, but these areas have a lower chance of insulation.

Geologically, there are good reasons to expect the presence of geothermal systems within the Pedirka / Eromanga basins, or the opportunity to create artificial systems. However, these regions have limited infrastructure.

The dominant risk in the Victoria-Birrindudu Basin is a lack of thermal insulation. The prospect for high heat flow seems good, given the nature of the underlying basement, and the northern section is relatively close to infrastructure.

The Daly Basin is well placed to host areas of elevated heat flow and is also well positioned, relative to infrastructure and markets. Sediment thickness may be inadequate to provide the required thermal insulation in some parts of the basin, but this may be less of an issue where it overlaps other sedimentary successions.

The relatively unexplored nature of the Lander Trough (in the Wiso Basin) makes it difficult to judge the likelihood of geothermal systems being present. Its distance from infrastructure and lack of data render it unattractive as an initial focus of geothermal exploration, though the fundamental geological prerequisites may exist.
The coastal basins (Bonaparte, Money Shoal, Arafura) are all underlain by the high heat-generating Pine Creek Orogen and contain layers of fine-grained sediment. All are relatively close to infrastructure and/or markets. Challenges include a relative lack of drill data.

**Summary**

Geological evidence suggests that all the fundamental requirements for geothermal systems exist within the Northern Territory. Archaean and Proterozoic basement should generate high surface heat flow and most sedimentary basins include formations capable of providing thermal insulation. In addition, the crust is in a state of tectonic compression and the basement is at a drillable depth beneath many parts of the basins. Basins may have naturally permeable formations, or formations susceptible to permeability enhancement.

**References**


The OZ SEEBASE™ Proterozoic Basins study provides a first-pass depth-to-basement model for selected Neoarchaean to Neoproterozoic Australian basins. Combined with the existing Phanerozoic SEEBASE™ model, this now provides a depth to basement surface for all major, relatively undeformed and unmetamorphosed Neoarchaean to Recent Basins (Figure 1). Furthermore, the study correlates basin initiation, sedimentation and major tectonic events on an Australia-wide scale, over the Neoarchaean and Proterozoic. The results of this study can be used as a kinematic, stratigraphic and temporal framework to examine the development of individual basins and the regional influence of tectonic events.

**Key products of interest for mineral exploration include:**

- SEEBASE™ – a 3D model of the top of basement
- sediment thickness
- composition and lithology of basement terranes
- tectonic history for each region – linked to basin-forming events
- interpreted stress directions for each tectonic event
- detailed mapping of regional faults, with reactivation history for each tectonic event (eg, maps of active faults for each event).
The OZ SEEBASE™ Proterozoic basins study presents a new perspective for understanding and assessing Proterozoic minerals systems. For example, the detailed kinematic history of the faults, in conjunction with the basin shape (i.e., the SEEBASE™ model), can be used to assess regional-scale fluid pathways relevant to intra-basinal deposits, such as the lead-zinc deposits of the McArthur region. In exploration for unconformity-related uranium deposits, the SEEBASE™ model provides a first-pass interpretation of the depth of the unconformity. In addition, the basement composition provides a constraint on the potential location of reducing lithologies. In general terms, the SEEBASE™ model can be used directly to indicate areas of shallow cover over areas of prospective basement. The tectonostratigraphic evolution and basement structure provide an exploration framework for mineralisation hosted within both Proterozoic basins and basement.

Tectonic events are broadly grouped into four major time intervals: the Neoarchaean and early Palaeoproterozoic (2775–2050 Ma), the mid–late Palaeoproterozoic to early Mesoproterozoic (2050–1400 Ma), the mid–late Mesoproterozoic (1400–1050 Ma) and the Neoproterozoic (1050–570 Ma). During the Neoarchaean and early Palaeoproterozoic, basins formed along the Pilbara margin, mainly in response to differential movements between the Pilbara and other Archaean cratons. Events in the mid–late Palaeoproterozoic to early Mesoproterozoic were related to the assembly and subsequent intracontinental extension of the Australian continent. The latter phase led to the formation of large, intra-continental superbasins on the North Australian Craton. Mid–late Mesoproterozoic events were due to interactions between Australia and other continents, during assembly of the supercontinent Rodinia. Preservation of sediments from this time period is limited. Neoproterozoic basin-forming events are mainly related to the break-up of Rodinia, and led to the formation of the Centralian Superbasin. Sedimentation in this basin was terminated at the end of the Neoproterozoic, due to compression associated with the amalgamation of the Gondwana Supercontinent.

Production of the depth-to-basement (SEEBASE™) surface and faults was largely based on interpretation of magnetic and gravity data, and was calibrated with well data, magnetic depth models, geological maps and depth data from cross-sections and literature. Derivatives from the SEEBASE™ surface include Proterozoic sediment thickness, total Phanerozoic + Proterozoic sediment thickness (Figure 2) and basement thickness. Tectonic events are correlated to basin formation and the deposition of basin units. Event maps include interpreted active faults and a principal stress direction, which has been assigned to each basin-forming tectonic event.

Figure 2. Total Phanerozoic + Proterozoic sediment thickness for the Australian continent.

The OZ SEEBASE™ Proterozoic basins study was carried out for Geoscience Australia, the Geological Survey of Western Australia, the Northern Territory Geological Survey, Primary Industries and Resources South Australia and the Queensland Government Department of Mines and Resources. Although this study was conducted at the scale of the Australian continent and is best utilised for “big picture” assessments of fluid migration and mineral potential, the same techniques and principles can be applied on a smaller scale, using more detailed data.


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Making the most out of NTGS geophysical data

Roger Clifton

High-resolution airborne geophysics has been a flagship product for the Northern Territory Geological Survey since the first surveys were flown in the early 1980s. Traditionally, when a geophysical survey was flown, the data was delivered as grids, which staff geophysicists would convert into images on paper for integration with other paper maps on light tables. However, two significant advances have evolved in the last few years. One of them is the technique of stitching together grids across the state, in this case the NT. The other is the practicality of serving images live across the internet.

Northern Territory Government exploration initiatives since 1998 have almost covered the Territory in high-resolution magnetic and radiometric data. Any area of the NT can now be studied by using stitches of magnetic, radiometric, elevation and gravity data. It is no longer necessary to have specialist software or specialist skills to turn the data into images and manipulate them, as the stitches have been imaged up and can be accessed across the web using nothing more complicated than a browser. Clients now have the capacity to zoom into the images, render them semitransparent to compare with other images, extract the location of features, email the subsetted images as JPEGs to their own email account, or directly connect the underlying image file into their own GIS workspace. Other software can access these underlying image files through the WMS protocol, combine them with second-party overlays, and serve them to third parties via the internet. STRIKE is an example of such a service.

The Image Web Server (IWS) is a software package that operates on a server at NTGS, manipulating images on a client’s commands through a small applet downloaded onto the client’s own PC, somewhere on the other side of the country or the world. All of the images to be shown in the presentation have been taken from the IWS via this method.

Using the IWS, at the longest scale of interest, Territory-wide, the image of the gravity stitch shows the main tectonic elements of the North Australian Craton. As NTGS collects new gravity data (Petrick this volume) the resolution improves so that, for example, the granite plutons can be more clearly resolved within the image.

On the scale of basins, NTGS’s magnetic stitch has allowed imaging of the magnetic depths in a red-green stereogram, also available on the IWS.

An innovation from NTGS, this technique is yet to be seen elsewhere. (Figure 1).

At intermediate scales, the standard magnetic images of TMI, VD and RTP allow almost everything clients have been able to do with printed maps. For every coloured geophysical image on the IWS, there is a greyscale image of a high-passed version of the same quantity, so that clients can zoom in closer.

When the 100 m cell size of the state stitches is too coarse, regridding or reprocessing the underlying line data is indicated. For such purposes, NTGS’s line data is now fully machine readable, and is the best in the country. Clients with software that can use line data will be able to upload it easily. The data is available from MEIC on CDs and via FTP.

The potential value of line data after some manipulation is demonstrated with an example from the Tennant Creek 1:250 000 mapsheet. Depths to the ironstone ore bodies have been imaged to show three-dimensional structures around existing mines. Further, where there is sufficient contrast in the magnetisation of targets, magnetic sections can be derived.

The improvements due to stitching also extend to the radiometric data. The quality of the data has allowed NTGS to make excellent radiometric stitches, to the point where a new imaging technique has been introduced to provide images of soils and the top of the regolith. The presentation demonstrates reading shape signatures rather than hue signatures from the image to map the regolith (Figure 2).

The elevation stitch of the NT has also been high-passed to create a grey scale relief image, also available on the IWS. The relief image allows clients to track the provenance of soil units identified on the previous image. It will also help track the provenance of geochemical anomalies.
Future geophysics work at NTGS is likely to be dominated by a series of ground-based gravity surveys at 4 km and 2 km spacing. Where there are access issues, NTGS may use airborne gravity acquisition for similar resolution. NTGS will also continue to use geophysical data for modelling, such as the ongoing 3D-modelling in the Tanami Region (Meixner et al this volume). A project is also underway to develop a map of depths to the top of the Kalkarindji flood basalts.

New and upcoming NTGS geophysical surveys

Clarke Petrick

The Northern Territory Geological Survey has completed extensive airborne geophysical surveys during the past 25 years. Approximately 92% of the NT has been covered during this period, with accelerated acquisition made possible over the past 7 years by the NT Governments exploration initiatives, including the current “Building the Territory’s Resource Base” initiative. Data acquisition during 2006 has comprised a ground gravity survey over a large portion of the northeastern Arunta Region and an airborne magnetic/radiometric survey over the entire extent of the Tiwi Islands. To complete geophysical acquisition under “Building the Territory’s Resource Base”, NTGS will be undertaking a high-resolution magnetic and radiometric airborne geophysical survey over the Hodgson Downs–Tanumbirini region in mid-2007.

The Eastern Arunta Gravity Survey is centred on the Jervois mineral field. The survey area extends from Harts Range to the Queensland border, broadly following major geological structures extending through this region. It replaces 11 km-spaced data, acquired with 1960s technology, which was considerably less accurate than that now available. The survey involved helicopter-supported acquisition and processing of over 5500 new gravity stations on a 2 km by 2 km grid, by Daishsat Geodetic Surveyors. The final dataset was publicly released in August 2006.

The primary value of this new data will be in delineating extensions to the mineralised Jervois structures, as well as providing fundamental insights into significant expanses of the poorly outcropping Palaeoproterozoic Aileron Province, which is considered to have potential for Fe-oxide Cu-Au, Ni-Cu-Cr, VHMS- and sedimentary-hosted base metal, and other mineralisation styles.

The new Tiwi Island airborne survey significantly updates the previous geophysical coverage of the islands, which was represented by poorly-located, 1600 m-spaced magnetics, acquired by Alliance Oil Development Australia in 1963. Approximately 25,000 line kilometres of magnetic, radiometric and elevation data has been acquired along north–south flight lines, spaced 400 m apart. It has been linked to the 1981 Litchfield North mainland airborne survey, allowing “re-calibration” of this older radiometric dataset.

The Tiwi Islands airborne survey was completed in November 2006, with the final data released on 7 February 2007. This new data has helped to complete coverage over the NT and increases the prospectivity of the Tiwi Islands. The survey has revealed details of Pine Creek Orogen basement beneath the Cretaceous cover of the islands, and also provides critical new data for mineral sands, bauxite and diamond exploration.

The Hodgson Downs–Tanumberini region encompasses an area with shallow Cretaceous and Cambrian cover over Palaeo- to Mesoproterozoic sediments of the McArthur Basin. The area has extremely low-resolution geophysical coverage (>3000 m line spacing), which was flown by the Commonwealth Government in the 1960s. NTGS will be conducting a 49,437 line km, 400 m line-spaced survey over this area, acquiring magnetic, radiometric and elevation data. During survey acquisition, geophysical imagery will be displayed online via the NTGS Geophysical Image Web Server and final data will be distributed through the Minerals and Energy Information Centre (MEIC). This survey will be the final major data acquisition program under the “Building the Territory’s Resource Base” initiative.
All you want to know on accessing NTGS information

Tracey Rogers

Information projects undertaken or started in 2006 include: a stocktake of the petroleum reports; further improvements to the minerals Industry Reports Management System (IRMS) records; further geochemical data capture; migration of the NTGS and Minerals and Energy websites; and modelling and design of a spatial relational database for geological mapping and geochemistry.

Web delivery systems

The Minerals and Energy and NTGS websites were migrated into a new content management system and launched in July 2006 and 30th September 2006, respectively. The new websites have new NT Government branding and a mandated look and feel. The NTGS website was slightly reorganised to ensure the best possible navigation in the new structure, but little updating occurred. A review of the content has commenced and there will be updates in many areas of the site over the next three months.

The Geophysical Image Web Server (GIWS) had 2687 visits in 2006. Two new NT-wide images, a mosaic of all the NT 1:250 000 geology maps and a mosaic of the 1:250 000 topographic maps of the NT, both georeferenced to GDA94, were added. Final images of the 2006 Arunta East ground gravity survey and the Tiwi Islands airborne magnetic and radiometric survey are now available on GIWS. New NT-wide stitches, incorporating the Eastern Arunta and Tiwi Islands data, are due for release in mid-March.

A significant upgrade of NTGS’s airborne magnetic and radiometric data was completed during the year, including reprojection, removal of corrupt data, replacement of missing datasets, and standardisation of metadata. All NTGS data is now available for download via the Geophysical Archive Data Delivery System (GADDS). The system can be accessed via the Australian government’s geoscience portal at www.geoscience.gov.au/gadds.

A new layer, indicating areas of current NTGS projects, was added to STRIKE in November 2006, and updates to the NT Geology and Geological Regions layers were uploaded in October. The two new mosaic images added to GIWS are also available through STRIKE and serve as useful backdrops to other layers. Other new layers are currently being developed, including the NT regolith.

STRIKE registered 3491 visits during January to July 2006, a 53% rise over the preceding six month period and 3144 visits during July to December 2006.

Spatial data and geochemical data capture

In the latter half of 2006, NTGS started a project to convert older GIS datasets into the current NTGS data dictionary. At the same time, the limited attributes will be updated and further attributes added, to produce vastly improved products. At the end of December 2006, six 1:250 000 mmapsheets had been converted, although attributes are still to be completed.

NTGS geochemical samples and drill collars in the Explorer3 database have increased to 355 180, as of January 2007; 10 684 were added in the last year. All of this data was included in an updated Digital Information Package (DIP 001), released in January 2007, and is also available via STRIKE. Exploration data capture undertaken by TerraSearch over the entire McArthur Basin is almost complete and all open file data will be available to explorers via STRIKE and as a part of DIP 001, when the data is released.

A preliminary version of DIP 007 Geology and Mineral Resources of the Southern Georgina Basin was released in August 2006. The comprehensive GIS dataset has been finalised and includes an extensive number of layers, including geology, structure, drilling, geophysics, geochronology, satellite imagery and administrative data. The final version of the product will be available shortly, and will include a full report, but in the preliminary version, the accompanying text is unformatted and has no figures.

Reports and data management

Work continued on updating the content of IRMS Minerals during 2006. A total of 1988 records were substantially upgraded by the inclusion of subject keywords, drilling and geochemical information, locations and abstracts during 2006. Names of mines, prospects and occurrences are being standardised to match other NTGS databases. Of the estimated 7000 records with no information in key fields in January 2004, approximately 4100 reports have been reindexed, as at the end of January 2006. One hundred and seventy-one legacy, non-statutory reports were also added to IRMS in 2006. Many of these were reports from the former Woodcutters mine.
A systematic upgrade of legacy reports, dealing with bulk commodities and industrial minerals (e.g., limestone and gypsum), was begun in December.

In 2006, 1093 mineral reports were scanned, including 610 small reports which were scanned in-house. Scanning of the remaining non-digital open file reports is scheduled to be finished by June 2007.

A stocktake of the offshore petroleum reports, seismic support data and well logs has been substantially completed. The stocktake identified items that are not indexed in the database, as well as items that have incorrect records and others that have been duplicated. Records are gradually being added and amended as necessary, including those added or changed by the splitting of records that covered more than one item. Over 370 legacy petroleum items and 102 newly received items have been added to the IRMS database in the last twelve months. A stocktake of onshore petroleum reports and data is scheduled before the end of June 2007.

In addition to the stocktake and upgrade of the database, work has started on a review and development of indexes for digital data management, and the identification of seismic data to be transcribed to more robust and archival media has almost been completed. One remaining large onshore survey, consisting of over 4000 x 9 track tapes, is scheduled to be transcribed to industry standard 3592 cartridge media during February and March, 2007.

**NTGS corporate database system**

During the last 12 months, work commenced on the development of a corporate database on an Oracle Spatial platform. The initial proof-of-concept phase includes the conversion of the existing MS Access geochemistry and drilling database to the new platform and the creation of a spatial database for geological mapping. The data model is compatible with GeoSciML, an international high-level data model, which will enable easy transfer of data between jurisdictions and organisations.

The modelling and design stages have been completed and building of the database is well underway. It is anticipated that testing will begin in March 2007. On completion of this phase, a review will be undertaken to consider the next steps in developing an integrated corporate system. Although in the short term, the system will primarily impact the internal processes and efficiency of NTGS, in the longer term, it will enable public client delivery systems to be directly connected to the production database, resulting in more functionality, including the ability to serve data in GeoSciML.

**Diverse terranes and mineral potential of the Casey Inlier, Arunta Region**

*Dorothy Close¹,², Ian Scrimgeour¹, Chris Carson³, Jon Claoué-Long³*

The Casey Inlier (HALE RIVER⁴) comprises Palaeoproterozoic basement that forms an isolated inlier within the northeastern Amadeus Basin. Recently acquired SHRIMP U-Pb zircon geochronology has confirmed the subdivision of the Casey Inlier into structurally bounded domains, defined by lithological packages, metamorphic grade and protolith ages (Close et al 2006). The Casey Inlier is now interpreted to contain elements of both the Aileron and Warumpi provinces of the Arunta Region, with locally distributed effects of the 1770–1760 Ma Yambah Event. The inlier also contains a newly recognised late Mesoproterozoic basin succession that underlies the Amadeus Basin. The four structurally-bounded domains are described below:

**Eastern domain**

The eastern domain comprises metasediments that include metapelite, metapsammite, quartz-magnetite layers, graphite-bearing calcisilicates and marble, together with mafic to ultramafic units and biotite granite. These lithologies have all been pervasively overprinted by an upper amphibolite-facies NW–SE-trending fabric. SHRIMP U-Pb zircon dating of the metasediments in the eastern domain has yielded an interpreted maximum deposition age of 1845 ± 6 Ma, whereas dating of a representative sample of the felsic intrusives of this zone has yielded a magmatic age of 1817 ± 3.9 Ma.

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5RECORD OF ABSTRACTS
Central domain

The central domain comprises granulite-facies migmatitic metapsammites, lesser metapelites and felsic to mafic intrusive rocks. The metasedimentary package in the central domain is relatively homogeneous, compared to the eastern domain. SHRIMP U-Pb zircon dating of granulite-facies metasediments in the central domain has yielded an interpreted maximum deposition age of 1865 ± 5 Ma, and dating of metamorphic rims on zircon within this metapelitic sample have yielded an age of 1768 ± 5 Ma. This metamorphic age overlaps with a U-Pb SHRIMP zircon crystallisation age of 1770.6 ± 5 Ma for a metagabbro in the central domain, suggesting that intrusions within this domain contributed to the heat source for the granulite-facies metamorphism. Granulite-facies rocks are retrogressed by the same regional amphibolite-facies NW–SE-trending fabric that is seen in the eastern domain.

Cover succession

A structurally bounded sedimentary succession of quartz conglomerate, quartzite and porphyroblastic pelitic schist lies between the eastern and central domains. This succession was deformed under peak upper greenschist-facies conditions, producing a pervasive schistose fabric that parallels the NW–SE regional amphibolite-facies fabric through the eastern and central domains. Kinematic indicators suggest that this greenschist-facies fabric is associated with easterly directed thrusting. SHRIMP U-Pb zircon dating of these metasediments has yielded an interpreted maximum deposition age of 1235 ± 74 Ma. A minimum age constraint for deposition and deformation of the succession is provided by the unconformably overlying Neoproterozoic Heavitree Quartzite (basal Amadeus Basin). This suggests that easterly directed thrusting in the cover succession is most likely to be associated with the 1200–1160 Ma Musgravian Orogeny.

Western domain

The western domain is dominated by magmatic units, comprising abundant muscovite-biotite leucogranite, and lesser biotite porphyroblastic granite and mafic rock. Peak metamorphic grade for this western zone has been interpreted to be amphibolite facies, which defines the regional NW–SE-trending fabric, as observed in the other two zones. Two biotite granites from the western domain have yielded SHRIMP U-Pb zircon crystallisation ages of 1638 ± 4.2 Ma and 1642 ± 3.5 Ma. This is characteristic of magmatic ages within the Warumpi Province and is also the age of the Andrew Young Igneous Complex in the southwestern Aileron Province. Therefore, the structural boundary that defines the eastern limit of western domain may represent a continuation of the Central Australian Suture, the northern bounding structure of the Warumpi Province.

Structural boundaries

Each of the domains of the Casey Inlier is bound by major NW–SE-trending structures, containing an east to northeast tectonic transport direction. These major structures were formed in the Palaeoproterozoic, probably with reactivation episodes. The boundary between the eastern domain and the Cover succession is defined by a multistage, steep, dextral strike-slip fault zone that has been reactivated during the 400–300 Ma Alice Springs Orogeny, so as to offset Amadeus Basin sedimentary rocks. Within the domains, several amphibolite- to greenschist-facies shear zones parallel these bounding structures with associated small- to regional-scale quartz- and dolomite-filled tension gashes suggesting transtension and fluid flow during deformation.

Metallogenic potential and structural influences

Many of the mafic units within the Casey Inlier and within the metamorphic complexes to the north contain anomalous levels of Au (≤71 ppm), Cu (3.4%), Ni (1600 ppm) and Cr (2550 ppm), as determined from whole rock geochemical data taken from different samples. The combination of fertile source rocks and reactivated structures provides indicators for a high level of mineral prospectivity. An example of the prospectivity within the Casey Inlier is the Arthur Pope Cu prospect in the eastern domain, which comprises metasediments overprinted by an amphibolite-facies shear zone. Targeted resampling of this prospect has yielded 21 ppb Au, 10 ppb Pt, ppb Pd, 12 ppm Ag and 8% Cu in one sample. Major structures that have been active from the Palaeoproterozoic through to the Palaeozoic (similar to that at the Arthur Pope prospect) are pervasive throughout the Casey Inlier and provide potential conduits for fluid flow and mineralisation.

Reference


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3Geoscience Australia.
4Names of 1:250 000 mapsheets are in CAPITALS.
Magnetotelluric imaging of the central Australian lithosphere

Kate Selway1,2, Graham Heinson1, Martin Hand1, Ian Scrimgeour3

Background

To reach a detailed understanding of the structure and tectonic evolution of a terrane, geological, geochronological and geochemical data must be integrated with geophysical data that can provide constraints on lithological structure at depth and under cover. Magnetotellurics (MT) is an electromagnetic geophysical technique that measures the electrical conductivity of the earth up to lithospheric-scale depths. Long-period MT can be used to image crustal- to lithospheric-scale features, such as terrane boundaries, major faults and zones of significant fluid flow. As part of a University of Adelaide PhD project, supported by NTGS, two MT surveys were carried out in central Australia (Figure 1), in order to develop a better understanding of the tectonic evolution of the Arunta region and its relationship to the Musgrave Province.

North Australia Craton to Musgrave Province

The ca 1690–1620 Ma Warumpi Province, which forms the southern margin of the Arunta Region, has recently been identified as a possible exotic terrane that collided with the older and more evolved North Australia Craton at ca 1640 Ma (eg Scrimgeour et al 2005). South of the Warumpi Province, the thick Neoproterozoic to Palaeozoic succession of the Amadeus Basin obscures the boundary of this terrane with the Musgrave Province. Long-period MT data were therefore collected along a 360 km-long transect, extending from the North Australia Craton to the Musgrave Province, and crossing the Warumpi Province and Amadeus Basin (Amadeus profile, Figure 1), with the aim of investigating the location, nature and dip of possible boundaries between these terranes.

Modelling of this profile imaged a region of higher conductivity that corresponds in outcrop to the North Australia Craton and a region of lower conductivity that corresponds in outcrop to the Warumpi Province. The comparatively conductive North Australia Craton has been imaged to extend beneath the more resistive Warumpi Province. The boundary between the two regions is sub-vertical at crustal scale (Selway et al 2006), but dips at 45ºS in the mantle, to depths of at least 150 km. We interpret this geometry to reflect lithospheric-scale underthrusting of the North Australia Craton beneath the Warumpi Province, and suggest it may provide a first-order constraint on subduction polarity at ca 1640 Ma. Beneath the Amadeus Basin, where any proposed boundary between the Warumpi and Musgrave provinces would be expected, no major electrical features were imaged. This result, together with seismic reflection data that has been similarly interpreted (Shaw et al 1991), suggests that no major structures exist in the lithosphere beneath the Amadeus Basin and that the Warumpi Province and Musgrave Province may form a contiguous piece of crust.

Eastern Arunta Region

During the Palaeozoic, the eastern Arunta Region was affected by two major tectonic events: the ca 545–450 Ma Larapinta rift and the ca 450–320 Ma Alice Springs Orogeny. During the Larapinta rift, more than 20 km of sediments were deposited in an area between the currently preserved Amadeus and Georgina basins (eg Hand et al 1999, Maidment 2005). The tectonic regime changed from extensional to compressional, with the onset of the intracratonic Alice Springs Orogeny, which was associated with regional-scale rehydration of Palaeoproterozoic basement rocks. MT data were collected along a 150 km-long profile in the eastern Arunta Region, extending from the Amadeus Basin in the south to the Georgina Basin in the north (eastern Arunta profile, Figure 1), with the aims of investigating crustal-scale structures and the extent of fluid flow associated with the Larapinta rift and Alice Springs Orogeny.

Inversion of the MT data shows a broad low-resistivity zone that spatially correlates with fluid-unaffected rocks at the surface and broad zones of higher resistivity, extending to 20 km depth, that spatially correlate with fluid-affected rocks at the surface. The low resistivity is interpreted to be caused by grain-boundary graphite films. In the fluid affected regions, these graphite films are interpreted to have been destroyed by oxidising fluids, leading to higher resistivities. This interpretation suggests that fluid-
rock interaction in the central eastern Alice Springs Orogen extended to lower crustal depths. Fluids could have penetrated to such a depth through initial deposition into the Larapinta rift system and subsequent intracratonic shortening, caused by compressional deformation in the Alice Springs Orogeny. This result highlights the potential use of MT as a tool to explore the depth and nature of fluid flow in the crust.

References


Figure 1. Location of MT profiles carried out in central Australia.

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A new digital 1:1 million-scale geology dataset of the Northern Territory

Ollie Raymond

Geoscience Australia is currently compiling a 1:1 million-scale digital outcrop geology dataset of Australia. The Northern Territory portion of this dataset has just been released (download at https://www.ga.gov.au/oracle/agsocat/textonly.jsp – note: type “surface geology” into the search engine). This dataset adjoins the previously released digital geology dataset of the eastern states of Australia. When completed in 2008, the digital geology of Australia will be a completely seamless dataset, eliminating state boundaries and map tile joins, and will be by far the most detailed and comprehensive geological dataset available, covering the whole nation for explorers, resource managers and land use decision-makers.

The project is being conducted with the full co-operation of all state and territory geological surveys, who have provided the latest, sometimes pre-release, geological mapping data to Geoscience Australia for inclusion in the 1:1 million dataset.

Data compilation

The 1:1 million data is being compiled mainly from the most current 1:250 000-scale geological maps, although in some areas 1:100 000- and even 1:50 000-scale maps have been used, where available. 1:250 000-scale maps are out of date. 1:500 000-scale regional or provincial geological maps are not often used for the compilation of linework, as typically, these maps are thematic and provide only highly generalised geology in areas outside the theme of the map (eg, no Quaternary geology is provided on regional maps of Proterozoic inliers, or no basement geology information is provided on maps of Palaeozoic basins). However, provincial-scale maps often provide valuable information of the latest regional stratigraphic correlations, which can be highly confused between individual 1:250 000-scale maps of different mapping generations.

The 1:1 million data is simplified from the 1:250 000-scale source data by hand tracing over existing maps, and scanning and vectorising these compilation sheets. This technique has been shown to be the most time efficient and consistent compilation method. Simplifying the complicated geological source data, which may have widely differing scales, vintages of publication and geological structure, is beyond the capabilities of automated generalisation in GIS software. There is no substitute for a geologist’s brain for resolving which geological units and structures to display at 1:1 million scale, interpreting the nuances of dozens of individual mapping teams, and edge-matching across map tile and political boundaries.

Dataset features

All geological linework and polygons in the data are fully attributed. Line types include geological contacts, faults, marker beds, dykes and veins. Geological unit polygons are attributed with their full stratigraphic name hierarchy (if applicable), which is current at the time of data release. Considerable effort has been put into coordinating with state and territory surveys and the Australian Stratigraphic Units Database to ensure that the stratigraphic nomenclature is current. Minimum and maximum ages assigned to all geological units indicate the most recent reliable age information.

Cenozoic regolith and rock units have been rationalised across the Northern Territory as part of an effort to standardise the representation of unconsolidated material across the whole of Australia. The 12-fold classification of regolith units includes sand plains, dunes, alluvial, colluvial-residual, lacustrine, estuarine and various duricrust units.

Geological units have been systematically coded to allow easy identification by age and lithology (Figure 1). The broad lithology of the unit is also reflected in a ‘lithgroup’ attribute attached to each unit (eg, igneous felsic intrusives, igneous mafic volcanics, sedimentary siliciclastics, sedimentary carbonates, high-grade metamorphics). This allows easy rendering and analysis of geological units in GIS applications.

At this stage, only a few units have numerical ages assigned to them. The exercise of populating numerical ages for all units is expected to be ongoing for future editions of the 1:1 million Geology of Australia dataset.

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![Figure 1. Examples of the construction of map symbols in the 1:1 million geology of Northern Territory dataset.](image-url)
Digital geological data standards and internet delivery

Ollie Raymond

Problems with delivering digital geological data

Digital geological maps and databases have been available via the websites of Australian geological surveys for some years. However, aside from mismatches in interpretive maps at state borders, each state has their own data structure, and they each may provide a different GIS software format (Figure 1). Industry clients have identified the process of having to reconcile the differing state data structures and software formats to be a major source of wasted time and money, when compiling data provided by governments (Minerals Exploration Action Agenda 2004). Reconciliation of data structures across state borders may be as simple as renaming attributes in a data table, or may involve a much more complicated and time-consuming reconstruction of attribute structures. A standard, open-source data format is required to address these issues.

Downloaded datasets from websites provide only a snapshot in time of the data. To ensure that they have the most recent data, clients must periodically check with the source website to see if the data has been updated and, if so, download a new copy. To alleviate this issue, an internet broadcast Web Map Service (WMS) or Web Feature Service (WFS) from geological surveys could provide clients with continuously updated geological data.

The solution – GeoSciML

National and international efforts are now underway to standardise the format and delivery of geological data exchanged via the internet. In 2003, the Commission for the Management and Application of Geoscience Information (CGI), a part of the International Union of Geological Sciences (IUGS), established a working group to develop a data model for exchange of geological map data, and an encoding of that model based on GML (Geography Markup Language). The data model is based on prior work carried out by North American, European and Australian geological surveys and research organisations. The current working group contains members from Australia (CSIRO, Geoscience Victoria, Geoscience Australia), USA, Canada, UK, France and Sweden.

The result is GeoSciML (Geoscience Markup Language). Version 1.1 was released in Liege, Belgium in September 2006 and is publicly available on the CSIRO SEEGrid website (https://www.seegrid.csiro.au/twiki/bin/view/CGIModel/WebHome). Australian geological surveys have had an opportunity to review the model, have had input into model vocabularies (ie, lists of geological terms), and have agreed, in principle, to adopt the GeoSciML standard as the Australian data exchange standard.

This first version of GeoSciML is a “lite” version, which accommodates geological information that is commonly represented on geological maps. The working group is currently addressing issues identified in version 1.1 and is extending the GeoSciML model to cover the more comprehensive geological information that many geological organisations compile in relational databases. GeoSciML version 2 is planned to be released in 2008.

What is a data exchange standard?

GeoSciML is designed to standardise geological data when it exchanged between organisations. It is not meant to supplant data structures that may already exist within an organisation. Data providers only need to map their internal data structures to the GeoSciML model structure, when delivering data to clients. In this way, users can expect similarly formatted data from organisations that may use different internal enterprise database structures.

GeoSciML WMS/WFS testbed

In addition to the data model, the GeoSciML working group constructed a testbed to demonstrate the delivery of digital geological map data to the internet, via a WMS/WFS service, based on OGC (Open Geospatial Consortium) standards (Duffy et al. 2006). GeoSciML-formatted data was served from seven WMS/WFS sites in Canada, USA, UK, France, Sweden and Australia (Figure 2). The WMS/WFS data can be accessed through web client sites in Canada, France, and more recently, through Geoscience Australia. This testbed demonstrates the ability to display, query, select and download GeoSciML-formatted geological data.

Geoscience Australia served a portion of the Australian 1:1 million-scale dataset, covering Victoria, to the GeoSciML testbed. The whole 1:1 million geology of Australia will be available via WMS/WFS service in the future, in parallel with the international OneGeology project (http://www.bgs.ac.uk/onegeology/home.html), which seeks to deliver geological map data from around the world using the GeoSciML WMS/WFS model.
Although users are currently limited to using web client software to access complex WFS services such as GeoSciML, major GIS software vendors are working to enable their GIS applications to read complex feature models. Existing GIS applications are able to read simple XML feature models, but software vendors (eg, ESRI, MapInfo) recognise that their user communities require access to complex data structures such as GeoSciML.

It is envisaged that the WMS/WFS GeoSciML model will eventually become the delivery model for all Australian government geoscience data. This will allow our clients to display, interrogate, download and integrate geological data from multiple sources in a single, consistent and documented format.

Reference


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Figure 1. Differing data structures in digital data provided by geological surveys at the NT/WA border.

Figure 2. Configuration of the GeoSciML testbed. Data is served from globally distributed WMS/WFS services, and accessed through a web client in Vancouver, Canada.
Why is the Pine Creek Orogen so mineralised?

Masood Ahmad

The Pine Creek Orogen (PCO) is part of the North Australian Craton and is correlated with other Palaeoproterozoic domains of northern Australia. Archaean (>2.5–2.7 Ga) granite and metamorphics are overlain by Palaeoproterozoic strata comprising sandstone, mudstone, and minor carbonate and volcanic rocks. Its age is constrained between 2.5 Ga and 1.86 Ga, and the succession is divided into two supergroups. The older Woodcutters Supergroup comprises <2.5 to 2.02 Ga arenites, stromatolitic dolostone and pyritic carbonaceous shale. The younger Cosmo Supergroup comprises carbonaceous shale, BIF, mudstone and tuff, succeeded by a monotonous flysch succession. Zircons from the tuff beds have provided an age of 1863 Ma, confirming a major depositional break of about 150 Ma between the Woodcutters and Cosmo supergroups (Figure 1).

Regional metamorphism, deformation and plutonic activity, associated with the 1.86–1.845 Ga Nimbubah Event of the craton-scale Barramundi Orogeny, followed sedimentation. Metamorphic grades range from sub-greenschist facies in the central PCO to upper amphibolite facies along the western and eastern margins. A felsic magmatic event (Cullen Event) at 1.83–1.82 Ga closely followed the Nimbubah Event and caused widespread thermal metamorphism. Coincident extensional tectonics in the South Alligator Valley produced narrow northwest-trending grabens, which were infilled by sedimentary and felsic volcanic rocks.

In comparison to other orogenic domains of the North Australian Craton, eg, Tennant Region (Au-Cu-Bi), Tanami Region (Au), Murphy Inlier (U±Au, Cu, W) and Halls Creek Orogen (Au, Ni, Cu-Pb-Zn), the Pine Creek Orogen is truly a multi-commodity metallogenic province and is extensively mineralized. It contains over 1500 mineral occurrences, including Au, U, Cu, Pb, Zn, Ni, Co, Pt, Pd, Sn, Ta, Fe, Mg and Phosphate. Production plus resources of major commodities include Au (13 Moz), U$_3$O$_8$ (400 000 t), Cu (750 000 t), Co (105 000 t) and Ni (93 000 t).

On the basis of structure, metamorphism and granite types, the PCO can be divided into five sub-provinces, each having a distinctive suite of mineral commodities. The Litchfield Province represents an area of isoclinally folded amphibolite-to-greenschist-facies metamorphic rocks. It is characterised by the presence of predominantly S-type granites and associated swarms of Sn-Ta-bearing pegmatites. The Rum Jungle and Central regions have sub-greenschist-facies metamorphic grades and simple structures dominated by upright northwest- or north-trending folds. The Rum Jungle Region surrounds the Archaean basement inliers and exhibits polyphase upright folds, domes and basins. It is endowed with a wide spectrum of mineral commodities including U, Zn-Pb-Ag, Cu-Pb-Ni-Co, magnesite, phosphate and iron ore.

Gold deposits are usually contained within folded, faulted and regionally metamorphosed flysch successions. Nearly all are within the thermal aureole of granites of the Cullen Supersuite. Gold is present in quartz veins, or stockwork, or occurs as stratiform lenses within BIF. It is accompanied by white mica, chlorite, K-feldspar, pyrite and arsenopyrite, with some pyrrhotite, chalcopyrite, sphalerite and galena. The base-metal sulfides are paragenetically younger. Grades are usually less than 3 g/t Au and individual deposits range from less than 0.5 to more than 50 t of gold. Fluid inclusion and stable isotope studies, spatial associations and geochronological data on these deposits are consistent with an intrusion-related thermal aureole gold model, with possible mixing of a reduced CH$_4$-CO$_2$-bearing low- to moderate-salinity fluid and an oxidised high-salinity fluid.

The Browns deposit is within black carbonaceous shale of the Whites Formation and is the largest base-metal deposit found to date in the PCO.
The large size and unusual composition, including 70 Mt of black pelites, with an average base metal content in excess of 4% Pb + Cu + Ni + Co + Zn, up to 8% C and up to 7.6% S, makes it distinct from other sediment-hosted stratiform deposits. The geologic setting, and stable isotope, textural and mineralogical data are suggestive of a syndiagenetic origin, with possible later local remobilization.

World-class uranium deposits of the PCO are near the unconformity with overlying platform-cover arenites of the McArthur Basin. These deposits account for about 20% of Australia’s total U resources inventory, and represent about 30% of the world’s low-cost category U resources. Most researchers favour a model in which U-bearing oxidised fluids, sourced from overlying platform-cover arenites were reduced by reaction with suitable lithologies in the PCO, so as to precipitate U. However, an alternative uranium source is possible, either from Archaean basement or overlying first-cycle arenites.

A series of low-temperature, hydrothermal, haematite-rich stratabound lenses at Frances Creek are hosted within ferruginous and carbonaceous pelites of the Wildman Siltstone. They contain a recently investigated resource of 6.84 Mt of 60.6% Fe.

A comparison of lithostratigraphy, based on newly acquired geochronological data, shows that strata older than 1860 Ma, which are assigned to the Woodcutters Supergroup, are either absent, or not yet identified in other orogenic domains of the North Australian Craton. This older succession hosts the major U±Au, Cu-Pb-Zn-Ni-Co, magnesite, phosphate and iron ore deposits of the PCO. The younger Cosmo Supergroup essentially contains small- to medium-sized deposits of Au, Sn and base metals. Rock formations that are stratigraphically equivalent to this younger supergroup are present in all the orogenic domains of the North Australian Craton and are essentially endowed with Au deposits. Efforts are needed to identify older rock groups in these domains and their surrounds, as they may have potential for other commodities.

Irrespective of the ore genesis models applied, it thus appears that stratigraphic setting has played a major role in the both the genesis and location of the multitude of deposits contained within the Pine Creek Orogen.

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**Geochemistry of mafic rocks in the Litchfield Province, western Pine Creek Orogen: Evidence for a Palaeoproterozoic arc-related setting and links to the Halls Creek Orogen**

**Linda Glass¹**

The Litchfield Province represents the westernmost margin of the Palaeoproterozoic Pine Creek Orogen, Northern Territory. It is bounded by the Mesozoic Bonaparte Basin to the west and by the northeast-trending Giants Reef Fault to the east (Figure 1).

It comprises low- to high-grade metamorphic rocks, which were extensively intruded by ca 1862 Ma voluminous granitoids (NTGS-GA Geochronology Project, unpublished data). The timing of peak metamorphism in the high-grade Hermit Creek Metamorphics and the mid-amphibolite facies Fog Bay Metamorphics is constrained by SHRIMP U-Pb monazite geochronology at ca 1855 Ma (Carson et al. 2006). Igneous activity of this age has also been recorded in the western and central Halls Creek Orogen (HCO, Blake et al. 2000). It has long been speculated that the Litchfield Province represents an extension of the HCO to the northeast.

This study focuses on a specific suite of mafic rocks in the province, the Wangi Basics, which comprise a suite of gabbros, leucogabbros, gabbronorites, dolerites (the majority of which have been metamorphosed to amphibolite facies) and rare basalt. They occur as scattered outcrop/subcrop to the west of the Giants Reef Fault. Magnetic imagery suggests that they may be more extensive in the subsurface, particularly in the west beneath.

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Permian cover. This study concentrates on the geochemistry of the individual suites to determine the nature of parental magmas and their tectonic affinity.

During the 2006 field season, samples of the Wangi Basics were collected throughout the province (except for Aboriginal freehold areas, where access is restricted) and were submitted for geochemical analysis. These were supplemented by geochemical data obtained in previous investigations. Although the majority of the Wangi Basics are metamorphosed, this metamorphism was isochemical and geochemical features of the protoliths are well preserved.

Six main geochemically distinctive suites of rocks were identified:
1. High-alumina gabbros and dolerites (HAG).
2. Depleted, low-Ti gabbros (LTG).
3. Low-Ti dolerites (LTD).
4. High-Ti, rift tholeiites (HTT).
5. Metamorphosed noritic cumulates (MNC).

A large igneous body in the southern Wangi Basics (Daly River region) is comprised largely of HAG suite rocks. These are highly aluminous, with $\text{Al}_2\text{O}_3 > 17$ wt% and as high as 22 wt%. The majority of samples also have high CaO (10–14 wt%). Of these, most (but not all) have positive Eu anomalies ($\text{Eu}/\text{Eu}^* >> 1$), indicating that they are plagioclase accumulative. However, some high-alumina samples have smooth Rare Earth Element (REE) patterns, (Eu/Eu* ca 1 and mg# ca 67), indicating that they may have been parental liquids to the suite. The HAG cumulate suite could have been derived by a combination of olivine and pyroxene fractionation/accumulation and plagioclase accumulation involving hydrous magmas within a subvolcanic magma chamber. The inferred parental liquids are geochemically similar to high alumina basalts (HAB), which are characteristic of oceanic and continental arc environments around the world.

The LTG suite occurs in the central Wangi Basics. They are characterised by unusual negative-sloping REE patterns, which indicates that they were derived from a depleted upper mantle source (ie, one that experienced a previous episode of melt extraction). MORB-normalized element abundance diagrams are distinctive. They show positive Sr peaks, coupled with low Ta-Nb, which is strongly characteristic of an island arc environment. A search of worldwide geochemical databases show they are most similar to pillow lavas of the Troodos ophiolite complex in Cyprus (Figure 2a, b) which is a section of obducted, back-arc oceanic crust.

Figure 2. (a) Chondrite-normalised and (b) MORB-normalised diagrams showing Wangi low-Ti gabbros compared to Troodos high-Ca boninites – grey boxed area (boninite data from T Falloon, 2007). (c) Chondrite-normalised. (d) MORB-normalised diagrams, showing Wangi low-Ti dolerites compared to primitive arc tholeiites – grey boxed area (compilation of published primitive arc data, 2007).
The LTD suite comprises dominantly doleritic rocks that outcrop to the north and south of the LTG ‘Troodos-type’ suite. Geochemically, the LTD suite is characterised by an arc-like signature, combined with flat REE patterns; they are reminiscent of primitive arc tholeiites, known worldwide from oceanic and continental arc settings (Figure 2c, d).

The HTT suite comprises a series of linear sills to the southwest of the main outcrops of the Wangi Basics. They have elevated LREE and positively sloping REE patterns. Geochemically, they are similar to rift-related tholeiites, which typically occur in attenuated passive margins or in post-collisional tectonic settings.

MNC suite rocks outcrop alongside the northern LTD suite and comprise formerly orthopyroxene-rich cumulates, with up to 22% MgO. They are now metamorphosed to tremolite-actinolite assemblages. They are most likely cumulates from the primitive arc-like LTD suite. MFG rocks also outcrop in this area and represent evolved compositions with positive Eu anomalies that have been metamorphosed to garnet amphibolites. Their relationship to other suites at this stage is not clear.

Figure 3 shows the distribution of newly identified individual suites in the Litchfield Province.

The distinctive geochemical signatures displayed by the majority of the Wangi Basics indicate that they are associated with an ancient island arc tectonic environment. By analogy with the Troodos ophiolite, the LTG suite probably represents a mid-level ‘slice’ of back-arc oceanic crust; no high-level pillow lava equivalents have yet been identified from the Wangi Basics. The HAG suite, which forms a large igneous body in the Daly River region (Figure 3), most likely represents the base of a subvolcanic magma chamber, formed within an island arc environment from parental HAB magmas. HAB are derived from primitive arc magmas by crystal fractionation under hydrous conditions (Crawford et al 1987). The magma chamber was subsequently buried and metamorphosed to amphibole facies conditions before exhumation. The LTD are a suite of relatively primitive arc tholeiites that most likely represent feeder dykes to lavas that have subsequently been eroded. They may have been part of an island arc originally located outboard of the back-arc, but subsequently tectonically juxtaposed with the back-arc. The HTT suite is most likely a late post-collisional suite, as they already have an arc-like subduction signature, which may have been acquired from subduction-modified mantle. A number of potassic rocks have been identified southeast of the HTT and may be part of this post-collisional suite (Figure 3). It is possible that the Wangi Basics represents part of a dismembered Palaeoproterozoic ophiolite suite; however, the suite only appears in section at subvolcanic levels, because basalts are rare and peridotites have not been identified.

The Troodos complex in Cyprus is the host to historical Cu-rich volcanic hosted massive sulfide (VHMS) deposits (Galley and Koski 1999). The majority of the mineralisation is hosted within pillow lavas, but some mineralisation is found in the sheeted dyke complex, stratigraphically below these lavas. In the Daly River region, a belt of copper anomalies, hosted within the 1862 Ma felsic Warrs Volcanic Member, lies immediately east of the Wangi Basic “Troodos-type” LTG suite rocks. One copper occurrence has been documented within the Wangi Basics LTG suite, but further work is required to determine the nature of this occurrence.

The precise age of the Wangi LTG and LTD suites is at present unknown. Preliminary comparative geochemistry suggests that the LTD suite may be co-magmatic with the Warrs Volcanic Member and further investigations are underway. SHRIMP U-Pb zircon dating of garnet-bearing amphibolite is currently in progress. Preliminary data suggest
an age in the range 1865–1850 Ma (Chris Carson, Geoscience Australia, pers comm 2007), consistent with most other volcanic and intrusive units in the region.

Given the geochemical similarities with the Troodos complex in Cyprus, the Wangi LTG suite has similar potential for hosting copper deposits. However, the economic potential of the HAG suite is considered to be low.

The Litchfield Province is thought to represent a structural and tectonic continuum of the western zone of the HCO in the Kimberley region of Western Australia (Pietsch and Edgoose 1988). Sheppard et al (1999) documented depleted Palaeoproterozoic metabasalt (Tickalara Metamorphics) in the central zone of the HCO, as being representative of an oceanic island arc/backarc basin tectonic setting [see also Tyler et al (1999) and Griffin et al (2000)]. The results of the current geochemical investigation support this tectonic concept, but not the intraplate hypothesis for the origin of the HCO proposed by earlier workers.

Results indicate that the majority of the Wangi Basics are heterogeneous, lithologically and geochemically, analogous to rock units in the central zone of the HCO, and formed in a volcanic island arc/back arc basin setting. Further work is required to place other rock units of the Litchfield Province into tectonic context.

References


Notes

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Alligator Rivers uranium field numerical modelling project: Using computer simulations of geologic processes to aid exploration

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This project investigates uranium deposits in the Alligator Rivers area of the Northern Territory using 3D deformation-fluid flow, geochemical modelling and 2D reactive transport modelling (computational simulation) of ore forming processes. The objective of this effort is to develop a predictive understanding of the processes and factors that control the formation of these uranium deposits and attempt to predict the relative favourability for the location of new deposits.

Viable models, based on computational simulation, for the formation of some known uranium ore systems in the ARUF will be established and used as a basis for predicting where new discoveries might occur in less well explored areas of the ARUF. They will also assess whether it is likely that very high-grade uranium deposits, similar to those hosted in the Athabasca Basin, are present in less explored areas underneath the Kombolgie Subgroup.

The study will focus on the Nabarlek, Ranger, Jabiluka and Koongarra deposits, in order to place constraints on how the ore bodies were formed. This may result in the generation of several viable working hypotheses, in order to generate the inferred fluid flows at the time of pre-ore alteration and mineralisation. Some of the factors that will be incorporated into deformation and fluid flow models include rheology and permeability variations, and far-field-stress orientation during mineralisation. Reactive transport modelling incorporates the coupling between fluid flow, heat, transport and chemical reaction processes. All modelling incorporates fluid pressure, the geometries of geological units and elements (eg faults), and the relative permeabilities of basement units and overlying sandstone.

This study will establish the composition of hydrothermal fluids responsible for wall rock alteration and mineralisation. Speciation calculations have shown that the total uranium dissolved in the fluid is a strong function of the oxygen fugacity of the fluid (Figure 1).

Figure 1. This phase diagram constructed in The Geochemist Workbench shows that decreases in aO2 and/or the pH of the fluid via reactions with the host lithology (ie, graphite and/or kaolinite) results in the decrease in the solubility of uranium. This diagram also shows that the higher pH values of the ore fluid associated with Alligator River deposits contains uranyl chloride complexes as opposed to uranyl carbonate complexes for ore fluids of the Athabasca region with more neutral pH values. These differences will be addressed in the 'five question' analysis.

Figure 2. A box diagram showing the modelling methodology of the fluid infiltration model used in this study (adapted from Cleverley and Oliver 2005). Where i = step and n = wave. So that at step i=0 fluid is reacted with rock and the resulting equilibrium fluid is passed to step i=1 for i steps. This is repeated n times and so the fluid infiltration front advances at each wave.

Studies of the major unconformity-related uranium deposits of the Alligator River region have identified a complex alteration history with pre- and syn-ore alteration assemblages. Therefore, compositions of both a pre- and syn-ore hydrothermal fluid will be established using fluid inclusion data and by conducting fluid infiltration models, which reproduce the complex alteration observed within the four major deposits mentioned above. Fluid-infiltration models (schematic representation in Figure 2) involve infiltrating fluid into a column of rock, while a series of geochemical/ and mineralogical fronts develop behind it.
Chemical models will include:

• infiltration of a pre-ore oxidised saline Na-Ca-Cl brine, containing Mg\(^{2+}\), Fe\(^{2+}\), K\(^{+}\), low U, SO\(_{4}\)\(^{2-}\) and C.

• infiltration of a syn-ore highly oxidised, highly saline and low pH Na-Ca-Cl brine, containing Mg\(^{2+}\), Fe\(^{2+}\), K\(^{+}\), low U, SO\(_{4}\)\(^{2-}\) and C.

Three different host rock lithologies will be modelled, as follows:

• Garnet-quartz-mica schist, representing the lower Cahill Formation present at Koongarra.

• Quartz-mica-plagioclase schist, representing the Cahill Formation at Ranger and Jabiluka.

• Amphibolite, representing the Myra Falls Metamorphics at Nabarlek.

Key questions pertaining to these deposits that will be addressed include:

• What are the key similarities and differences revealed by a “Five Questions” analysis of the Athabasca Basin and ARUF? Do these lead to a series of tests?

• Why is Nabarlek relatively high grade? Could an understanding of this question provide a basis for a predictive model for undiscovered ore systems with an average grade ≥2% \(\text{U}_3\text{O}_8\)? To address this problem, first-order approximations on the fluid fluxes required to produce high-grade uranium deposits will be made, using models that will involve varying the fluid:rock ratios used in the fluid infiltration models for each of the host rock lithologies.

• At Nabarlek, there are three sub-parallel faults, but it appears that only one is mineralised. Under what circumstances is such a result likely to occur?

• Can we explain the detailed alteration parageneses at Nabarlek and Jabiluka established in the work of Polito \textit{et al} (2004, 2005)?

• At Koongarra, why is the mineralisation localised close to the graphite-chlorite-quartz schist and not in, or close to the larger fault that brings the host succession in contact with the Mamadawerre Sandstone?

• Why is all of the known mineralisation in the basement? Is there a viable model for a pre-Kombolgie Subgroup mineralised event that takes into account geochemical and structural data at the various deposits? Alternatively, with post-Kombolgie timing, could an ore system be hosted partly or wholly within the Kombolgie Subgroup, and if so, under what circumstances?

• Is carbon content relevant to ore formation under some circumstances? What is the role of chlorite in uranium precipitation? To answer this question various fluid infiltration models will test the reducing and/or buffering capacity of the host lithologies, by changing the modal proportions of Fe-bearing minerals and the graphite component of the host rock.

Initially, deformation and fluid flow models (Figure 3) will be run in isolation from reactive transport models. Clearly, formation of these ore systems has involved the coupling of physical and chemical processes, and as modelling progresses, we will be integrating the results from both deformation and fluid flow models, and reactive transport models, so that loosely coupled models can be run. In the synthesis stage, we will develop a predictive model for uranium mineralisation, in which we will identify some circumstances under which larger and possibly higher-grade uranium deposits may exist. We will not be able to produce a comprehensive description of favourable ore environments as there are too many scenarios to test in this project. Nevertheless, parameters which we will be able to define include:

• stress conditions at the time of mineralisation

• favourable geometries and rheology contrasts for dilation.

• favourable chemical gradients for uranium deposition. For example, fluid mixing is considered to be a viable method for the deposition of uranium (Wilson and Kyser 1987; Bray \textit{et al} 1988). Therefore, some models will include the infiltration of an uraniferous oxidising solution with \(\text{CH}_4\)-\(\text{CO}_2\)-rich fluid. The mineralogy of the rock column within models investigating the processes of fluid mixing will be varied to represent the various host rock lithologies listed above.

All of the above parameters will also provide a very strong basis for predictive modelling of new uranium prospects to identify favourable conditions for ore deposits and optimum locations and strategies for drilling.
Targeting Callie-style gold mineralisation through the regolith in the Tanami Region

Lisa Worrall1,2,3, John Joseph1,4, Brad Pillans1,5, Dirk Kirste6, Tony Eggleton7, Martin Smith1,2, Nathan Reid1,4, Anna Petts1,4 and Steve Hill1,4

A number of significant gold deposits, including the world-class Callie gold deposit, are located in the Tanami Region in Northern Australia. The Callie deposit is characterised by sheeted vein sets in the hinges of tightly folded Palaeoproterozoic deep-water sediments, known as the Dead Bullock Formation. Gold is believed to have precipitated at redox fronts, established when oxidised gold bearing fluids encountered reduced graphitic sediments.

Exploration for Callie-style deposits in the Tanami is hampered by two factors: the poor contrast in the physical properties of elements of the primary mineral system, which has made the interpretation of airborne geophysical datasets problematic; and the extensive development of the regolith. The regolith is comprised of both in situ and transported regolith materials and elements of the weathering profile. It may be over 200 m thick and has been dated to the Permo-Carboniferous.

The collaborative research project “Exploring through the cover in the Tanami” has been working to overcome these exploration challenges and to develop an effective strategy for targeting mineralisation through the regolith. The strategy which has been developed integrates the interpretation of geophysical and geochemical data and has enabled the identification of preferred geochemical sampling media. This presentation will highlight aspects of that work, relating to the geophysical expression of the mineral system within the regolith.

References


Figure 3. Example of initial geometry for deformation - fluid flow models (Jabiluka).
Overview of new seismic data from the Tanami Seismic Collaborative Research Project

Leon Vandenberg¹, David Huston², Bruce Goleby³, Leon Bagas⁴, Leonie Jones⁵, Patrick Lyons⁶, Wade Johnston⁶, Tim Smith⁶, Tim Barton⁶.

Introduction

From May through to July 2005, seismic reflection data totalling 720 line kilometres were acquired across the Tanami Region of Western Australia and the Northern Territory (Figure 1). The seismic survey was part of an ongoing collaborative project between Geoscience Australia (GA), the Northern Territory Geological Survey (NTGS), the Geological Survey of Western Australia (GSWA), Newmont Exploration Pty Ltd and Tanami Gold NL. The seismic program was conducted by ANSIR (National Research Facility for Earth Sounding), through its facilities manager, Terrex Seismic Pty Ltd. The program was designed to investigate the crustal architecture of the Tanami Region and key structures relating to gold mineralisation, through the acquisition and interpretation of high-quality regional seismic data. The Tanami seismic data and interpretations were released as a series of workshop notes in June 2006 and are available through Geoscience Australia (Tanami Seismic Workshop Notes 2006).

The main objectives of the Tanami project were to:

- image the geometry of the main crustal-scale features
- determine relative temporal relationships between crustal-scale features
- determine the thicknesses of the main stratigraphic packages and granite bodies
- investigate potential tectonostratigraphic relationships between stratigraphic packages and controlling structures
- investigate the crustal setting of mineralised domains
- better define the relationship of Tanami Group stratigraphy to underlying early Palaeoproterozoic or Archaean basement
- investigate the nature of deep crustal gravity features
- investigate the character of the Tanami–Arunta boundary.

Regional geology

The Tanami Region, approximately 600 km northwest of Alice Springs and straddling the NT–WA border, hosts the Callie, Tanami, Granites, Groundrush, and Coyote mine sites, and the Bald Hill deposits. The region has gold resources and production in excess of 10 million ounces and is considered highly prospective for further large gold deposits.

Deposition of sediments and granite emplacement in the Tanami Region postdated the Barramundi Orogeny (and associated 1880 Ma metamorphism). The Tanami Group (1864–1830 Ma) is predominantly turbiditic, consists of the Stubbins, Dead Bullock and Killi Killi formations, and was probably deposited on extended sub-continental Archaean crust (D Maidment, Geoscience Australia, unpublished data, Bagas et al 2007, Cross and Crispe 2007, Crispe et al 2007). The Tanami Group hosts most of the regions 1800 Ma gold deposits (Cross et al 2005). Sedimentation of the Tanami Group was terminated by the 1830 Ma Tanami Event, the onset of which was probably associated with the ongoing subduction and continental collision processes responsible for the Hall Creek Event (1835–1805 Ma), further to the west (Sheppard et al 1999). The period between 1825 and 1790 Ma was punctuated by several periods of localised rifting, volcanism and sedimentation, regional shortening and granite intrusion. Sediments and volcanics of the Ware Group and Mount Charles Formation were deposited at 1825–1810 Ma and 1800 Ma, respectively. Most of the economic gold deposits formed in association with faults and shear zones at around 1800 Ma (Crispe et al 2007, Huston et al 2007). These rocks are overlain by rocks of the Pargee Sandstone (<1735 Ma) and the Birrindudu Group. The results of geochronological studies in the region indicate that correlatives of the Tanami Group extend into the northern Arunta Region to the south (A Cross and J Claoué-Long, Geoscience Australia, unpublished data). Late brittle faults cut all units in the Tanami Region and...
are probably due to the King Leopold Orogeny in the Halls Creek Region and Kimberly Craton, and the younger Alice Springs Orogeny.

Seismic survey

The Tanami seismic survey consisted of four regional deep seismic traverses, 05GA-T1 through to 05GA-T4 (Figures 1, 2, 3, 4, 5, 6). Traverse 05GA-T1 is a northwest–southeast regional transect, whereas traverses 05GA-T2, 05GA-T3 and 05GA-T4 provide orthogonal three-dimensional (3D) control on the geometry of regional geological features, defined by previous mapping and modelling. The seismic traverses were also planned to provide information on deeper structures within known mineral-rich areas. By defining the regional 3D crustal architecture, mineralisation settings and controls, the program aims to minimise exploration risk and increase exploration success, through the provision of data that may enhance prospective target generation.

The seismic reflection data were acquired using ANSIR’s seismic reflection system, consisting of a 240 channel ARAM24 (24 bit) seismic reflection recording system with 10 Hz geophones and 3 x IVI 60 000 lb vibrators operating at all times. Geoscience Australia, through ANSIR, also collected wide-angle velocity data along regional traverse 05GA-T1 to provide additional velocity constraints on the upper crust.

Processing commenced in June 2005 and was completed in June 2006. Processing was undertaken using the DISCO/FOCUS seismic processing package. Several of the major processing steps, identified as being most critical in improving the quality of data, included refraction statics corrections, velocity analysis and correct migration of the data.

Interpretation of the seismic data by geoscientists from all of the collaborative organisations commenced in late 2005 and was completed in June 2006. Results from the Tanami seismic project data and interpretations were released to the public at the Tanami Seismic Workshop, June 2006 (Tanami Seismic Workshop Notes 2006).
Seismic survey results

Large-scale features, interpreted from the seismic data, include the following:

- The Moho appears to have been imaged on all sections, and ranges in depth from 35–60 km.
- Changes in Moho topography appear to be coincident with significant observed changes in other geophysical data, in particular, regional gravity.
- Many large crustal structures appear to extend from the surface to the Moho boundary. Several are interpreted to be of fundamental significance to the architecture of the crust.
- There appears to be a broad correlation of known mineralised domains and the position of secondary structures associated with larger-scale features.
- Domains with previously unrecognised complexities in the crustal architecture have been imaged. Several of these domains, which have been subjected to only limited exploration, display relationships similar to those imaged in known mineralised areas.
- Several granite bodies in close proximity to known mineralisation appear to have been successfully imaged. Although aerially extensive and coincident with regional density lows, the imaging suggests that the granite bodies are relatively thin (<5 km thick). No significant granite bodies were imaged in the middle to lower crust.

- Broad correlations appear to exist between the geological relationships in these initial seismic interpretations to those modelled in the top 15 km of the crust in the Tanami 3D web-model (www.ga.gov.au/map/web3d/tanami/index.jsp). Significant refinement and improvement to the 3D web-model are anticipated, following incorporation of the new seismic data.
- In light of our interpretations, it is anticipated that the seismic data will have a significant impact on current and future exploration strategies in the Tanami Region, as well as redefining our current understanding of the region.

The whole of Tanami crust section

The seismic reflection sections show a well-defined reflective Moho on almost all parts of the four traverses. The Tanami crust thickens from approximately 35 km in the northwest to approximately 42 km in the southeast near The Granites. From this point southwards, there is a rapid thickening of the crust to a maximum recorded depth of approximately 60 km. This thickening of the crust in the southeast coincides with changes in the regional gravity field that define the east-northeast-trending Willowra Gravity Ridge (Figure 1).

The seismic section of line 05GA-T1 shows the presence of a series of crustal-penetrating structures that extend from the surface to the Moho boundary (Figure 3). We interpret several of these as being fundamental to the evolution of the region and the establishment of the current architecture. Other structures link the mid-crust to shallower ‘thin-skinned’ structures within the uppermost crust.

One such major southeast-dipping structure is interpreted as a suture zone that separates the Tanami Region from the Arunta Region. Within the hangingwall of this suture, a pop-up structure has been interpreted. This structure is characterised by higher metamorphic grade, changes in Ar-Ar geochronology and changes in fluid composition (Vandenberg et al 2002, Fraser 2003, Wygralak and Mernagh 2003).

The uppermost Tanami Region

The Tanami Region is characterised by domains of less complex reflectivity patterns, juxtaposed against areas of complex deformation showing southeast-, northeast- and northwest-dipping thrusts, with associated hangingwall anticlines. Several of these thrusts appear to link with crustal-penetrating structures.

Known ore deposits are all within these more complexly deformed zones and, therefore, have a direct association with structural anomalies, including through-going thrusts and associated pop-up structures and ramp anticlines. The seismic sections show several additional structurally anomalous areas that might be considered to have mineral potential.
The seismic images indicate that two internal ‘domes’ within the region, the Coomarie and Frankenlia domes of Blake et al. 1979, are not actually domes in the strict sense, rather they appear to be structural regions of overall synclinal form, bowled up by blind large-scale hangingwall anticlines.

The Suplejack Fault Zone, initially suggested as the eastern boundary to the Tanami Region (Crispe et al. 2007), is imaged as a zone of linked structures that extend to mid-crustal levels. The seismic reflectivity characteristics on both side of this zone are not significantly different, suggesting that the Tanami Region extends further eastward towards the Wiso Basin.

The youngest deformation structures, for example the Tanami Fault (‘Trans-Tanami Structure’) and the Mongrel Fault, are not imaged as major structures, but as uppermost crustal structures that link to deeper structures.

The middle and lower crust
Seismic images indicate that there is a pronounced banding within the crust, with a partitioning into an overall less-reflective, although well imaged upper crust, a strongly reflective middle crust and a lower crust that is variable in reflectivity, but shows large-scale sub-horizontal bands of reflectivity.

Conclusion
The Tanami Seismic Collaborative Research Project, with its 354 km long ‘backbone’ traverse, 05GA-T1, and the three cross-lines, 05GA-T2, 05GA-T3, and 05GA-T4, have provided a better understanding of the three-dimensional structure of the Tanami Region. The project has supplied results that will assist mineral explorers in a region that has known gold resources, but where explorers are now facing the challenges of discovering new ‘blind’ deposits.

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References


The Tanami 3D model, version 3 – incorporating the results of the 2005 Tanami Seismic Collaborative Research Project

Tony Meixner

The Tanami 3D model combines surface (geological outcrop maps) and sub-cover (interpreted solid geology maps) 2D datasets with datasets that delineate the third (depth) dimension (seismic and gravity data), in order to test, visualise and enhance our understanding of the 3D geological architecture of the Tanami Region.

The Tanami 3D model covers a 300 km x 300 km area of the Tanami Region and Arunta Region (Aileron Province), primarily in the Northern Territory, but also extending into Western Australia. The model incorporates the whole of the crust from the surface down to the Moho.

Two previous iterations of the 3D model concentrated on testing 2D geological sections against potential field modelling (Meixner et al 2002, Vandenberg and Meixner 2003, Meixner et al 2004). The current 3D model was constructed using 3D GeoModeller, a mathematically based surface-modelling package that constructs 3D volumetric models, based on a range of geological information (www.geomodeller.com/geo/index.php). Meixner et al (2006) demonstrated the use of GeoModeller in constructing 3D models. The geological input consists of: a defined stratigraphic pile, with the geological units related by conformable, onlapping, or erosional contacts; geological contact points; geological orientation data; and faults. Geological boundaries within the models are then computed as mathematical functions that take into account the lithological contacts and orientation measurements supplied by the user. The advantage 3D GeoModeller has over the more traditional CAD-based packages is that it takes less time to build complex 3D surfaces and volumes, and these can easily be modified by altering the initial input parameters. For this model building exercise, the 3D surfaces generated in 3D GeoModeller were then input into GoCad for display.

The current 3D Tanami model incorporates the results of the 2005 Tanami Seismic Collaborative Research Project (Huston et al 2006). This seismic project was a collaborative project between Geoscience Australia, the Northern Territory Geological Survey, the Geological Survey of Western Australia, Newmont Australia Limited and Tanami Gold NL, using the facilities of ANSIR (the National Research Facility for Earth Sounding). The survey acquired 720 line km of deep seismic reflection data along four regional traverses (Figure 1) and was designed to test our understanding of the 3D architecture. The layout of the survey, consisting of a backbone traverse (05GA-T1) with three intersecting high-angle traverses (05GA-T2, 05GA-T3 and 05GA-T4), provided 3D control.

In order to assist in constraining the interpretation, 2D gravity forward modelling was conducted on sections generated from the interpreted seismic. Densities were assigned to known rock units and packages based on a statistical analysis of over 250 density measurements in the region (https://www.ga.gov.au/products/servlet/controller?event=FILE_SELECTION&catno=63759). Densities of 2.7 g/cm³ were assigned to the Tanami Region and Arunta Region basements and 3.3 g/cm³ for the upper mantle. The results of the gravity modelling indicated a general consistency between the interpreted seismic sections and the observed gravity field.

Key geological elements identified in the seismic data and tested by 2D potential field modelling were consistent with outcrop and solid geology interpretations. Three-dimensional surfaces of these key geological elements were incorporated into the model and include:

• topographic surface
• base of post Tanami Group cover sediments
• major granitic bodies
• base of the Tanami Group
• major through-going crustal shears
• suture between Tanami Region and Arunta Region (Aileron Province) active prior to the deposition of the Tanami Group
• Moho.

A number of granites, including the Coomarie and Frankenania granites, are crossed by the seismic survey. The seismic data indicate that the granites are thin, generally in excess of 1 km, with the exception of the Coomarie granite which may reach depths approaching 3 km (Huston et al 2006). Significant gravity lows are associated with the Coomarie and Frankenania granites. The observed gravity anomaly can be replicated by forward modelling the thicker Coomarie granite (2.64 g/cm³) flanked by antiformal thrust stacks of the denser Dead Bullock Formation (DBF) (2.79 g/cm³). This formation consists of siltstone, chert, mafic sills, and BIFs (Hendrickx et al 2000). It is
floored by the lower-density Killi Killi Formation (KKF) (2.7 g/cm³), which consists predominantly of siliciclastic rocks (Hendrickx et al 2000). A large gravity low associated with the relatively thin (1 km) Frankenia granite is not reproducible by forward modelling. The seismic data suggest that the Frankenia granite sits on the highly reflective DBF; however, it is possible that the high reflectivity may be due to reflectivity produced by a zone of intermixed felsic pods or dykes at the base of the granite that formed at the time of granite emplacement. Consequently, a zone of intermixing of felsic material with KKF may produce a seismic signature similar to that of the DBF.

Depth constraints for the granite surfaces in the 3D model are based on the seismic interpretation, whereas the horizontal extent is constrained by the seismic, geology and solid geology data.

The interpreted location of the bottom of the Tanami Group in the 3D model is based on a change in the seismic character (Huston et al 2006).

A number of antiformal thrust stacks were identified on 05GA-T1 in the vicinity of the Coomarie and Frankenia granites and two thrust stacks occur on the northeastern portion 05GA-T3 (Huston et al 2006). All but one of the thrust stacks correspond to gravity highs and are interpreted to be sourced by tectonically thickened successions of denser DBF. A thrust stack to the southeast of the Frankenia Granite (imaged on 05GA-T1) that does not correspond to a gravity high may be the result of thrusting occurring within the DBF, which consists mostly of sedimentary rocks with only a small proportion, if any, of higher-density mafic rocks and BIFs. The approximate location of the intersection of the axial plane surface of the thrust stacks with the topographic surface is represented in the 3D model.

A series of southeast-dipping reflectors, interpreted as through-going crustal shear zones, have been identified on 05GA-T1 and are often associated with the near-surface antiformal thrust stacks (Huston et al 2006). These dipping reflectors correspond with reflectors on the intersecting traverses (05GA-T2, 05GA-T3 and 05GA-T4) and, thereby, reveal the geometries of these structures in 3D.

The Moho is clearly imaged in the seismic sections and generally ranges in depth from approximately 32 km to 40 km (Huston et al 2006). The depth to Moho increases on the southeastern portion of 05GA-T1, where the crust thickens to approximately 60 km as the traverse crosses the Willowra Gravity Ridge (Figure 1, Huston et al 2006). The seismic character of the mid to lower crust changes dramatically from apparent southeast-dipping reflectors in the northwest to high amplitude, apparent northwest-dipping reflectors in the southeast (Huston et al 2006). The thickening of the crust and change of seismic character suggest a region of collision between Tanami Region basement and Arunta Region basement (Huston et al 2006). Modelling of the gravity field indicates that the abrupt change in the depth of the Moho dominates the gravity signature, and accounts for a broad gravity low associated with the northern Arunta Region. The modelling also indicates that the Willowra Gravity Ridge may be primarily sourced from a wedge of upthrusted granulite-facies crust. Gravity modelling also suggests that the Tanami Region basement is of a lower average density than that of the northern portion of the Arunta Region basement.

This third generation of the 3D model includes images of the seismic data, with interpreted overlays, and forms the basis of the next version of the Tanami 3D VRML Model. This new version should be available on Geosciences Australia’s website (http://www.ga.gov.au/map/web3d/tanami/index.jsp) before September 2007. In the interim, the previous version of the 3D model constructed prior to the acquisition of the seismic data is available.

The VRML technology allows users to remotely access and manipulate the model, including turning layers on and off, rotating, panning and zooming in and out of the model over the web, without the need for specialised software. Additional layers, viewable as part of the Tanami 3D VRML model, include:

- roads/tracks
- images of topographic, magnetic, gravity, radiometric, and satellite data
- maps of outcrop geology, regolith and solid geology
- deposit locations
- geochronology locations, including a live connection to Geoscience Australia’s geochronology database, OZCHRON
- 3D depth to basement surface
- magnetic and gravity strings
- magnetic and gravity inversion surfaces.
References


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**Figure 1.** Location of the 2005 Tanami Seismic Collaborative Research Project, including a schematic location of the Coomarie and Frankenia granites. The figure outline defines the area of the 3D model. Deposits are shown as solid triangles.