Minister’s foreword

Welcome to the 13th Annual Geoscience Exploration Seminar (AGES), which is the Territory’s premier exploration-focussed conference, and which forms a key element of the Government’s strategy to grow and develop the Territory’s exploration and mining sector.

AGES 2012 is being held at a time when the Territory’s mining industry has never been stronger, with major expansions planned or underway at a number of our mines, record levels of exploration being undertaken and a strong and diverse pipeline of new mining projects going through the approvals process. Mineral exploration in the Territory is projected to have been more than $200 million in 2011, a remarkable result which reflects the confidence and excitement that currently exists regarding the Territory’s exploration potential.

In recognition of the ongoing importance of exploration in growing the Territory’s mining industry, in the 2011 Budget the Territory Government announced a further 3 year extension of the Bringing Forward Discovery initiative until the middle of 2014. This takes the total Territory Government investment in Bringing Forward Discovery to $25.8 million over seven years. This investment allows the Northern Territory Geological Survey to continue to deliver the kind of industry-focussed exploration incentives that have delivered so much success for the Territory over the past few years. AGES remains the most important forum to deliver the ongoing results of the initiative, and promote new concepts on the Territory’s geological potential.

Thank you for travelling to Alice Springs for AGES 2012, and I hope that the technical program will provide you with new information and concepts to bring forward your next discovery in the Territory.

Hon. Kon Vatskalis MLA
Site plan

AGES and Mining Services Expo, Alice Springs Convention Centre
27–28 March 2012

Booth and Exhibitor
01–02 Department of Resources, NT Geological Survey
03 Bowgan Minerals Limited
04 Alice Springs Resources, Oneva Exploration
05 The Alice Springs Watershed
06 ALS Group
07 Thrifty
08 Energy Power Systems Australia P/L
09 CSA Global
10 Aboriginal Areas Protection Authority
11 Tanami Gold
12 Signet Pty Ltd
13 Chartair
14 Alice Springs Helicopters
15 Austwide Mining Title Management
16 Arafura Resources
17 Ausurv Pty Ltd
18 Ausfuel
19 Australian Mining and Exploration Title Services
20 Northline Pty Ltd
21 The AusIMM
22 Chubb Fire and Security
23 St John Ambulance NT
24 Territory Instruments
25 Territory Hirex
26 Brian Blakeman Surveys
27 Arnhem Exploration Services
28 Adelaide Resources
29 Barrick
30 Westgold Resources Limited
31 Emmerson Resources
32 Wild Drilling Pty Ltd
33 Minerals Council of Australia - NT Division
34 Bureau Veritas
35 TNG Limited
36 Alice Bush Haulage and Mining Services
37 Perry’s Power Equipment
38 Central Car Rentals
39–40 Central Communications / TJM
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## AGES 2012 program

### DAY 1 Monday 26 March
5:30–7:30  Registration and Ice Breaker

### DAY 2 Tuesday 27 March
8:00–8:30  Registration
8:30–8:40  Welcome to Country
8:40–8:50  Minister Vatskalis NT Government Official opening

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<td>8:50–9:20</td>
<td>Ian Scrimgeour</td>
<td>NTGS</td>
<td>Mineral exploration and mining overview 2011</td>
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<td>9:20–9:35</td>
<td>Alan Holland</td>
<td>Dept of Resources</td>
<td>Petroleum activity in the Territory and progress of the Mineral Titles Act</td>
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<td>Dorothy Close</td>
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10:00–10:40  Morning tea

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<td>What’s new? NTGS systems, client services, products and implementing a new Act</td>
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<td>11:00–11:20</td>
<td>Mark King</td>
<td>Cameco Australia</td>
<td>Exploration for unconformity-style uranium deposits geology and mineralisation of the Angularri Prospect Wellington Range Project, West Arnhem Land</td>
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<td>James Cleverley</td>
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<td>Linking deposit scale studies and mineral systems thinking: The Ranger U system</td>
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<td>11:50–12:10</td>
<td>Rob Sowerby</td>
<td>Alligator Energy</td>
<td>Uranium mineralisation styles in the Caramal-South Horn Trend, Alligator Rivers Uranium Province</td>
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<td>New amendments to the NT’s Mining Management Act</td>
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<td>13:35–13:50</td>
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<td>Prospectivity of high-heat producing granites of the central Arunta Region, Northern Territory</td>
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14:30–15:10  Afternoon tea

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19:00–late  Dinner speaker: Professor Allan Trench, Centre for Exploration Targeting, UWA
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AGES 2012 major sponsor
Networking ice-breaker drinks sponsor

AGES 2012 sponsors
Networking sundowner drinks sponsor

Networking pre-dinner drinks sponsor

Dinner wine sponsor

Coffee sponsor
Mineral exploration and mining overview 2011

Ian R Scrimgeour1,2

Exploration statistics

Mineral exploration was at record levels in the Northern Territory in 2011, with total exploration expenditure of $195.3M in 2010/11, up 31% on the previous record of $149.4M in 2009/10. Total Australian mineral exploration was $2.95B, up 32% from $2.23B in 2009/10. The Northern Territory’s share of total Australian expenditure remained steady at 6.6%. The Territory is the only Australian jurisdiction to have had steadily increasing exploration expenditure every year since 2003/04.

Expenditure continued to increase in 2011/12, with a new record of $71.6M spent in the NT in the September 2011 quarter, 28% higher than the previous record of $55.8M set in the September quarter of 2010. Expenditure on mineral exploration for the 12-month period up to September 30 2011 was $211.1M. These figures show that levels of exploration expenditure in the Territory is back on a rapid upward trajectory after the rate of increase flattened out during the GFC (Figure 1).

Much of Australia’s recent exploration expenditure is in brownfields areas (in and around an existing orebody). In Australia, the proportion of greenfields (areas away from known deposits) to brownfields exploration dropped from 38% to 35% in 2010/11. In comparison, the proportion of greenfields exploration in the Territory is higher than the national average, although it decreased from a record high of 59% in 2009/10 to 46% in 2010/11. This remains much higher than the levels of greenfields exploration in the Territory prior to 2006, when it comprised only 25–30% of total expenditure on exploration.

According to ABS figures, in 2010/11, the top commodities by expenditure were gold ($53.3M, up 20% on 2009/10), then uranium ($41.9M, up 9%), iron ore ($24.4M, up from effectively zero the previous year) and copper ($11.9M, up 216%). Expenditure for lead, zinc, nickel, cobalt and diamonds was relatively low. Exploration expenditure for ‘other’ commodities, which includes rare earths, phosphate, manganese, vanadium and multi-commodity projects, was up 45% to $48.4M (Figure 2).

At the end of 2011, there were 1377 granted non-extractive exploration licences (compared with 1254 at the end of 2010) and 1216 exploration applications. During 2011, 432 applications were received and 339 were granted.

Exploration and mining highlights

Exploration during 2011 has substantially added to the Territory’s resource base, with significant increases in identified resources for copper, gold, phosphate, iron ore and uranium. In the following summary, all resources stated are JORC-compliant or NI43-101-compliant, unless stated otherwise. Most material cited here has been sourced from company websites, news releases and Stock Exchange announcements by companies. The Northern Territory Department of Resources also maintains a database of Northern Territory exploration news that can be accessed from: http://apps.minerals.nt.gov.au/explornews. Figure 3 shows the distribution of copper, copper-gold and gold deposits and projects in the Northern Territory discussed below; Figure 4 shows the distribution of iron ore, lead-zinc, manganese, molybdenum-tungsten, nickel and vanadium-titanium deposits and projects; and Figure 5 shows the distribution of mineral sands, rare earths, phosphate, potash, and uranium deposits and projects.

Copper

In early 2011, Kentor Gold Ltd purchased the Jervois copper-silver-gold project, northeast of Alice Springs

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1 Northern Territory Geological Survey, PO Box 3000, Darwin, NT 0801, Australia.
2 Email: ian.scrimgceour@nt.gov.au.

Figure 1. Annual mineral exploration expenditure in the Northern Territory, calculated quarterly, for the 10 years up to the September 2011 quarter.
(Figure 3), from Reward Minerals Ltd. Mineralisation occurs in a series of stratabound, subvertical sulfide-rich deposits along a 12 km strike length in the 1807 Ma Bonya Schist, in the Aileron Province of the Arunta Region. The field was mined intermittently in the last century, including an open-cut operation at the Green Parrot deposit in the early 1980s. The company undertook an extensive drilling campaign during 2011, particularly targeting extensions of mineralisation along strike and at depth. At the Reward prospect, intersections included 72 m at 3.27% Cu, 1.16 g/t Au and 51.3 g/t Ag from 414 m (true width ca 16 m) and 8.1 m at 2.56% Cu and 14.6% Ag from 321 m. At Bellbird, results from drilling north of the existing copper resource include 3.4 m at 6.39% Cu, 46 g/t Ag and 0.12 g/t Au from 309 m and 6 m at 3.18% Cu, 0.45 g/t Au and 23.55 g/t Ag from 59 m. On the basis of historical drilling data and 2011 drilling results, Kentor defined a JORC-compliant resource of 11.9 Mt at 1.3% Cu and 25.2 g/t Ag for the Reward, Green Parrot, Bellbird and Bellbird North deposits, for 150 500 t of contained copper. Gold was not included in this resource, as much of the historical drilling was not assayed for gold. Kentor Gold have commenced a scoping study at Jervois, and have announced high recoveries from initial metallurgical testing. Following completion of the scoping study, the company plans to move to a full feasibility study during 2012.

Thundelarra Exploration Ltd announced copper intersections from their Allamber uranium-copper project north of Pine Creek. This follows their 2010 discovery of 7 m at 9.69% Cu from 13 m at the Lucas prospect. In 2011, drilling at the Hatrick prospect intersected 19 m at 1.94% Cu from 43 m including 2 m at 6.07% Cu, and more regional drilling intersected broad zones of anomalous copper, along a 20 km-long prospective horizon. Thundelarra consider the mineralisation to be stratabound in nature, occurring as broad zones within dolomitic, pyritic and graphitic shale of the metapelite succession in the Palaeoproterozoic Masson Formation.

Redbank Copper Ltd has a substantial land holding in the McArthur Basin near the Queensland border, including the Redbank project, where copper mineralisation is hosted in breccia pipes. Total Indicated and Inferred JORC resources for the Redbank project area are 6.24 Mt at 1.5% Cu for 95 900 t of Cu. In 2011, Redbank revised their development plans for the project, deciding that an increase in both oxide and sulfide open-cut resources to a minimum of 5 years of production was required before proceeding to development. The company undertook a limited exploration program in 2011, including a high-resolution magnetic and radiometric survey along the Calvert Fracture Zone, co-funded under the NTGS Geophysics and Drilling Collaborations program. The company also announced a joint venture with Gulf Mines Ltd to explore Gulf’s tenements surrounding the Redbank deposit, and commenced a collaborative project with CSIRO to undertake 3D modelling of the breccia pipes, and sampling and micro-characterisation of the copper breccia systems.

In the Pine Creek Orogen, carbonaceous shale within the Whites Formation, close to the contact with the underlying Coomalie Dolostone, hosts several polymetallic prospects and orebodies. HNC (Australia) Resources Pty Ltd (HAR)’s Browns project in the Pine Creek Orogen has an oxide resource of 9.4 Mt at 0.82% Cu, 0.14% Co and 0.14% Ni, and a sulfide resource of 45.1 Mt at 0.35% Cu, 3.74% Pb, 0.73% Zn, 0.09% Co and 0.07% Ni. The project remains on long-term care and maintenance.

Mithril Resources Ltd (Mithril) have continued drilling at their Basil copper prospect, within their Huckitta project area in the Harts Range. Basil is a greenfields discovery made in 2009, and comprises a 10 km-long trend of copper-bearing gossanous outcrop and hydrothermal alteration, associated with a large-scale EM anomaly. Drilling at the Peaks Zone within the Basil prospect yielded some of the highest grade intersections reported from the prospect, including 12.4 m at 1.14%Cu, 0.06% Co and 4.9 g/t Ag from 257 m, 8 m at 1.20% Cu from 291.3 m and 11.45 m at 1.01%Cu and 0.08%Co from 262 m. Mineralisation is associated with massive (20–50%) and stringer sulfides, comprising pyrrhotite, pyrite and chalcopyrite, within mafic amphibolite of the Irindina Province, close to a crustal-scale shear zone that forms the contact with the Aileron Province.
Mithril also commenced exploration on their *Albarta Bore* project area in the Arunta Region south of the Harts Range, following the identification by NTGS (announced at AGES 2011) of widespread haematite and fluorite alteration in the area. Initial exploration by Mithril identified a number of new iron oxide copper-gold (IOCG) prospects associated with these alteration systems. At the *Bigglesworth* prospect, rockchips have returned up to 4.5% Cu, 0.2 g/t Au and 2.3 g/t Ag. The mineralised samples occur over a broad area and are generally associated with outcrops of silica- and haematite-altered granite, consistent with an IOCG mineralising system. Mithril reported that the alteration appears to be structurally controlled, and copper and gold mineralisation has been confirmed at multiple locations. At the *Austin* prospect, 20 km to the southeast along strike from Bigglesworth, malachite and chalcopyrite were discovered at surface over 200 m of strike in intensely haematite-, silica- and carbonate-altered granite. The alteration and mineralisation are coincident with a large east-trending gravity anomaly and a surface copper geochemical anomaly. Mithril have announced that they plan to aggressively explore this area during 2012.

**Copper-gold**

Tennant Creek-style IOCG orebodies are believed to have resulted from mineralised hydrothermal fluids passing along shear zones and reacting with Proterozoic iron-rich sedimentary rocks of the Warramunga Formation, resulting in what are now steeply plunging, zoned, high-grade Au-Cu-Bi sulphide orebodies. Exploration for this style of orebody is focused in the historic Tennant Creek mineral field, and in the Rover field, where Tennant Creek-style mineralisation occurs beneath 150–300 m of overlying Wiso Basin sedimentary rocks.

Following a major HeliTEM survey in the Tennant Creek mineral field, Emmerson Resources Ltd undertook a drilling program to test identified HeliTEM anomalies in the area of the historic *Gecko* copper-gold mine. This drilling led to the discovery of two significant copper-gold prospects, *Monitor* and *Goanna*, along the Gecko mine corridor. The mineralisation typically comprises chalcopyrite-quartz-chlorite veins bounded by sub-vertical shear zones, within dilational zones within the Gecko structural corridor. It represents a different mineralisation style to the typical ironstone-hosted deposits at Tennant Creek, and has been difficult to detect using the geophysical techniques employed in past exploration programs in the field. Drilling intersections at Goanna included 15 m at 4.19% Cu and 8.13 g/t Au from 288 m, 21 m at 2.63% Cu from 297 m (including 7 m at 4.96% Cu) and 15 m at 2.74% Cu, 1 g/t Ag and 0.24% Bi. At Monitor, 2.5 km to the east, intersections included 12 m at 2.00% Cu and 16.9 g/t Au from 437 m (including a high-grade gold zone of 4 m at 37.4 g/t Au) and 27 m at 1.75% Cu from 291 m (including 6 m at 3.53% Cu). Based on historical drilling, Emmerson announced a maiden resource of 1.48 Mt at 2.5% Cu at Gecko and 0.98 Mt at 1.4% Cu and 2.0 g/t Au at the nearby *Orlando* mine. Under the terms of the $28M farm-in and joint venture between Emmerson Resources and Ivanhoe Australia Ltd, the Gecko and Orlando areas of interest have been carved out of the JV, with Emmerson funding and retaining 100% ownership. Numerous greenfields HeliTEM targets await testing.

The Rover field, 70 km southwest of Tennant Creek, has been the focus of considerable recent success in exploration for Tennant Creek-style orebodies. The most advanced exploration project in the Rover field is the *Rover 1* deposit, which straddles tenements owned by Westgold Resources Ltd, who have the majority of the defined orebody, and Adelaide Resources Ltd. In 2011, Westgold Resources announced an updated resource estimate for Rover 1, of 6.8 Mt at 1.73 g/t Au, 1.21% Cu, 2.1 g/t Ag, 0.14% Bi and 0.1% Co for 1.22 Moz AuEq (gold equivalent), with a high-grade gold zone of 1.32 Mt at 7.01 g/t Au and 0.81% Cu. The updated resource included a 110% increase in resources in the Indicated category. Drilling results announced in early 2011 extended mineralisation in the Jupiter Zone 190 m down plunge of the existing resource estimate, with intersections including 9 m at 12.2 g/t Au and 0.53% Cu from 939 m and 20 m at 6.13 g/t Au and 3.26% Cu from 935 m (including 6 m at 15.14 g/t Au and 6.02% Cu). Westgold’s program at Rover 1 is now focused on completing the necessary studies to obtain approvals for an exploration decline as a platform for effective infill drilling.

The Western Zone of Rover 1 extends into an adjacent tenement held by Adelaide Resources. Drilling by Adelaide Resources during 2011 extended the known limit of mineralisation within their tenement 40 m to the west, with an intersection of 10 m at 1.79% Cu and 0.4 g/t Au from 354 m.

Adelaide Resources continued exploration at the *Rover 4* prospect, 2 km north of Rover 1, which is a copper-gold system of similar style to Rover 1. Eleven holes were completed at Rover 4 in 2011, with all holes intersecting the alteration system, which has a strike length of 600 m and is open in both directions along strike. Significant results included 28 m at 1.62% Cu from 221 m (including 15 m at 2.37% Cu) and 2 m at 11.79 g/t Au from 245 m. Adelaide Resources reported that the system has a west to northwest plunge, and the style of alteration and mineralisation is typical of the upper part of a typical Tennant Creek-style mineral system. Adelaide Resources also intersected visible copper mineralisation at their Rover 12 prospect, 20 km west-northwest of Rover 1, with assays pending.

Westgold Resources also undertook a major regional exploration program in the Rover field during 2011. This included drilling at the previously untested targets of Rover 7, *Pathfinder 1* and *Pathfinder 7*, and additional drilling to extend the encouraging Explorer 142 copper-gold discovery. Although encouraging host rocks and alteration systems were intersected by drilling at these prospects, no intersections of an economic grade have been announced.

Truscott Mining Corporation Ltd have announced a maiden resource at their *Westminster Project*, which covers 5.96 km² just west of Tennant Creek township along the Big Ben–Peter Pan–Wheat Doria trend. The inferred resource of 111 330 t at 25.6 g/t Au is contained within the upper
portions of shoots F and G. The mineralisation is hosted in, or adjacent to ironstones within strongly altered and sheared sedimentary rocks. A lower cutoff of 5 g/t Au was applied to the deposit, with the aim of building a resource with the potential to be amenable to selective underground mining methods. Highlights of drilling in 2011 included 2 m at 81.0 g/t Au and 0.52% Bi from 67 m in F shoot.

**Gold**

**Pine Creek Orogen**

During 2011, Crocodile Gold Australia Pty Ltd continued gold production from their operations in the Pine Creek region, and have identified additional resources. Production from the Union Reefs mill during 2011 totalled 1.89 Mt at an average grade of 1.21 g/t Au, for 68 019 oz of gold. Production was mainly from open-cut operations at Princess Louise, Howley and Mottrams. Production is scheduled to commence at the Rising Tide and North Point open pits in 2012, along with full production from the Cosmo Deeps underground operations. Crocodile Gold projects in the Pine Creek Orogen have combined Measured and Indicated Resources of 51.8 Mt at 1.9 g/t Au, and Inferred Resources of 36.3 Mt at 1.8 g/t Au, for a total resource of 5.32 Moz Au. Underground development of the [Cosmo Deeps](#) deposit continued during 2011, with first development ore extracted in September, and full production scheduled for 2012. The Cosmo Deeps deposit has an Indicated Resource of 5.3 Mt at 4.6 g/t Au and an Inferred Resource of 5.65 Mt at 3.7 g/t Au, for a total resource of 1.45 Moz Au. Exploration highlights at Cosmo Deeps during 2011 included the discovery of southern extensions of the known resource in the Cosmo West Lode with a drill intersection of 8.6 m at 5.14 g/t Au from 449 m and the discovery of a high-grade core in the 100 Lode, with intersections including 8 m at 15.7 g/t Au from 102 m. At the [Union Reefs](#) project, Crocodile Gold announced a number of high-grade intersections from drilling between and beneath existing open cuts at [Prospect](#), [Crosscourse](#) and [Lady Alice](#). Drilling between the main Crosscourse pit and the Prospect pit immediately to the north yielded intersections including 10 m at 6.9 g/t Au from 28 m and 5 m at 13.1 g/t Au from 29 m. Drilling beneath the Prospect pit yielded a best intersection of 4.23 m at 27.0 g/t Au from 182 m, whereas beneath the Crosscourse pit, the best drill intersections included 8.1 m at 10.16 g/t Au from 393 m and 12.3 m at 8.89 g/t Au from 389 m. Drilling beneath the Lady Alice pit yielded an intersection of 9 m at 3.6 g/t Au.

The [Spring Hill](#) gold deposit, 25 km north of Pine Creek, is hosted in greywacke and siltstone of the Mount Bonnie Formation, with gold occurring mainly in quartz veins that are concentrated in fracture zones and the axial zones of anticlines. The deposit has an existing resource of 3.64 Mt at 2.34 g/t Au for 274 000 oz Au. Past drilling was limited to within 150 m of the surface and the existing resource was only calculated to 100–130 m depth. Early in 2011, Thor Mining PLC announced a staged acquisition of an 80% interest in the Spring Hill project from Western Desert Resources Ltd. Six diamond holes were drilled at Spring Hill in 2012, for a total of 1574 m, with best intersections of 3.4 m at 9.7 g/t Au from 25 m and 4.7 m at 5.7 g/t Au from 29 m.

Thundelarra Exploration Ltd completed a 30-hole, 3578 m RC drilling program as a preliminary assessment of selected targets at their [Priscilla](#) gold prospect. Most holes returned elevated gold grades, with a best intersection of 4 m at 118 g/t Au from 40 m. The Priscilla prospect is located 160 km south of Darwin and is 300 m to the south and along strike from the Princess Louise gold mine.

Vista Gold Corporation (Vista) continued to progress their [Mount Todd](#) project, northwest of Katherine. Mineralisation at the [Batman](#) orebody at Mount Todd is contained in a stockwork of quartz veins and their margins, within metamorphosed interbedded silstone, shale and minor tuff of the Burrell Creek Formation. Proven and Probable Mineral Reserves at Mount Todd are 149.9 Mt at 0.85 g/t Au, for 4.11 Moz Au. Measured and Indicated Resources at Mount Todd have increased to 222 Mt at

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**Figure 3.** Location of copper, copper-gold and gold deposits and projects discussed in the text.
Callie was discovered in 1991 and open-cut mining siltstone in the lower part of the Dead Bullock Formation. Corporation (Newmont). Mineralisation at Callie consists of gold at 7.66 g/t Au, and a metallurgical drillhole within the known orebody intersected 152 m at 1.24 g/t Au, including 25 m at 2.37 g/t Au. Following a pre-feasibility study released in 2010, Vista have announced that they expect to complete a full feasibility study for the Mount Todd gold project in the first quarter of 2012. Recently completed metallurgical testing has resulted in further process improvement and optimisation.

Tanami–Arunta regions
The Tanami gold province straddles the Northern Territory–Western Australia border. There is currently one working mine in the Tanami Region in the Northern Territory, at Callie, operated by Newmont Mining Corporation (Newmont). Mineralisation at Callie consists of high-grade Au-quartz veins in folded carbonaceous siltstone in the lower part of the Dead Bullock Formation. Callie was discovered in 1991 and open-cut mining commenced in 1995. As of 31 December 2010, the Proven and Probable Reserves at Newmont’s Tanami operations were 14.3 Mt at 4.03 g/t Au for 2.04 Moz Au. In 2011, Newmont announced that their board had approved a $450M expansion of their Tanami operations, with development of a shaft to support underground expansion at the Callie and the newly discovered Auron ore bodies. Newmont announced that this would lead to an additional average annual production for the first five years of 60 000 to 90 000 oz of gold, bringing total annual production at Tanami to approximately 340 000 to 400 000 oz. First production from the shaft is expected in late 2014 to early 2015, and the project is set to extend the mine life by 5 years to 2027.

During 2011, Tanami Gold NL continued to increase resources at their Central Tanami project, which includes the historic Tanami goldfield that produced 2 Moz of gold from 43 open pits between 1987 and 2005. The project area comprises multiple gold deposits within economic trucking distance of a 1.25 Mt pa treatment plant and associated infrastructure. In September 2011, the total resource for the Central Tanami project stood at 21.28 Mt at 3.0 g/t Au, for 2.03 Moz Au. Exploration in 2011 particularly focused on expanding the resource at the Groundrush deposit. The historic Groundrush open cut is approximately 1.5 km in length, 100 m deep, and produced more than 600 000 oz of gold between 2001 and 2004, at a recovered grade of 4.3 g/t Au. The deposit is hosted within a thick fractionated dolerite unit and a secondary discrete high-grade quartz vein. Drilling in 2011 extended the north-plunging main ore body to over 700 m in length and it remains open down plunge. A further two footwall zones of mineralisation have also been extended for over 200 m in length. Both of these zones remain open in all directions. Drilling highlights in the past year include 4.3 m at 159.5 g/t Au from 183 m, 9.5 m at 38.8 g/t Au from 233 m, 6.8 m at 53.2 g/t Au from 239 m, 12.7 m at 15.1 g/t Au from 192 m and 16 m at 10.4 g/t Au from 302 m. The resource at the Groundrush deposit has increased to 3.6 Mt at 4.6 g/t Au, for 0.535 Moz Au. Tanami Gold also continued drilling beneath and between existing open-cut mines in the Tanami goldfield. Highlights have included 7.1 m at 5.9 g/t Au from 400 m and 30.2 m at 3.8 g/t Au from 144 m at Hurricane, and 8.5 m at 5.3 g/t Au from 235 m at Carbine. In December 2011, Tanami Gold announced that, in view of the increase in mineral resources over the previous six months and the potential for a further upgrade of the Groundrush resource, the development strategy for the Central Tanami Project was to be reviewed and fully assessed before a decision is made to proceed to development.

ABM Resources NL (ABM) continued to have drilling success in 2011 in the Tanami Region at the Twin Bonanza project area, which includes the Buccaneer porphyry and Old Pirate prospects. In March 2011, ABM announced a maiden inferred resource for the Buccaneer deposit of 65.8 Mt at 0.79 g/t Au for 1.67 Moz Au, with higher grade components of 36.9 Mt at 1.01 g/t Au and 8.7 Mt at 2.01 g/t Au. The Buccaneer deposit has been interpreted to be a porphyry gold system, hosted within a porphyritic syeno-monzonite, and is the only significant granite-hosted gold system identified to date in the Tanami. ABM have interpreted an early disseminated gold phase with a later, structurally controlled higher-grade phase. Sediment-hosted mineralised zones were also identified during 2011, immediately west and east of the porphyry. Highlights of drilling at Buccaneer in 2011 included 427 m at 0.52 g/t Au from 68 m (including 39 m at 2.22 g/t Au), 174 m at 0.94 g/t Au from 117 m (including 29 m at 3.56 g/t Au) and 221 m at 0.95 g/t Au (including 81 m at 2.03 g/t Au). At the newly discovered Caribbean Zone, 250 km northwest of the Buccaneer resource, drill intersections included 21 m at 2.55 g/t Au from 227 m (including 13 m at 3.93 g/t Au) and 47 m at 1.67 g/t Au from 209 m (including 11 m at 3.16 g/t Au). 1 km north of Buccaneer, the Cypress Zone comprises mineralisation in fractured and veined porphyry, with intersections of up to 26 m at 5.53 g/t Au (including 7 m at 20.13 g/t Au). Drilling between the Caribbean and Cypress Zones is suggestive of continuity of mineralisation between the zones, and includes an intersection of 31 m at 1.92 g/t Au from 228 m (including 4 m at 13.23 g/t Au). The Old Pirate prospect, 2 km southwest of Buccaneer, contains multiple high-grade gold veins up to several metres wide. Significant drill intersections from 2011 drilling include 9 m at 100.9 g/t Au from 231 m (including 2 m at 413.5 g/t Au) and 5 m at 13.34 g/t Au from 80 m. ABM Resources also undertook trench sampling along surface veins at Old Pirate, with a combined average assay over 582 m of sampled veins of 23.98 g/t Au.

ABM also undertook exploration at the Kroda project area, near Barrow Creek in the Arunta Region. This project consists of four individual prospects (Kroda 1–4) with a combined strike length of 14 km. Drilling by ABM focused on the Kroda 3 prospect, where a mineralised
system has been identified over a strike length of 400 m and is interpreted to comprise steeply dipping shoots of quartz veins in layered dolerite and schists. Intersections included 57 m at 3.83 g/t Au from 10 m (including 12 m at 15.69 g/t Au) and 10 m at 4.97 g/t Au.

At the Lake Mackay project area, in the western Arunta Region near the Western Australian border, ABM undertook their first phase of drilling in the area. At the Tekapo prospect, which is considered to have potential as an iron-oxide copper-gold prospect, drilling returned intersections including 26 m at 2.22 g/t Au from 28 m (including 18 m at 3.05 g/t Au) and 17 m at 0.25% Cu from 17 m.

**Coal and coal derivatives**

A number of companies have tenure under both the Mineral Titles Act and the Petroleum Act to assess the potential of the Permian Purni Formation in the largely subsurface Pedirka Basin in the southeast of the Territory for coal mining, coal seam gas and in situ coal seam gasification. Central Petroleum Ltd and its wholly owned subsidiary, Merlin Coal Pty Ltd drilled six exploration holes between 2008 and June 2010 that intersected significant coal at depth within the formation. Net intersections of coal in seams greater than one metre in thickness averaged over 120 m per drillhole, with the thickness of individual seams ranging up to 35 m. The coal is generally sub-bituminous in rank and has good thermal/steaming qualities. It occurs within a ca 200 m interval, typically below 400 m deep, which is generally too deep for conventional mining, although coal may occur at shallower minable depths towards the western margins of the basin.

In early 2011, Central Petroleum completed a three-hole stratigraphic drilling program for coal in the Pedirka Basin. Holes SHEL27109-1 and -2 were both drilled to greater than 1100 m depth, and encountered net intersections of coal in seams greater than 1 m of 70 m and 42 m, respectively. The thickest seam in SHEL27109-1 was 18 m thick. A third hole, drilled to step out to relatively unexplored parts of the basin, failed to intersect significant coal.

**Diamonds**

North Australian Diamonds Ltd (NAD) commenced a definitive feasibility study for a proposed 1.5 Mtpa [approximately 300 000 ct (carats) per annum] diamond mining operation at their Merlin Project in the McArthur Basin. The Merlin Project comprises 14 kimberlite pipes, of which nine were subject to open-cut mining between 1998 and 2003, producing 507 000 ct of diamonds. The combined Probable Ore Reserve for all diamond pipes at Merlin is 11.1 Mt at 0.26 carats per tonne (ct/t) for a total of 2.89 Mct, and the Indicated and Inferred Mineral Resource is 19.02 Mt at 0.24 ct/t for a total of 4.31 Mct. The company undertook production trials at Merlin in 2011, and expect to release the results of the feasibility study in early 2012. The company also commenced bulk sampling on the Borroloola alluvial diamond project, targeting a major alluvial concentration in a catchment known to host diamond deposits. The bulk sampling program extracted 5000 t of material from five locations. NAD also undertook regional exploration at its Lancelot and Arnhem Land projects during 2011.

**Bauxite and alumina**

Rio Tinto Alcan’s Gove bauxite mine and alumina refinery continues to be a major contributor to the Territory economy. The resource at Gove includes Proved Resources of 111 Mt at 49.5% Al2O3 and Probable Resources of 64 Mt at 49% Al2O3. During 2011, Rio Tinto secured a 42-year extension on their mining leases at Gove. Rio Tinto also announced that they plan to transfer their interests in a number of aluminium projects, including Gove, into a new business unit called Pacific Aluminium, to be managed and reported separately from Rio Tinto Alcan. Exploration for bauxite has been fairly limited in the Territory, although Rio Tinto Exploration Pty Ltd continued to explore on the Cato Plateau in partnership with BHP Minerals Pty Ltd. Intercept Minerals Ltd also agreed to principal terms with Rio Tinto Exploration for a farm-in agreement covering Intercept’s Tiwi Islands bauxite project, which comprises an exploration licence application in the northeastern region of Melville Island.

**Iron ore**

Territory Resources Ltd operates a 2.0 Mtpa iron ore mine at Frances Creek (Figure 4), which has been in operation since 2007. The iron mineralisation occurs in a fault breccia in the lower Wildman Siltstone and ranges in composition from haematite to goethite and limonite. There are over 50 named occurrences and prospects covering a distance of approximately 35 km. During 2011, Territory Resources was acquired by Noble Group. In January 2011, a $4.3M beneficiation plant was commissioned at Frances Creek, to beneficiate 800 000 t of 51% Fe scalp ore on stockpiles to produce approximately 44 000 t of high-grade fines ore per month. Resources and reserves at Frances Creek announced in 2010 included total Probable Reserves of 5.8 Mt at 57.9% Fe and Indicated and Inferred Resources of 9.9 Mt at 58.1% Fe.

Aggressive iron ore exploration continued in the Roper iron field in the McArthur Basin. Iron ore in the Roper field varies from massive to oolitic and pisolithic haematite, and occurs within interbedded medium- to very coarse-grained ferruginous sandstone and siltstone of the Mesoproterozoic Sherwin Ironstone Member. Western Desert Resources Ltd (WDR) has continued an exploration drilling and resource definition program in their Roper Bar project area. Early in 2011, a maiden Inferred Resource of 116 Mt at 40.3% Fe was announced for Area D (North), bringing the total resource in Areas D, E and F to 312 Mt at 40% Fe, including a global direct shipping ore (DSO) component of 14.5 Mt at 57.4% Fe. At Area F (East) the resource is 20 Mt at 48% Fe, including a DSO component of 9.8 Mt at 58.3% Fe, 10.7% SiO2, 2.6% Al2O3, 0.01% P and 2.1% LOI. Area E (East) has an Indicated Resource of 12.1 Mt at 46.1% Fe, including a DSO component of 4.7 Mt at 55.6% Fe, 14.1% SiO2, 1.1%
Al₂O₃, 0.01% P and 4.2% LOI. Area E (South) and Area D both have large beneficiable resources of 72 Mt at 39% Fe and 91 Mt at 37% Fe, respectively. Drilling during 2011 intersected high-grade iron ore at a number of areas, with the potential to significantly increase the DSO resource. At Area F (East) drilling at depth in steeply dipping ore intersected 126 m at 60.7% Fe from 93 m, and 57 m at 60.1% Fe from 56 m. Western extensions of high-grade iron ore at Area F were confirmed by drilling at Area F (West), with intersections including 5 m at 65.6% Fe. At Area E (East), drilling intersected a thickened zone of shallowly-dipping mineralisation at depth, with an intersection of 32 m at 59% Fe from 69 m. A resource update is expected in early 2012. In November 2011, WDR signed a Memorandum of Understanding with Xstrata Zinc to investigate the feasibility of gaining access to Xstrata Zinc’s McArthur River Mine loading facility at Bing Bong on the Gulf of Carpentaria to export iron ore from Roper Bar. This would require an access road of approximately 160 km from the Roper Bar project area to Bing Bong, and would accelerate the development timetable for the project, with iron ore exports possible by early 2013 at a proposed rate of production of 2.5–3.0 Mtpa. Exporting through Bing Bong would reduce the immediate requirement for access to McArthur River Mine loading facility at Bing Bong on the Gulf of Carpentaria to export iron ore from Roper Bar. This would require an access road of approximately 160 km from the Roper Bar project area to Bing Bong, and would accelerate the development timetable for the project, with iron ore exports possible by early 2013 at a proposed rate of production of 2.5–3.0 Mtpa. Exporting through Bing Bong would reduce the immediate requirement for investment in new pipeline infrastructure and an export facility on Maria Island, which was previously proposed by the company.

Sherwin Iron Ltd (Sherwin) continued exploration at their Roper River project, located around 100 km west and northwest of the Roper Bar project. During 2011, the total resource at the Roper River project increased by over 350 Mt, to 488 Mt at 41.7% Fe. Much of the exploration in 2011 was focused in the Sherwin Creek area, where a maiden resource of 320 Mt at 40.1% Fe, 34.4% SiO₂, 1.82% Al₂O₃, 0.006% P and 0.04% S was announced. The Sherwin Creek resource is contained within two separate layers (Middle and Lower) that are shallow, continuous and open down dip. At Hodgson Downs, 70 km southwest of Sherwin Creek, where a maiden resource was announced in 2010, the resource has increased to 152.5 Mt at 44.8% Fe, 29.9% SiO₂, 2.1% Al₂O₃ and 0.03% P. A maiden inferred resource has also been announced for Mount Fisher, 15–20 km southwest of Sherwin Creek, of 15.6 Mt at 44.0% Fe. Sherwin also announced the discovery of high-grade iron ore at surface at their Yumanji tenement, in the southeast of their project area close to Western Desert Resources’ Roper Bar project, with numerous rock chip samples in excess of 60%, up to a maximum of 68.27% Fe. Sherwin announced a plan to proceed towards an early export strategy that involves mining at Hodgson Downs, and processing to upgrade the material to a saleable concentrate grading 61–63% Fe. The concentrate would then be pumped to a location near the Darwin railway line, where it would be dewatered and placed into containers for rail transfer to Darwin Port. This early export strategy is designed to generate early cash flow, while continuing studies for the long-term potential of shipping 10 Mtpa through the Gulf of Carpentaria.

Phosphate Australia Ltd have continued to investigate the iron ore potential at their Nicholson iron project, in the Mesoproterozoic South Nicholson Basin. A preliminary mapping and rock-chip sampling program in 2010 yielded numerous samples assaying in the range 48–64% Fe, with a best result of 63.7% Fe, 5.1% SiO₂, 1.8% Al₂O₃, 0.04% P and 1.2% LOI. During 2011, metallurgical testing on a one-tonne sample of iron ore grading 55.8% Fe demonstrated that the ore could be beneficiated to a higher grade product of 59.1% Fe.

Aard Metals Ltd Warrego tailings project is located 36 km northwest of the township of Tennant Creek. The project area comprises five tailings dams from historical mining of ironstone-hosted copper and gold. Aard Metals are evaluating the project with a view to the production of a magnetite concentrate, along with copper and gold as by-products. The project has an Indicated Resource of iron (as magnetite) for the Warrego tailings of 7.72 Mt (dry) at 35.2% Fe, upgradeable to a concentrate of 2.92 Mt at 67.1% Fe. This is accompanied by an Inferred copper and gold resource of 7.79 Mt (dry) at 0.21% Cu and 0.48 g/t Au.

Figure 4. Location of iron ore, lead-zinc, manganese, tungsten-molybdenum, nickel and vanadium magnetite deposits and projects discussed in the text.
**Lead-zinc-silver**

Although the Territory continued to be a major zinc producer from the giant McArthur River mine, exploration for zinc and lead was relatively subdued during 2011. The *McArthur River* mine is situated about 70 km southwest of Borroloola, in the McArthur Basin. It is operated by McArthur River Mining Pty Ltd (MRM), a subsidiary of Xstrata PLC. It opened as an opened underground mine in 1995 and has now been converted to open cut. The McArthur River mine has a total resource of 144 Mt at 11.2% Zn, 4.8% Pb and 48 g/t Ag; total reserves were recorded as 46.3 Mt at 9.6% Zn, 4.2% Pb and 43 g/t Ag. In 2010, MRM produced 2.2 Mt of ore and 384 000 t of bulk concentrate. The very fine-grained thinly bedded sulfide ore is hosted in the HUC Pyritic Shale Member of the Barney Creek Formation. During 2011, MRM announced a proposal to increase mine production from McArthur River to approximately 5 Mtpa resulting in an increase in bulk zinc/lead concentrate volume to 800 000 tpa. The indicative cost of this expansion is $270M. Subject to the completion of studies and necessary approvals, work on the expansion may commence in 2012.

Rox Resources Ltd’s *Myrtle* prospect, 20 km south of the McArthur River mine, contains near-surface zinc-lead mineralisation with a strike length of at least 700 m along the Main Zone of mineralisation, and this remains open in all directions. The style of mineralisation is similar to that at McArthur River, although the coarser grain size of mineralisation at Myrtle suggests that metallurgical recoveries should be better than at McArthur River. The Inferred Resource at Myrtle is 43.6 Mt at 4.09% Zn and 0.95% Pb, at a 3% Zn+Pb cutoff, with a higher-grade core of 15 Mt at 5.45% Zn and 1.0% Pb. Following the signing of a 4-year $5M joint venture agreement with Teck Australia Ltd to explore the Myrtle project tenements, Teck is now the operator of the project. The 2011 field season on the Myrtle tenements was cut short by the early onset of the wet season, with the first hole being drilled to just 220 m before being suspended due to the weather, well short of the target depth of 400 m.

TNG Ltd announced a joint venture with the Sorby Hills Joint Venture (SHJV) for the continued exploration and potential development of the *Manbarrum* zinc-lead-silver project. This project includes a number of Mississippi Valley-style deposits hosted within the Bonaparte Basin, close to the Western Australian border. The SHJV, which is managed by KBL Mining Ltd (formally Kimberley Metals), also controls the Sorby Hills lead-zinc deposit immediately across the border in WA. The most significant known deposit at Manbarrum is the *Sandy Creek* orebody, which has a JORC-compliant resource of 24.3 Mt at 1.81% Zn, 0.45% Pb and 4.57 g/t Ag, with a higher-grade core of 12.6 Mt at 2.37% Zn, 0.59% Pb and 5.5 g/t Ag.

At the *Jerroco* base metals project in the Arunta Region, Kentor Gold Ltd announced a lead-zinc-silver resource of 1.0 Mt at 2.6% Pb, 2.2% Zn and 73 g/t Ag at the *Green Parrot* deposit, as part of a much larger (8.8 Mt) copper-silver resource. Follow-up drilling at Green Parrot yielded intersections including 4.3 m at 8.49% Pb, 1.02% Zn, 1.70% Cu, 362 g/t Ag and 0.06 g/t Au from 70 m, including 1.7 m at 17.91% Pb. Kentor also released historical drilling results from Green Parrot including 9 m at 9.42% Pb, 7.13% Zn, 4.29% Cu and 450 g/t Ag.

**Manganese**

Oolitic and pisolithic ore in Mesozoic sedimentary rocks forms one of the world’s highest-grade manganese deposits of 170 Mt at 47.1% Mn. It was discovered in 1960 and has been continuously mined by the Groote Eylandt Mining Company (GEMCO) for decades. Production from Groote Eylandt in 2011 totalled 3.958 Mt of manganese ore. In 2011, GEMCO announced plans to proceed with the $280M Phase 2 expansion of the operation, which will increase GEMCO’s beneficiated product capacity to 4.8 Mtpa and is expected to be completed in 2013. Northern Manganese Ltd (formerly Groote Resources Ltd) have been granted tenements over marine waters offshore from Groote Eylandt, where the company has interpreted the manganese orebody to extend below the seafloor. No exploration was undertaken during 2011 as the company sought regulatory approval for a marine acoustic and resistivity sub-bottom profiling survey.

The other operating manganese mine in the Northern Territory occurs in Proterozoic rocks at *Booto Creek* 110 km north of Tennant Creek. OM Manganese Ltd began mining operations at Booto Creek in November 2005. At 31 December 2010, the total Mineral Resources were 32.5 Mt at 22.6% Mn and Ore Reserves were 21.5 Mt at 21.0% Mn. Full year production in 2011 was 902 082 t grading 36.7% manganese, representing an increase of 10% on 2010. Manganese exploration has been undertaken along strike from the Booto orebodies by OM Manganese and several other companies.

There were few public announcements on manganese exploration in the Northern Territory during 2011, although a number of companies were exploring for manganese, including Universal Splendour Investments (Amadeus Basin, McArthur Basin and Birrindudu Basin), Sinosteel Australia (Tomkinson Province and McArthur Basin) and Natural Resources Exploration. Sandfire Resources NL entered into an agreement in 2010 with the ASX-listed mining services and contracting company, Mineral Resources Ltd, to fund exploration and development of its Borroloola manganese project. The *Masterton 2* manganese prospect in the McArthur Basin has yielded surface rock-chip samples varying from 43.5% to 53.1% Mn, although exploration by Genesis Resources Ltd in 2011 suggested that this mineralisation is surficial in nature.

**Molybdenum—tungsten**

During 2011, Thor Mining PLC undertook a drilling campaign and commenced a revised feasibility study at their *Molyhil* molybdenum-tungsten project, near the Plenty Highway, northeast of Alice Springs. Molyhil is a skarn-related deposit within the Arunta Region with a resource of...
3.75 Mt at 0.32% WO₃, 0.19% MoS₂, and 28% Fe₂O₃. Thor undertook a two-stage drilling program in 2011, comprising reverse circulation (RC) drilling, to test for additional down-plunge resources, and a diamond drilling program to test mineralisation previously defined by RC drilling, with the aim of determining what differences (if any) there may be in results from the two drilling methods. The RC program defined down-plunge and easterly extensions to the orebody with intersections including 16 m at 0.81% WO₃ and 0.44% MoS₂, from 189 m and 13 m at 0.38% WO₃ and 0.13% MoS₂, from 290 m. Assays from the diamond drilling program include 16.4 m at 0.84% WO₃ and 0.56% MoS₂, from 43.6 m (including 4 m at 2.12% WO₃ and 0.33% MoS₂) and 9 m at 1.48% WO₃ and 0.10% MoS₂, from 48 m (including 4 m at 2.93% WO₃ and 0.17% MoS₂). A resource update, based on 2011 drilling and the results of the definitive feasibility study, is expected to be released in early 2012. Thor have reported that the capital and operating cost estimates for the first phase of production have been estimated at A$66 million and A$79/t, respectively.

Nickel

Mithril Resources Ltd (Mithril) has discovered Ni-Cu-PGE mineralisation at several locations in their Huckitta project area in the eastern Arunta Region (including the Baldrick prospect, where drilling in 2009 yielded a best result of 9 m at 0.48% Ni and 0.37% Cu). During 2011, Mithril announced a $4 million option and joint venture agreement with MMG Exploration Pty Ltd relating to the nickel rights on Mithril’s wholly owned tenements in the Huckitta project area, in order to progress nickel exploration in the region.

Vanadium-titanium-iron

TNG Ltd’s Mount Peake project is a gabbro-hosted vanadium-titanium-magnetite prospect in the northern Arunta Region, 60 km west-southwest of Barrow Creek. In 2011, TNG upgraded the JORC Inferred Resource estimate to 160 Mt at 0.3% V₂O₅, 5.0% TiO₂ and 23.0% Fe. Drilling at Mount Peake during 2011 resulted in the thickest and highest-grade intersections to date at Mount Peake, including 145.5 m at 0.39% V₂O₅, 7.26% TiO₂ and 29.4% Fe (including 50.0 m at 0.55% V₂O₅, 9.4% TiO₂ and 32.2% Fe). Interim pre-feasibility study results from Mount Peake suggest an initial 17.2-year mine life with a 2.5 Mtpa operation ramping up to 5 Mtpa, producing vanadium, iron and titanium through a newly developed hydrometallurgical process, and with potential downstream value-adding process to produce ferrovanadium. TNG have signed an agreement with the Jiangsu East China Mineral Investment & Development Bureau (ECE), formalising a $13.4M investment and strategic partnership in TNG to assist in the development of Mount Peake.

Mineral sands (zircon-ilmenite-rutile)

In December 2011, Matilda Zircon commenced mining their Lethbridge South mineral sands project on Melville Island in the Tiwi Islands (Figure 5), with first production of concentrate planned for early 2012. The deposit is projected to produce 27 520 t of zircon and titanium concentrate, with a mine life of under a year. Matilda also announced the definition of a new mineral sands resource at Kilimiraka on southwestern Bathurst Island. The Kilimiraka deposit has an inferred resource of 56.2 Mt at 1.6% heavy minerals, for 893 700 t of heavy minerals, comprising 92 000 t zircon, 57 000 t rutile, 127 000 t leucoxene and 368 000 t ilmenite. Matilda reported that the Kilimiraka resource has the potential to underpin an 8–10-year mining operation, assuming mining rates of approximately 700 t per hour.

Australian Ilmenite Resources Pty Ltd’s Roper Heavy Mineral project is targeting ilmenite-bearing Derim Derim dolerite sills in the Roper Group and associated placer deposits. This project has a Measured Resource of over 300 000 t ilmenite with a further 4 Mt either Indicated or Inferred. The ilmenite is very low in deleterious minerals such as Cr₂O₃, U and Th, and is suitable for the production of both synthetic rutile and titanium sponge.

Rare earths

Arafura Resources Ltd (Arafura)’s Nolans Bore rare earth elements-phosphate-uranium orebody is located in the Reynolds Range, 135 km northwest of Alice Springs. About one-third of the rare earths are in phosphate-rich apatite and two-thirds are in cheralite (a phosphate mineral). Measured, Indicated and Inferred Resources total 30.3 Mt to a depth of 130 m, with grades of 2.8% rare earth oxides (REO), 12.9% PO₄, 0.02% U₂O₅, and 0.27% Th. The orebody contains 848 000 t REO, 3.9 Mt PO₄, and 13.3 Mt (6031 t) U₂O₅. Arafura undertook a major resource drilling campaign in 2011, comprising 52 169 m of RC and diamond core drilling, in order to convert much of the inferred resource to the indicated category, increase the overall resource, and provide improved geotechnical and metallurgical data. Drilling in the South Zone of the resource confirmed that mineralisation was open along strike and at depth across large parts of the resource, with intersections including 79.3 m at 4.0% REO, 20.0% PO₄ and 272 ppm U₂O₅ from 46.6 m, and 21.0 m at 6.1% REO, 25.3% PO₄ and 480 ppm U₂O₅ from 141.0 m. Deep drilling in the northern part of the resource has extended the known mineralisation at depth, with intersections including 55.4 m at 3.3% REO, 15.1% PO₄ and 308 ppm U₂O₅ from 194.6 m. Arafura also announced a new discovery of mineralisation during first-pass RC drilling of geophysical targets located 0.5–1.0 km beyond the eastern limit of the known resource, with mineralised intercepts including 28 m at 2.6% REO, 2.6% PO₄ and 163 ppm U₂O₅ from 92 m. An updated resource estimate is expected in early 2012, to contribute to the Nolans bankable feasibility study (BFS). During 2011, Arafura announced an expansion to the scope of their BFS to pursue opportunities to simplify the Nolans project flow sheet to focus predominantly on production of rare earths products, including the design and optimisation of a modified mine site beneficiation circuit to generate a higher mineral concentrate grade. Arafura are targeting first production in 2014, with planned annual
production of 20 000 t REO, 80 000 t $\text{P}_2\text{O}_5$, 150 t $\text{UO}_2$ and 500 000 t $\text{CaSO}_4$ (gypsum).

In late 2010, TUC Resources Ltd (TUC) announced a new rare earths discovery at their Quantum prospect, around 60 km west of Pine Creek. The deposit is hosted within Pine Creek Orogen stratigraphy under 100 m of sedimentary cover of the Daly Basin. Initial drilling of the prospect yielded an intersection of 50 m at 1.55% total REO (TREO) from 245 m, including 12 m at 4.51% TREO. The mineralisation is associated with intense quartz/fluorite veining and sulfide mineralisation in a black carbonaceous shale unit, thought to be part of the Gerowie Tuff. Mineralogical analysis has shown concentrations of the REE-rich mineral allanite in a hydrothermal vein and alteration system. The allanite is variably altered to rims to allanite crystals. Ongoing diamond and RC drilling at Quantum during 2011 has revealed multiple, high-grade zones of REE mineralisation over a 300+ m strike length.

Highlights of drilling in 2011 included 21.9 m at 2.55% TREO from 276.1 m (including 9.2 m at 3.78% TREO) and 3.2 m at 3.13% TREO from 296 m.

TUC announced a new heavy rare earth elements (HREE) discovery during 2011 at Stromberg (formerly the Energy uranium prospect), 200 km south of Darwin. Reassaying of samples from uranium drilling at Stromberg during 2011 identified significant HREE mineralisation hosted within flat-lying, near-surface sandstone of the Tolmer Group (Birrindudu Basin), with up to 7 m at 1.0% TREO (total rare earth oxides). Within that intersection, 95% of the TREO are heavy rare earth elements, with dysprosium comprising 7.2% of total REE distribution, ytrrium (68.2% of distribution), erbium (5.2%), ytterbium (4.8%), gadolinium (3.3%) terbium (0.86%), europium (0.36%) and holmium (1.8%). This compares very favourably to most rare earths deposits worldwide in terms of the value of the contained rare earths, and is a higher proportion of heavy REE of any of the major global REE projects. The HREEs are contained in xenotime. The nature of the Stromberg prospect supports a conceptual project development timetable that could be less than five years, with low capital expenditure requirements, producing a xenotime concentrate for export. TUC Resources undertook a drilling program at Stromberg in late 2011, which demonstrated the existence of coherent zones of mineralisation over a strike length of over two kilometres, with a best intersections of 8 m at 0.72% TREO from surface (comprising 93.5% HREE including 7.9% Dy). The mineralisation remains open, and is associated with significant uranium (averaging 450 ppm U) which may be an economic by-product. Thorium content is extremely low.

TUC has identified additional HREE targets in the vicinity of Stromberg, of which the most significant to date is the Drax prospect, located about 30 km north of Stromberg, which is a HREE soil anomaly associated with a similar radiometric anomaly as at Stromberg. The percentage of HREE in the soil assay results is high; on average heavy REEs account for 44% of TREO. TUC Resources are planning drilling at this and other HREE prospects in the area in 2012.

Crossland Uranium Mines Ltd (Crossland) has identified potentially extensive alluvial deposits at its Charley Creek project, 120 km west of Alice Springs, containing significant rare earth elements hosted within phosphate minerals. Heavy mineral concentrates produced by Crossland from samples of stream channel alluvium have locally returned >50% TREO, with relatively high proportions of heavy REE (average of ca 17% of total REE). During 2011, Crossland has undertaken a stream sediment sampling and auger drilling program at their Cockroach prospect, to establish the size and grade of the potential resource. This resource estimation was almost complete in late 2011, although check assay results of REE concentrates from a second laboratory indicated substantially different (higher) REE estimates that those obtained by Crossland’s regular laboratory. Release of a resource awaits resolution of this issue. Eight key areas have been identified that have widespread and strongly anomalous REE in shallow alluvium, with potential for very large tonnages of REE-
Inferred resources (at 10% P2O5 cut-off) for the project are increased the estimated inferred resources in the Main Barkly Highway. During 2011, an 82-hole drilling program within the Georgina Basin, close to the Cambrian upper Gum Ridge Formation or basal Wonarah Formation within the Georgina Basin, which is a world-class province for sedimentary phosphate. During the course of 2011, Northern Minerals announced a Joint Venture Heads of Agreement with Toro Energy to earn up to 80% interest in other (non-REE bearing) heavy minerals such as zircon. Testwork to develop a flowsheet and costing for an alluvial mining project has commenced.

The Tanami Region also has high potential for rare earths. In the Browns Range, in WA within 10 km of the NT border, Northern Minerals Ltd have discovered significant new HREE prospects, with broad drilling intersections of >1% TREO including >1000 ppm dysprosium. In late 2011, Northern Minerals announced a Joint Venture Heads of Agreement with Toro Energy to earn up to 80% interest in all mineral rights other than uranium within Toro Energy’s Browns Range tenements within the Northern Territory. Rare earths exploration on these tenements is planned to commence in 2012.

**Phosphate**

2011 was another strong year for phosphate exploration in the Northern Territory, particularly in the Georgina Basin, which is a world-class province for sedimentary phosphate. During the course of 2011, 415 Mt of ore was added to the Territory’s phosphate resource base (at 10% P2O5 cut-off), representing a 60% increase in the JORC-compliant resources in the Georgina Basin within the Northern Territory.

Minemakers Ltd’s Woronah phosphate deposit occurs in the Cambrian upper Gum Ridge Formation or basal Woronah Formation within the Georgina Basin, close to the Barkly Highway. During 2011, an 82-hole drilling program increased the estimated inferred resources in the Main Zone by around 50%. The updated combined Indicated and Inferred resources (at 10% P2O5 cut-off) for the project are 782 Mt at 18% P2O5, comprising 647 Mt in the Main Zone and 135 Mt in the Aruwarra deposit. Also during 2011, Minemakers commissioned a study to model the economics of the development of Woronah, which proposed downstream processing facilities to produce superphosphoric acid or N-P (nitrogen phosphorus) fertilisers such as diammonium phosphate (DAP). Minemakers considered that this study justified the commitment of a bankable feasibility study, which they plan to commence upon the completion of a joint venture agreement with Bombay-listed NMDC Ltd.

A significant new phosphate discovery was made in late 2010 by Rum Jungle Resources Ltd at the Barrow Creek-1 prospect, which forms part of their Ammaroo project. This project, which is approximately 80 km from the Alice Springs–Darwin railway, is emerging as the most significant new phosphate discovery in the Georgina Basin in recent decades. The company announced a maiden resource in June and then a resource upgrade in December, with total Indicated and Inferred resources of 253 Mt at 15% P2O5 (at a 10% P2O5 cut-off) or 97 Mt at 18% P2O5 (at a 15% cut-off). The resource is based on 843 RC holes and 32 diamond drillholes for a total of 25 428 m. The area of the existing resource is 6.6 km east–west by 5.1 km north–south. The average thickness of the deposit is 5.9 m with an average depth to the top of mineralisation of 24 m. In 2012, further drilling is planned with a view to converting much of the Inferred resource to Indicated status, as well as extensional drilling of the resource, which remains open in most directions.

NuPower Resources Ltd (NuPower) undertook a 357-hole, 12 602 m drilling program at their Arganara project, immediately to the east of the Barrow Creek-1 deposit. The first phase of the program was designed to test the eastern extension of the Barrow Creek-1 deposit where it continues onto NuPower’s tenement. Highlights from drilling included 5 m at 28.6% P2O5 (including 2 m at 34.6% P2O5) and 7 m at 24.8% P2O5 (including 2 m at 35.3% P2O5). Mineralisation has now been identified in a 3 km-wide zone extending 3.2 km east from the edge of the existing Barrow Creek-1 resource.

NuPower also announced assays of 1 m splits from previously reported drilling at the Patanella deposit within their Lucy Creek phosphate project in the Georgina Basin. Highest grade drilling intersections included 8 m at 34.2% P2O5 and 4 m at 30.9% P2O5. Phosphate Australia Ltd has the Highland Plains deposit, which abuts the Northern Territory/Queensland border. Phosphate occurs in the Cambrian Border Waterhole Formation in the Georgina Basin. The total Inferred Resource is 56 Mt at 16% P2O5 with a lower cut-off grade of 10% P2O5. This includes 14 Mt at 20% P2O5 in the Western Mine Target Zone of the deposit. No exploration activity was reported in 2011, as Phosphate Australia continue to seek a partner to take the project forward.

The multi-commodity Nolans Bore orebody (see Rare earths) has Measured, Indicated and Inferred Resources totalling 30.3 Mt to a depth of 130 m which includes 12.9% P2O5.

**Potash**

Rum Jungle Resources Ltd, in joint venture with Reward Minerals Ltd, have continued to explore their Karinga Creek potash project, located between Eldundra and Curtin Springs along the Lasseters Highway, approximately 200–300 km southwest of Alice Springs. The Karinga Creek drainage system contains hundreds of salt lakes, representing the eastern extension of the Lake Amadeus system. These playa lakes contain brines enriched in salts such as potassium, magnesium and sulfate, and have been the subject of previous investigations for the recovery of commercial evaporite minerals during the 1990s. The joint venture is investigating the potassium- and magnesium-rich brine resources for their potential as a feedstock for...
the production of potassium sulfate (SOP) and potassium magnesium sulfate (schoenite). Since exploration commenced on the project, the joint venture has taken over 150 brine samples, conducted recharge tests from four trenches, drilled eight vibracore and 55 sonic drillholes and installed twelve piezometers. Brine assay results received in 2011 show very high levels of sulfate (up to 7.9%) and magnesium (2.2%), which compare favourably with other Australian and global potash projects. Drilling confirmed that two distinct aquifers are present. The first aquifer is contained in unconsolidated near-surface lake sediments. The second aquifer is hosted in siltstone and sandy interbeds of the Devonian Horseshoe Bend Shale of the Finke Group (Amadeus Basin). The Horseshoe Bend Shale forms basement to most lakes, and where it is fractured it contains free-flowing brine, leading Rum Jungle Resources to interpret that this is the aquifer that supplies most of the recharge water to the salt lake system. The Horseshoe Bend Shale is evaporitic and is probably also the source for most of the salt in the lakes. A maiden Inferred Resource estimate for the project is due in early 2012.

**Uranium**

**Pine Creek Orogen**

The Ranger mine is a world-class uranium deposit hosted in the lower Cahill Formation in the Pine Creek Orogen, close to the structural contact with the underlying Archaean Nanambu Complex. Existing Ore Reserves at Ranger are 27.69 Mt at 0.14% U3O8, and Mineral Resources are 127 Mt at 0.09% U3O8. During 2011, Energy Resources of Australia Ltd (ERA)’s Ranger Mine produced 2641 t uranium oxide, a significant reduction from the 2010 and 2009 figures of 3793 t and 5240 t, respectively. Production in 2011 was significantly impacted by a temporary suspension of processing plant operations from 28 January to 15 June, in response to significantly above-average rainfall in the 2010/11 wet season. The ERA board have chosen not to proceed with the facility. Exploration program at their **Nabarlek** tenements, located immediately to the north of the U40 prospect. Gamma logging of drillholes yielded anomalous uranium with a best intersection of 1.31 m at 460 ppm U3O8.

**Allambee Resources Ltd** undertook their first drilling program at their **Nabarlek North** tenements, located immediately to the north of the U40 prospect. Gamma logging of drillholes yielded anomalous uranium with a best intersection of 1.31 m at 460 ppm U3O8.

After listing on the ASX in early 2011, Alligator Energy Ltd commenced exploration on their Tin Camp Creek project, on tenements purchased from Cameco Australia. Most of their 2011 exploration program was focused on the **Caramal** prospect, in which high-grade mineralisation is associated with strongly chloritised meta-arcsines of the lower Cahill Formation, with strong geological similarities to mineralisation at Ranger and Jabiluka. Thirty-three diamond holes for a total of 4500 m were drilled during the year and confirmed and extended high-grade mineralisation, which remains open along strike and down dip. Best intersections from Caramal include 14 m at 0.71% U3O8 from 108 m (including 9 m at 1.01% U3O8), 14 m at 0.70% U3O8 from 33 m (including 7 m at 1.00% U3O8), 18 m at 0.34% U3O8 from 116 m and 11 m at 0.37% U3O8 from 18 m. Drilling at **South Horn** yielded a best intersection of 2 m at 0.14% U from 76 m.

During 2011, Thundelarra Exploration Ltd (Thundelarra) secured 100% ownership of its **Allambee** uranium project, 36 km north-northeast of Pine Creek. The project has a near-surface inferred resource of 1.4 Mt at 304 ppm U3O8 at the Cleos, Twin and Dam prospects, which were discovered by Total Mining Australia Pty Ltd in 1983. At **Cliff South**, four holes were drilled, which intersected broad zones of uranium mineralisation, including 38 m at 527 ppm U3O8 (including 9 m at 0.15% U3O8) and 42 m at 611 ppm U3O8 (including 8 m at 0.16% U3O8). At the **Lucas** prospect, two holes were drilled to test the southern extension of a mineralised zone discovered in 2010, with best intersections of 2 m at 0.10% U and 7 m at 576 ppm U3O8. All six holes drilled at the Cliff South and Lucas Prospects also intersected zones of highly anomalous copper.

Thundelarra released a maiden resource at its **Thunderball** project near Hayes Creek, which forms part of its Hayes Creek project. Thunderball is a grassroots discovery made in 2008 near Hayes Creek in the Pine
Creek region. Using a conservative 4000 ppm upper cut-off to exclude bonanza grades (up to 20% U₃O₈), the resource was 829 000 t at 924 ppm U₃O₈ for 1.69Mlb U₃O₈ (400 ppm lower cut-off). Uranium mineralisation occurs in a sheared and tightly folded succession of metasedimentary rocks and tuffaceous units of the Gerowie Tuff, near the contact with the overlying Mount Bonnie Formation. Mineralisation appears to consist of uraninite, both in structurally controlled veins and disseminated through the host rocks. During July, a 1810 m RC drilling program was conducted at the Hayes Creek project. Eight holes were drilled at the Bella Rose, Lady Josephine, Corkscrew and Moonraker uranium prospects, with six returning intercepts above 100 ppm U₃O₈, but with no high-grade intersections. A four-hole diamond drilling program at Thunderball failed to intersect significant uranium mineralisation.

Westmoreland-Murphy area (Murphy Inlier, southern McArthur Basin)

In May 2011, Laramide Resources Ltd (Laramide) signed a farm-in and joint venture agreement (Murphy Joint Venture) with Rio Tinto Exploration Pty Ltd to explore two prospective exploration tenements that are situated along strike from Laramide’s Westmoreland Project in Queensland. Under the terms of the agreement, Laramide can earn 51% in the project by spending $10M over 4 years. The first SIM of this earn-in is a firm commitment by Laramide, and will be dedicated to a large-scale, helicopter-supported, airborne magnetic and radiometric survey.

At the Eva uranium-gold deposit in the Murphy Inlier, Nupower Resources Ltd announced a maiden JORC-compliant resource of 0.54 Mt at 0.12% U₃O₈ for 650 t U₃O₈ (1.43 Mlb U₃O₈). This is associated with a smaller gold resource of 101 600 t at 3.77 g/t Au.

Central Australia (Ngalia Basin, Amadeus Basin, Arunta Region)

Energy Metals Ltd have continued evaluating the Bigryli uranium deposit in the Mount Eclipse Sandstone of the northern Ngalia Basin. The company announced a resource update for Bigryli, with total Indicated and Inferred Resources of 7.5 Mt at 0.13% U₃O₈ and 0.12% V₂O₅ at a 500 ppm U cut-off, for 9600 t (21.1 Mlb) of U₃O₈ and 8900 t of V₂O₅. The Bigryli mineralisation remains open at depth and along strike. The results of a pre-feasibility study on Bigryli were released in mid-2011, and although they suggested that the project was technically feasible, an important finding was that a substantial increase in the resource base was required to improve project economics. Subsequent drilling at Bigryli has been designed to target depth extensions and additional near-surface material, with results including 16.95 m at 0.87% eU₃O₈ from 72 m, 7.4 m at 0.71% eU₃O₈ from 28 m and 13.9 m at 0.32% eU₃O₈ from 55 m at Anomaly 4, and 10.25 m at 0.93% eU₃O₈ from 1 m at Anomaly 15. Energy Metals reported that drilling has resulted in several extensions of the mineralisation at depth and in close proximity to current optimised pit shells. Drilling of eastern extensions of the Bigryli mineralisation, at Anomaly 15 East, gave encouraging results with intersections including 6 m at 0.19% eU₃O₈ from 60 m.

At the Camel Flat uranium prospect, 33 km southeast of Bigryli, Energy Metals undertook a drilling program to follow-up encouraging exploration results reported in 2010, including 5 m at 1.33% U₃O₈. Mineralisation at Camel Flat is steeply dipping within the Mount Eclipse Sandstone. Drilling in 2011 gave a best intersection of 8.35 m at 735 ppm eU₃O₈ from 62 m.

Thundelarra Exploration Ltd continued to define palaeochannel-hosted uranium mineralisation in the Ngalia Basin following the discovery of the Afghan Swan prospect in late 2010. Mineralisation occurs along a package of grey, unconsolidated channel sediments at the base of the Cenozoic succession. During 2011, Thundelarra commenced a systematic drill assessment of the Afghan Swan prospect with nearly 13 000 m of mud rotary and RC drilling. Results included 5.28 m at 0.16% eU₃O₈, 7.1 m at 0.14% eU₃O₈ from 135 m (including 0.15 m at 0.52% eU₃O₈) and 1.6 m at 0.12% eU₃O₈. Drilling has identified significant uranium mineralisation (greater than 100 ppm eU₃O₈) over a 15 km strike extent within the one palaeovalley system that has been tested. This represents the first major palaeochannel-hosted uranium mineral system identified in the Northern Territory.

Callabonna Uranium Ltd announced the results of an MMI survey over their Mount Denison project area, in the Arunta Region northeast of the Ngalia Basin, which defined a new prospect named Five Mile Creek. Anomalism within the Five Mile Creek prospect is interpreted to extend for at least 4 km along the axis of a modern drainage system and includes uranium response ratios exceeding 150 times background. Waters draining through the Five Mile Creek prospect are shed from the uranium-enriched Wangala Granite. Callabonna reported that they plan to drill test the anomaly at the soonest possible opportunity.

A maiden JORC-compliant resource has been announced for the Angela uranium deposit by a Cameco Australia Pty Ltd and Paladin Energy Ltd joint venture. The orebody is in the northern Amadeus Basin, 25 km south of Alice Springs. The resource contains 10.7 Mt at 0.13% U₃O₈, for 13 980 t U₃O₈ (30.8 Mlb U₃O₈), making it the Territory’s largest known uranium resource outside of the Alligator Rivers uranium field. The resource estimate is based on 794 holes totalling 180 468 m and covers the Angela (1 to 5) and Pamela deposits. The mineralisation plunges shallowly, at approximately 9°, to the west and the larger of the deposits, Angela 1, has been defined up to 4.3 km to the west at depths up to 600 m and remains open. The mineralisation is contained within nine individual stratigraphic successions with mineralised thicknesses of up to 10.4 m.
In the 2011 NT Budget, the Territory Government announced a three-year, $11.4M extension to the successful Bringing Forward Discovery initiative. The renewed initiative builds on the first four years of Bringing Forward Discovery and takes the total Government investment in the initiative to $25.8 million over seven years. The initiative is designed to assist explorers to make the next major mineral and petroleum discoveries in the Territory, and has already delivered major successes in increasing the Territory’s share of Australian exploration activity.

Bringing Forward Discovery comprises three broad elements – geoscience programs, industry collaborations, and project facilitation and promotion.

Future geoscience programs

A major component of the Bringing Forward Discovery initiative is the acquisition and delivery of new geoscience data by NTGS. NTGS aims to build a comprehensive 3D understanding of the Territory’s geology and to pinpoint exploration opportunities in greenfields regions with the emphasis on areas that are under cover. This includes:

- regional gravity surveys
- high-quality targeted geoscience
- detailed prospectivity analyses of greenfields terranes
- improved online access to data and information.

A campaign of regional gravity data acquisition is being undertaken over prospective, but poorly exposed terranes, to complement the Territory’s near-complete coverage of magnetic and radiometric coverage. Since the beginning of Bringing Forward Discovery, coverage of the Territory with regional gravity data at less than 4 km station spacing has increased from 9% to 36%. This figure is projected to increase to more than 50% by 2014. Companies are invited to partner with NTGS to infill or extend the surveys.

Targeted geoscience data acquisition and interpretation remains a key focus. This includes 3-dimensional mapping and geochemical analyses in areas that have high potential to yield new discoveries, especially where the prospective geology is poorly understood or buried under cover. A focus of the targeted geoscience data acquisition program is a continued boots-on-ground field data collection and observation approach to upgrade 1:250 000 and 1:100 000 geological maps within the Northern Territory. Under the extended Bringing Forward Discovery initiative, priority regions for geoscientific mapping will be the Amadeus Basin, Arunta Region and Murphy Province.

Although the focus of much of the field-based programs during Bringing Forward Discovery will be in under-explored greenfields areas, there are also programs to add value in areas of known mineralisation. For example, in collaboration with exploration companies, NTGS plans to strategically use its HyLogger™ instrument to spectrally fingerprint alteration systems around known deposits by scanning drill core and rock chips within mineralised systems. This will add an important third and depth dimension to existing surface geophysical datasets. The HyLogger will also routinely scan drill core acquired through the NTGS Geophysics and Drilling Collaborations program to provide an extra level of data in greenfields areas.

A key commitment under the renewal of Bringing Forward Discovery is to commence an intensive study into the Neoproterozoic to Palaeozoic Amadeus Basin, a region known for its hydrocarbon and uranium potential, but underexplored for base metals and other commodities. In 2012, CSIRO, NTGS and a number of exploration companies will commence COBRA (Central Oz Basins Resource Assessment), a collaborative project that will improve the understanding of the stratigraphy, structure and evolution of the Amadeus Basin, provide a 3D basin architecture model of the basin and advance the understanding of the known and the potential mineral systems. The first stage in upgrading existing geoscientific datasets over the basin is the regional Eastern Amadeus gravity survey, which is being funded by NTGS under Bringing Forward Discovery. This survey will be undertaken during the May to August 2012 period and will comprise a minimum of 6600 ground gravity stations over the eastern two-thirds of the Amadeus Basin at a spacing of 4 km or less. Two exploration companies have taken advantage of infill opportunities from this survey and this will provide an enhanced dataset to improve the building of an updated 3D basin model.

A comprehensive review of the base metals deposits of the Northern Territory is anticipated to be released in 2012. This will be the first publication detailing all significant known copper, lead, zinc and silver deposits in the NT, and will complement the existing suite of NT-based commodity review volumes.

Geophysics and drilling collaborations

A major component of Bringing Forward Discovery is the Geophysics and Drilling Collaborations program, which is designed to increase the intensity of exploration drilling and geophysics in greenfields areas of the Northern Territory. Under the program, the Northern Territory Government co-funds 50% (up to $100 000 per project) of the direct costs of selected exploration drilling and geophysical acquisition projects in greenfields areas. Particular preference is being given to projects where there is a paucity of geological information, and where the results of drilling or geophysical surveys have high potential to open up new areas for exploration. A map showing the distribution of projects awarded funding for the 2011/12 financial year is shown in Figure 1. The call for applications for collaboration funding in financial year 2012/13 opened on 13 February and will

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1 Northern Territory Geological Survey, PO Box 3000, Darwin, NT 0801, Australia.
2 Email: dorothy.close@nt.gov.au.
close on 2 April. Successful applicants are expected to be announced on 24 April to allow time for programs to be completed during the 2012 field season.

To find out more about the Geophysics and Drilling Collaborations program, including details of projects funded to date, and guidelines on how to apply, please visit www.minerals.nt.gov.au/collaborations.

**Promotion and investment attraction**

Promotion of the Territory’s prospectivity under *Bringing Forward Discovery* ensures that the Northern Territory is competitively positioned as a preferred location of exploration and mining investment. This includes participation at domestic and international promotional...
conferences, as well as more pro-active investment attraction activities through the Department’s International Minerals Investment Attraction Strategy in China, Korea and Japan. The strategy continues to have success in attracting investment from Asian markets into exploration or mining development projects in the Northern Territory. This includes Government-led industry delegations to China, Korea and Japan, where exploration companies have the opportunity to present their Territory-based exploration projects to potential investors. If you are interested in attracting investment from East Asia into your projects, please contact Cindy McIntyre (cindy.mcintyre@nt.gov.au; 08 89996222).

Recent highlights from Bringing Forward Discovery

Since AGES 2011, a number of products have either been released, or are due for imminent release under the Bringing Forward Discovery initiative, to upgrade existing geoscientific datasets and provide new information on the geological framework and prospectivity of the Northern Territory.

Geophysics and Drilling Collaborations 2011/12

Round 4 of the Geophysics and Drilling Collaboration program saw a total six projects funded under the Bringing Forward Discovery initiative; four drilling projects and two geophysical acquisition programs. A highlight of this Collaborations round is the co-funded, regional-scale, airborne electro-magnetic (EM) survey with Eclipse Uranium Ltd over tenements within the Ngalia Basin. This survey has complemented previous co-funded AEM acquisition in this region and has ensured a large-scale dataset of open file electromagnetic data over the Ngalia Basin. Co-funded diamond drilling programs by Mincor Resources NL in the Georgina Basin and Ausquest Ltd in the Eromanga Basin have provided excellent stratigraphic information to assist in understanding the geological framework of these areas.

Territory wide projects

A completely upgraded Diamond Exploration Database for the Northern Territory has recently been released and now includes an expanded range of fields for each data location. The upgraded database now includes bulk geochemical sample locations of diamond exploration relevance, trace element mineral chemistry, application of contemporary discrimination models to indicator mineral chemistry, background mineral chemistry to provide a context to exploration, background mineral recovery to provide a platform for commodity diversification, reference to relevant geophysical surveys; copies of diamond-positive company reports, and integration of non-company report data. The database is presented in a GIS-integrated fashion and with accompanying explanatory documentation. A review of diamond exploration activity in the NT to date, with an analysis of prospective and underexplored areas, is currently in the editorial process and will be released before June 2012.

The Australia-wide multi-element geochemical dataset collected under Geoscience Australia’s National Geochemical Survey of Australia as part of the 2006–2011 Onshore Energy Security Program initiative, has provided an opportunity to analyse regional-scale geochemical anomalism across the NT. AGES 2012 will see the release of an NT-wide geochemical atlas that illustrates the distribution of anomalous levels of selected strategic elements.

To increase the accessibility of the geochronological data and studies that NTGS undertakes during regional geoscientific investigations, AGES 2012 will see the release of an NT-wide spatial layer of U-Pb geochronology through the online web mapping system STRIKE. This spatial layer will initially include all U-Pb analyses undertaken by NTGS and collaborative SHRIMP analyses undertaken by Geoscience Australia. A link will be provided in this spatial layer to the relevant NTGS Record which will provide detailed data on individual analyses. In the future, NTGS will look to add all published U-Pb analyses to this layer, which will involve capturing information from university theses and open-file company reports.

NTGS has also invested in CSIRO’s Australia-wide seamless ASTER stitch, which has resulted in a complementary set of NT-wide mineral maps to assist explorers in identifying regional-scale alteration systems. The WA Centre of Excellence for 3D Mineral Mapping (C3DMM), led by CSIRO, has developed new methods and software that has transformed raw ASTER satellite data into a new suite of 14 mineral group maps. These GIS-compatible images are due for release in April 2012.

An updated Metallogenic Map of the NT (1:2.5 million scale) is being released at AGES 2012. This map shows the spatial distribution of the various styles of mineral deposits and major occurrences in the context of the style of mineralisation, broad lithostratigraphic subdivisions, lithological host units and major structures. The map utilises the latest data available in the MODAT database, and includes new discoveries and resource estimates from the past twelve months.

Pine Creek Orogen

Recent work by NTGS in the Pine Creek Orogen has identified widespread and previously unknown outcropping Neoarchaean basement throughout western Arnhem Land and correlated major stratigraphic successions across the orogen. Mafic units in the Litchfield Province have also been characterised and subdivided, with implications for the tectonic development and nickel, platinum, copper and zinc prospectivity of the area. New geoscientific datasets and analyses undertaken by NTGS in the Pine Creek Orogen are available through the release of First Edition Howship and Oenpelli 1:100 000 outcrop maps, GIS datasets and accompanying explanatory notes from the West Arnhem Land region; the release of an upgraded Pine Creek 1:250 000 outcrop map and GIS dataset, and
the release of NTGS Record 2010-005: Palaeoproterozoic island-arc-related mafic rocks of the Litchfield Province, western Pine Creek Orogen, Northern Territory.

**Tanami Region**

To continue to provide seamless geological datasets over important geological terrains, an updated Birrindudu 1:250 000 outcrop map and GIS dataset from the Tanami Region will be released at AGES 2012. The next few months will also see the release of the The Granites 1:250 000 outcrop map and GIS dataset.

**Arunta Region**

A major focus for NTGS continues to be to improve the geoscience mapping coverage and understanding of the geological framework of the Arunta Region, which is increasingly emerging as an important Proterozoic mineral province. Recent results from mapping in the Arunta Region (announced at AGES 2011) have directly contributed to new discoveries of copper-gold mineralisation, in the eastern Arunta Region. Programs in the Arunta are ongoing and a number of new maps and reports are pending.

**Mineral system studies**

The Joint Surveys Uranium (JSU) mineral systems initiative was implemented to facilitate an improved understanding of uranium mineral systems and formation processes in South Australia and the Northern Territory by integrating knowledge and skill sets from CSIRO, geological surveys and exploration companies. Two entirely different key areas were targeted within the NT – the Ranger U system in the Palaeoproterozoic Pine Creek Orogen, and the Bigryli U-V system in the Neoproterozoic–Palaeozoic Ngalia Basin. By using both existing and newly acquired datasets, an improved understanding of these uranium mineral systems has been gained. Through the Ngalia Basin Uranium Mineral System study and under the Bringing Forward Discovery initiative, NTGS has funded a regional-scale gravity acquisition program over the Ngalia Basin that has significantly contributed to the 3D modelling of the architecture of the Basin.

At AGES 2012, reports and 3D datasets from both the uranium mineral systems studies at Ranger and the Ngalia Basin will be released into the public domain. NTGS is currently expanding the mineral systems understanding of the Ngalia Basin via the hyperspectral scanning and analysis of all Ngalia Basin drill core held at the Department of Resources Core Library in Alice Springs with the HyLogger instrument. The purposes of this study are to investigate the regional extent of the alteration systems, recognise depositional environments identified from the JSU project, and to spectrally fingerprint uranium bearing minerals.

**Summary**

Through the programs of Bringing Forward Discovery, NTGS continues to improve the quality, consistency and currency of geoscientific datasets across the Territory, to stimulate exploration, particularly in greenfields areas. This is complemented by specialist and collaborative studies on existing mineral systems to better understand their formation and the criteria for targeting similar deposits. In addition to these geoscientific programs, Bringing Forward Discovery is providing direct assistance to explorers through collaborative funding for exploration and the provision of assistance for explorers in attracting investment.

**What’s new? NTGS systems, client services, products and implementing a new Act**

**Tracey Rogers**

NTGS is continuing efforts to upgrade its digital datasets and systems to improve accessibility for clients. With the upgrade and purchase of customised software for the Minerals and Energy InfoCentre library catalogue, completion of the new online product catalogue database was delayed to take advantage of new features available in the new application. The upgraded version of the InfoCentre library catalogue and the new NTGS product catalogue database are being launched just prior to AGES 2012. The product catalogue database will contain details of all NTGS published material and products, and many will be available for direct download.

The STRIKE web mapping system has been upgraded with a new user interface and is now compatible with more recent versions of Internet Explorer, while the Geophysical Image Web Server can now be accessed without the ERDAS ECW plugin for browsers.

Other significant achievements include the completion and release of 16 new and updated GIS datasets, a new Digital Information Package for the Diamond Exploration Database and the explanatory notes, outcrop geological maps and GIS datasets for the Howship and Oenpelli 1:100 000 mapsheets.

**Web delivery systems – upgrades and a new product catalogue**

The project to upgrade the STRIKE web mapping system in 2011 ran into some issues that have pushed the completion date into 2012. The project is now on track for the launch of an updated version and demonstrations at AGES 2012. STRIKE v2 is compatible with Internet Explorer 7, 8 and 9 and Firefox 10, resolving some ongoing issues with the previous version. The user interface has a completely new look and feel, and displaying the image layers no longer requires the ECW browser plugin.

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In conjunction with a major upgrade to the Minerals and Energy InfoCentre Library Catalogue, an online NTGS product catalogue database has been developed and is due to be launched in mid to late March 2012. The catalogue will enable users to search any word, several bibliographic elements, geological provinces, mapsheets and product types. Clients will be able to find products and published material on particular topics or areas in one search, regardless of product type. Search results can be viewed in several different ways and include details on availability, data and file formats. Many records will also have thumbnail images and links to downloadable files as more products, including explanatory notes, are now being made available online. The application includes a shopping cart facility which allows clients to select multiple product records and forward a request to the InfoCentre. This is particularly useful for requesting products that are not available for download.

The Minerals and Energy InfoCentre Library Catalogue has also undergone a major upgrade with a new look and feel, and some additional hyperlink search capability. The library catalogue covers the library collections in both Darwin and Alice Springs, which include all minerals- and energy-related publications of the department. In particular, the catalogue is the primary discovery tool for information on the NTGS unpublished report collection. These reports are not listed in the product catalogue. In September 2011, NTGS released an update to the Geophysical Image Web Server that provides users with faster image loads and more user-friendly access. Users are now able to view images without any third-party plugins installed – although installing the ECW Browser Plugin by ERDAS will load images faster and at a slightly higher quality. Other new features include the ability to zoom into and out of images with the mouse’s scroll wheel and image exporting (email, print etc) from all image modes both with, and without the plugin enabled. As a result of the upgrade, GIWS also now has a direct URL: geoscience.nt.gov.au/giws.

**Reporting and the new Mineral Titles Act 2010**

The new Mineral Titles Act 2010 came into force on 7 November 2011. Significant changes related to reporting and core submission under the new Act include the separation of expenditure reports from annual reports, release of reports after 5 years, the introduction of approved forms and guidelines, and fees for late lodgement of reports. With the introduction of the new Act, there is a stronger focus on compliance with reporting requirements. All reports must now substantially comply with Guideline 7: Reporting on mineral titles. This guideline mandates digital reporting and provides details on the required content, data and media formats for report submission. In particular, drilling and geochemical data must be submitted in ASCII format and comply with the data templates specified in the guidelines. Industry will benefit in the future by having all data available in a standard format and the process of capturing the data for updating databases will be streamlined.

**NTGS products, spatial data and client services**

The Alice Springs Second edition and a further thirteen First edition 1:250k outcrop geology maps became available in GIS format during 2011. The Waterloo 1:250K outcrop geology map was slightly updated and migrated to a GDA94 base and, together with the GIS dataset, was released as a revised edition in June 2011. A new Pine Creek 1:250k outcrop geology map and the corresponding GIS dataset, compiled from previous and new 1:100k-scale mapping, were released in November. The Second edition Birrindudu 250k outcrop geology map and GIS dataset will be available by AGES, as will be the Howship and Oenpelli 1:100k outcrop geology maps and GIS dataset. Combined explanatory notes for the Howship and Oenpelli maps will also be published in March.

A new geochronology layer will be available on STRIKE in March. The dataset currently contains data on around 600 published geochronological samples across the NT.

DIP 11, Northern Territory Diamond Exploration Database, was recently released. The database replaces DIP 6, the NT Diamond Indicator and Mineral Chemistry Database and includes many new data points, each with an expanded range of attributes, more mineral chemistry data and an explanatory note detailing methodology, assumptions and coverage.

Five new NTGS Records were released in the last year, including a summary of geochronology results up to June 2009 and work on the Palaeoproterozoic mafic rocks of the Litchfield Province.

The 3176 client requests and enquiries handled by the InfoCentre for 2010–11 was lower than the 4546 in 2009–2010 after a three-year period hovering around 4500. Numbers of products distributed increased by 13.5% in 2010–11 compared to the previous year. Company report and data requests were down, but the 2010–11 figure of 46 980 is not directly comparable to the previous year’s record of 63 654, as most petroleum report requests are now satisfied by providing complete basin seismic and well packages. The data packages contain many reports and datasets, but are only counted once on the InfoCentre statistics.
Exploration for unconformity-style uranium deposits: Geology and mineralisation of the Angularli Prospect, Wellington Range Project, west Arnhem Land

Mark King\textsuperscript{1}

Since 1997, Cameco Australia Pty Ltd (Cameco) have been exploring in Arnhem Land in the northeastern NT for uranium mineralisation. For many years the target model has been unconformity-style analogous to the type of mineral deposits present in the Athabasca Basin in Canada, as well as the more local deposit models present in the Alligator Rivers Uranium Field. Unconformity-style deposits are high-grade uranium concentrations located at the unconformity between relatively undeformed quartz-rich sandstone basins and underlying metamorphic basement rocks. Although the Athabasca Basin has a more-or-less universally accepted empirical deposit model and relatively well established strategies for exploration, this cannot be said for uranium deposits in Arnhem Land. Of the four known economic uranium deposits (Ranger, Jabiluka, Koongarra, and Nabarlek), each one has distinctly different geometries, host lithologies, alteration, structure and mineralisation.

The Wellington Range project area is located within the eastern margin of the Neoarchaean and Palaeoproterozoic Pine Creek Orogen (PCO), in a region that has been subdivided into the Nimbuwah Domain of the Alligator Rivers region (Needham and Stuart-Smith 1980, Needham \textit{et al} 1988, Needham 1990, 1998).

The basement geology of the Wellington Range project has been clarified in the last three years from regional diamond core and air core drilling by Cameco. The diamond drilling programs have been and will continue to be guided by mineralisation, as well as by interpreted geophysics, specifically airborne and/or ground-based surveys in radiometrics, magnetics, TEMPEST, gravity, EM and IP.

Interpreted Palaeoproterozoic Cahill Formation rocks form an arcuate linear trend, which parallels the northwestern boundary of the project. Recent drilling has shown these metasedimentary rocks to consist of characteristic Cahill Formation ‘marker’ horizons such as the magnetic pelite and an underlying carbonate-calcisilicate unit. Semipelitic graphite-bearing units are also present at different stratigraphic levels. However, the bulk of the succession consists of pelitic and semipelitic rocks with minor psammitic and interlayered amphibolite. Intrusive rocks include pegmatite and dolerite. The intersected stratigraphy suggests that both upper and lower Cahill Formation rocks are present.

A flaggy quartzite has been observed outcropping at or near the Kombolgie Subgroup sandstone unconformity on the western side of the tenement adjacent to the escarpment. These isolated outcrops were mapped as Cahill Formation by BMR in the 1970s, but it is uncertain where they fit into the stratigraphic succession. Quartzitic rocks have been cored in some of the Wellington Range drillholes and scattered outcrops of flaggy quartzite have been mapped by PNC Exploration Australia Pty Ltd geologists near the top of the Myra Falls Metamorphics succession on the neighbouring King River licence (SEL 25064, Cameco 100\%). Regional correlation of these ‘quartzites’ may provide an idea as to the stratigraphic position of the Wellington Range intercepts of Cahill Formation in relation to the Mesoproterozoic unconformity.

Granitic and quartzofeldspathic gneiss and minor migmatite of the Palaeoproterozoic Nimbuwah Complex form the basement rocks in the southern part of the tenement. Large silt-like bodies of Oenpelli Dolerite intrude the basement and unconformably overlying Early to Middle Proterozoic Kombolgie Subgroup Sandstones. The basal Mamadawerre Sandstone of the Kombolgie Subgroup forms the Wellington Range escarpment, which dominates the southwestern quarter of the project area. Several smaller isolated outcrops of sandstone occur in the southeast. In places above the unconformity, a prominent cobble conglomerate has been mapped.

Up to 300 m of Cretaceous sedimentary rocks, interpreted to be part of the Bathurst Island Formation, obscure the basement geology in the northern part of the Wellington Range tenement. The succession consists principally of dark-coloured micaceous mudstone with intercalated thin sandy beds. Other lithotypes include calcareous sandstone, siltstone and green glauconitic sandstone. Recent cover materials include sand, clay, gravel and cemented ferruginous deposits (King \textit{et al} 2011).

Since 2008, exploration on the Wellington Range tenement has been focused primarily within a 20 km\textsuperscript{2} area in the northeastern corner of the tenement, adjacent to the King River tenements to the east. Seventy-one diamond drillholes varying from 130 to over 500 m in depth have been drilled within this area, which is known as the Angularli prospect.

The original target was based on an offset in TEMPEST data coinciding with a northwest-trending magnetic feature parallel to the mineralised Aurari Fault in the King River tenements. The original drillhole failed to intersect a significant structure or a displacement of the unconformity, but did intersect minor uranium mineralisation from 260.7 m, 20 m above the unconformity. From there, follow-up drilling was primarily based on continuity of mineralisation and targeting the identified geophysics anomaly in an attempt to correlate the two.

The uranium mineralisation intersected at the Angularli prospect is primarily associated with a post-Kombolgie, north-northwest-trending reverse fault. The Aurari Fault in the King River tenement is of a similar nature. Uranium mineralisation has been well documented along portions of this northwest-trending post-sandstone structure, notably from the Aurari North prospect to the Kuroikin prospect, a distance exceeding 10 km.

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along the Angularli Fault can be found discontinuously in variable proportions for a strike length of 1.7 km (and remains open along strike).

Uranium mineralisation is hosted in altered amphibolite-facies metasedimentary and felsic to intermediate magmatic rocks of the Nimbuwah Domain. These basement rocks are unconformably overlain by Palaeo- to Mesoproterozoic Kombolgie Subgroup sandstones. The mineralisation primarily occurs in the hanging wall of a structural zone that extends from the basement into the sandstone cover. Some minor mineralisation also occurs in proximity to a prospect-wide redox boundary. Mineralisation is associated with intervals of intense brittle and brittle-ductile deformation. Intense silica-sericite-clay-pyrite alteration forms an envelope around the primary zone of mineralisation. The primary mineralised body occurs texturally in the form of patches, veins, stringers and breccia matrix infill, consisting primarily of uraninite and pitchblende. Minor instances of coffinite have been intersected in the footwall above the unconformity.

Although the area has not been explored in the detail necessary for resource definition and modelling, intersections of 20.2 m at 5.2% U₃O₈ (including 0.5 m at 27.8% U₂O₅) not only confirms the exploration methodology, but ensures that the Angularli prospect, the Angularli trend, and parallel structures will remain a focus in Arnhem Land for Cameco through the foreseeable future.

References


Linking deposit scale studies and mineral systems thinking: The Ranger U system

James S Cleverley¹,², Louise A Fisher¹, Mark Pownceby¹ and Colin MacRae¹

This paper describes some of the outcomes of the Ranger Mineral Systems project that was conducted as a module of the Joint Surveys Uranium program, an R&D joint venture between CSIRO, DMITRE³, NTGS and industry. The Ranger project specifically was a collaboration between CSIRO, Energy Resources of Australia Ltd (ERA) and NTGS. The project aimed to bring together diverse research skills and techniques from structural geology, 3D modelling, hyperspectral data analysis and geochemistry to build an understanding of the Ranger deposit that can be applied to other unconformity-related U mineral systems. This ultimately would help with future discoveries by delivering models for ore formation, exploration targeting and the demonstration of new technologies that could be used in these systems. This work would not have achieved what it did without the contribution of a large (world-class), mine-scale, multi-element geochemical dataset that had been routinely collected by ERA, and the power of industry datasets should not be underestimated as a platform for research. Although this paper focuses on the geochemical and mineralogical work, the complete outcomes from this project are due to be released as an NTGS record in 2012.

Geological setting

The Ranger 1 No 3 deposit (hereafter termed Ranger 3) is described as an unconformity-related uranium mineral system, one of the largest in the Pine Creek Orogen (PCO) of the Northern Territory. The deposit is hosted by the Palaeoproterozoic Cahill Formation, which consists of intercalated schist and amphibolite overlying a sequence of dolomitic carbonate rocks intercalated with lenses of sedimentary rocks. This sequence is underlain by Archaean granitoid gneiss with some evidence from ERA drilling of a sandstone/siltstone unit between the dolostone and gneiss. This package of rocks is cut by a major angular unconformity with overlying sandstone of the Kombolgie Subgroup. At the mine scale, there are 3 main informal sequences identified: Lower Mine Sequence (LMS) – dolomitic carbonate rocks; Upper Mine Sequence (UMS) – chlorite-rich schist; Hanging Wall Sequence (HWS) – muscovite- and biotite-bearing schist. This mine sequence likely represents both lithology and alteration.

The main locus of uranium mineralisation in the Ranger 3 deposit is along the lithological boundary between the dolostone and schist. A major structure at the eastern
end of the deposit cuts and partly redistributes U at the edge of the Ranger 3 Deeps. At the scale of the Ranger 3 mine sequence, there is mineralisation at the upper Kombolgie unconformity only in the far western part of the mine. Although the complex structure and lack of deep drilling make understanding of the key controls on mineralisation difficult, it appears that the dominant control on the Ranger 3 uranium system is a lithological contact between carbonate rocks and schist, rather than a major stratigraphic unconformity.

3D geochemistry at Ranger

The Ranger deposit has been systematically sampled for multi-element data since the start of exploration and there are ca 30 000 data points for between 13 and 29 elements distributed throughout the deposit. These data were analysed in a twofold approach as part of this project: (a) multivariant analysis of the geochemical data; and (b) modelling of the data and its clusters in 3D to understand the spatial relationships. Analyses of these data showed that Mg is a key discriminator component in the system and much of the clustering of the data is done relative to this component (ie, Figure 1: Al vs Mg). The geochemical variability is controlled by three factors: (1) lithology (dolostone, schist, amphibolite), (2) metamorphism, and (3) metsomatism (chloritisation of the schists). Distinguishing between metamorphism and metsomatism is still a challenge in these types of systems. Major controlling phases include K-feldspar, muscovite and chlorite in the schist, and dolomite and magnesite in the carbonate rocks. For this exercise, the clustering was completed manually, although techniques such as Self Organising Maps could also be used for an automated approach.

The clustered data was imported into Leapfrog Mining™ to help understand the spatial relationships of the main groups. The main clusters broadly change from K-Ba-rich to K-rich (loss of Na, Ba) to transitional chlorite to chlorite-ore, from distal- to proximal-ore respectively. In the dolostone, there is a localised group of magnesite-rich rocks and haematised dolostone underlying the uranium. A detailed E–W cross-section through isosurfaces of the chemistry (Mg, S and K. Figure 2) illustrates the complexity in spatial geochemical variability, with steep zones of Mg-enrichment and K-removal associated with the uranium and other ore components (S, Cu etc). These zones are related to intense chlorite development along fluid up-flow pathways. This indicates that, superimposed on the broad zonation, there are detailed patterns related to the architecture that was active at the time of U mineralisation.

Mass transfer in the Ranger system

Using the geochemistry from the mine database and other niche samples collected for complete 60 element analysis, it is possible to build a model for the mass transfer of chemistry in the Ranger 3 system. Overall, there is addition of Mg and siderophile components such as S, Ni, Co etc into the ore zone and the whole-scale stripping of alkalis (Na, K, Ca) and Ba as part of the alteration. Coupled to this, there is a distinctive depletion of LREEs with resistate HREEs that leads to a unique fingerprint of REEs in the alteration pattern (see Cleverley et al 2010). At the scale of the mine, all the mass transfer is upward directed, with depletion of the alkalis and LREEs at the scale of the observations (ca 500 m around the mine).

Advanced characterisation

Understanding the broad geochemical character of the deposit is useful, but it is important to understand the main controls on the geochemistry at the micro-scale. Using cutting-edge electron microscopy techniques (CSIRO Melbourne superprobe system), the nature of uranium ore was studied, based on the macro-scale controls observed in the 3D dataset, in order to understand the control on the geochemistry by mineralogy (eg fate of the LREEs, distribution of Ba). Using the information from the
geochemistry, it can be shown that the nature of U changes with depth in the system and the shallow Mg-chlorite–uraninite gives way to more complex U-Si-O phases with a greater proportion of base metals, including chalcopyrite and quartz, in the deeper system. This is in agreement with the increased Cu seen at depth in the 3D dataset. The advanced characterisation also shows that at least some of the LREEs stripped from the ore zone can be found in distal rocks as LREE-monazite overgrowing apatite. This work demonstrates the importance of linking geochemistry, 3D spatial relationships and samples that could be taken to understand the geology of the mineral system. These data and these techniques should be linked much more dynamically than they currently are and this will be a focus for CSIRO Minerals Down Under research in the future.

Exploration for more Ranger systems?

By building a mineral systems-scale understanding of the Ranger 3 U system, it is possible to make predictions on possible exploration strategies. In particular, the geochemical analysis has shown that there is a distinct proximal halo to the Ranger system (ca 400 m wide) showing the transition from K-rich to Mg-rich rocks, coupled with feldspar destruction and the development of Mg-chlorite. At a larger scale than this, the system is depleted in K, Na, Ba, Ca and LREEs and these components are not observed to be enriched within the mine sequence. On the basis of this, it can be predicted that alkali and LREE (± U) metasomatism in the overlying Kombolgie Subgroup sandstone could predict the occurrence of buried U systems beneath the unconformity. This simple model, when coupled to a regional architectural framework, could improve the discovery of further ‘Ranger’ systems in the Pine Creek Orogen. The subtle zonation at Ranger to more Cu-rich ore at depth (as seen in the 3D geochemistry), and the spatial relationship with the Jabiluka system (Au-rich), may indicate that these mineral systems are related. In this case, the dominant metal in the hydrothermal system is a function of local host rock chemical control and location in a larger zoned system. Further work should be undertaken to see if there is a common link between all the U-Cu-Pb/Zn systems in the PCO.

Conclusions

- Techniques exist to spatially analyse the large datasets that exist in most mine sites. This is an important resource for the next generation of research.
- Geochemistry can be used to understand mine-scale mass transfer, and look for the proximal and distal (outflow) footprints of large systems. Geochemistry can also elucidate the important architecture within a system.
- It will be critical in the future to use exploration-related datasets to determine the characterisation of ore bodies for geology and processing problems. Ore bodies are not homogenous.
- The Ranger work predicts that geochemical outflow from the system could form an alkali-LREE-rich distal footprint that could be used for deep targeting.
- New studies should look at the link between many of the U-Cu-(Au)-Pb/Zn systems in the PCO and attempt to determine whether these systems are part of a large regional hydrothermal system or separate distinct events.
- The results of this project will be released as an NTGS record in 2012.

Acknowledgements

CSIRO would like to thank all the staff at ERA for their help and support with this project, and the enthusiasm of NTGS in collaborating with CSIRO to understand controls on mineral systems in the NT. This work was funded collaboratively between CSIRO Minerals Down Under, ERA, NTGS and DMITRE as part of the Joint Surveys Uranium program.

Reference


Uranium mineralisation styles in the Caramal-South Horn Trend, Alligator Rivers Uranium Province

Rob Sowerby

Alligator Energy Ltd (Alligator) is a new exploration company with a sole focus on the Alligator Rivers Uranium Province (ARUP) in the Northern Territory. The ARUP is one of two uranium provinces of the world that are characterised by unconformity-style uranium deposits; the other includes the Athabasca and Thelon basins in Canada. Despite this style of mineralisation being highly prized as a target, application of this model to exploration in other terranes has generally been unsuccessful. Alligator’s exploration strategy is based in part on understanding the uniqueness of these terranes, their similarities and just as importantly their differences, and considering possible variations.

Alligator’s exploration model has been formulated from consideration of the gross geological setting, timing of mineralisation, structural history of the region, and alteration and geochemical features. Comparison with Athabasca Basin deposits highlights the obvious similarities, but also key differences between the two terranes. Mineralisation styles in the Thelon Basin also provide clues on possible variations between broadly contemporaneous settings.

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In summary, Alligator’s exploration model is focused on the recognition of specific basement lithological settings, the timing of major mineralising events between 1750 Ma and 1640 Ma, the structures active during this period and the substantial fluid flow responsible for the pervasive alteration and formation of multiple deposits.

Alligator’s recent exploration focus has been the Caramal-South Horn trend within the Myra Inlier in western Arnhem Land. This area is considered by Alligator to meet its model criteria so as to be prospective for the discovery of multiple significant uranium deposits.

Uranium mineralisation has been intersected at a number of locations along and adjacent to this trend, most notably at Caramal. During 2011, Alligator commenced exploration in the area, targeting extensions to known mineralisation to define resources and establish the relationship of structure, alteration and lithology to mineralisation. Definition of the Palaeoproterozoic stratigraphy has also been an important aspect of exploration.

At Caramal, uranium mineralisation is associated with intensely altered quartz-chlorite schists and breccias. Breccias are associated with a northeast-trending, northwest-dipping structural zone. Potential remains for extensions to mineralisation along strike and possibly down dip. A dolerite is considered to have intruded post-mineralisation and is contemporaneous with 1370 Ma east–west dykes.

Drilling and detailed geophysical surveys also indicate the presence of structural offsets to the geology and potentially mineralisation. Further repetitions of prospective host rocks and structures that have been offset by late movement on faults are indicated by detailed aeromagnetic and ground gravity surveys.

At South Horn, uranium mineralisation has been intersected by previous explorers in Oenpelli Dolerite. Uranium occurs in narrow fracture zones, primarily within chloritised selvage zones adjacent to fractures and quartz veining. The dolerite-hosted mineralisation is considered by Alligator to demonstrate the presence of uranium-rich fluids, but the dolerite appears to be a poor structural host in this area. High-resolution airborne magnetic survey and ground gravity data obtained in 2011, in conjunction with sparse stratigraphic drilling, indicates the presence of prospective Cahill Formation lithologies to the immediate west of the dolerite-hosted mineralisation and will be a priority target area for follow up in 2012.

In summary, the Caramal-South Horn trend is considered by Alligator to demonstrate key characteristics indicative of a uranium mineralising system capable of generating multiple deposits. These characteristics include, the presence of uranium-rich fluids over a significant strike length, presence of characteristic alteration over broad areas, prospective basement host rocks and a favourable structural regime.

Cracking the code of the Tennant Creek Mineral Field – luck is not a good strategy!

Grant A Osborne1,2, Rob T Bills3 and Steve C Russell3

At the highest level, mineral exploration is no different to any other business, and success is typically rewarded to those few companies that have a deep understanding of the business, including the risks, a clear strategic intent and a business plan that persecutes the strategy with relentless focus – luck is not a good strategy!

It is a ‘people focused business’ and therefore getting the right people is paramount – exploration is of course a multidisciplinary activity, so our team at Emmerson Resources Ltd (ERM) includes geologists, geophysicists and specialist outside consultants. A great benefit of being a well funded junior explorer like Emmerson is that we are nimble – with the ability to respond to changed circumstances, such as the fast adoption of new technology and new ideas, and harnessing the growing band of highly specialised consultants who have moved away from many of the major mining houses.

‘Nimbleness’ has been a critical success factor in exploring a mature province such as Tennant Creek, where we have assimilated the great work of previous explorers but applied it in very different ways. Simply doing what had been done before, albeit with the advantages of present-day technology, was not going to crack the code. The Tennant Creek Mineral Field (TCMF) hosts over 700 ‘ironstones’, with 130 being mineralised, but only 10 yielding significant mines. This presents an exploration challenge but also a fantastic opportunity – particularly given that these ironstones are the host rather than the mineralisation! Fortunately one of the great legacies inherited by Emmerson was a large ground holding that stretches across the entire field – providing greatly increased probability for an undiscovered, world-class deposit lurking either at depth or blind to previous exploration techniques.

The Emmerson approach to discovery is underpinned by understanding the fundamentals of the mineralising process and associated fingerprints, rather than the more empirical approach of searching for ‘look-alikes’. The old adage of “you find what you are looking for” sums this up nicely and reinforces the need to keep your mind open to new possibilities. Again this approach is not possible if you are not well funded and was recognised early in ERM’s history, driving the $28M JV with Ivanhoe Australia – most of you will know the enviable track record of discovery throughout the world by the Ivanhoe group. This JV was instrumental to our later success – it funded the high-risk part of our early exploration and actively encouraged and challenged the Emmerson team to test new ideas and concepts (with particular acknowledgement to Doug Kirwan of Ivanhoe Mines for his active support and expertise).

Our exploration methodology rapidly evolved over time, as we tested numerous targets derived from cutting-edge technology and reprocessing of data, new geochemical techniques, spectral studies of drill core, new down-hole techniques, trace element and metal zonation patterns, new
ideas on the geodynamic and structural setting – many of these investigations are ongoing and the science is far from settled; however, the importance of this approach is already paying dividends, in providing ‘fertile ground’ to think outside of the current paradigm.

One of the breakthroughs came last year from a systematic analysis of historic drill core, where it was realised that many of the sulfide-bearing ironstones, such as those at Warrego and Gecko, displayed conductivities many times greater than the background (up to 80x in the case of Gecko), and although not great conductors when compared to massive sulfides, the contrast and lack of conductors in the barren wall rocks provided the impetus to trial a new, very powerful Heli-copter-borne Time domain ElectroMagnetics (HeliTEM) survey over selected mineralized camps. The underlying aim was ‘direct detection’ of alteration (sulfide) or mineralisation, regardless of whether it was hosted by haematite or magnetite iron oxide. Moreover our process-orientated exploration model predicted and supported the contention that these early, oxidised, low pH gold-bearing fluids typically pass through the pyrite stability field and into the chalcopyrite field as they become reduced and progressively neutralised. Thus, many (most) deposits should display a sulfide halo that, depending on size, concentration and depth, could be detected by the HeliTEM system.

In parallel, a reinterpretation of the Gecko mine area indicated that it sat astride a major WNW-trending tectonic feature called the Gecko Corridor and that the economic potential, both in the near-mine area and regionally within the Gecko corridor, was high.

The HeliTEM survey (Figure 1) was flown in early April 2011 and collected a total of 2226 line km of data. Processing of the data was tedious, given we were working with conductors close to the ‘noise floor’ of the system, where even the experts in the field of Airborne EM processing have limited experience. Even today, the source of some of the anomalies is open to debate – nonetheless, given the exploration success at Goanna and Monitor, this is now somewhat academic. A critical but often invisible part of this success has been the multi-disciplinary approach and internal ‘peer review and debate’ – leading to multiple iterations and interpretations of the geophysics, geology and metal/alteration model. Although the model is not yet resolved, the results speak for themselves with the discovery of Monitor (27 m at 1.75% Cu – ASX release 22 August 2011), rapidly followed by Goanna (21 m at 2.63% Cu – ASX release 6 October 2011). Once sulfides

Figure 1. Orlando-Gecko area Tennant Creek Mineral Field HeliTEM image and structures.
Prospectivity of high-heat producing granites of the central Arunta Region, Northern Territory

Eloise E Beyer1, Natalie Kositcin2 and Daniel J Dunkley2

Introduction

A series of high-heat producing granites in the central Arunta Region, including the Wangala and Ennugan Mountains granites in NAPPERBURY3, have been historically investigated for a range of commodities including U, Th, W, Sn, Nb and Ta. Recent renewed interest in the Wangala Granite has been sparked by an increasing global demand and rising prices for uranium and rare earth elements (REE), commodities for which the granite is considered to be prospective (Hussey 2003). The paucity of information about the Wangala and Ennugan Mountains granites has led to a detailed NTGS study to understand their nature and prospectivity.

The Arunta Region of central Australia is one of the most geologically complex areas on the continent. It extends over approximately 200 000 km² and has undergone multiple tectonothermal events from the Palaeoproterozoic to the Palaeozoic. The region is subdivided into three provinces, each with distinct protolith ages and complex stratigraphic and tectonic histories (Figure 1). The Palaeoproterozoic Aileron Province, which comprises most of the Arunta Region, has a geological history punctuated by several episodes of predominantly felsic magmatism synchronous with, or postdating regional metamorphic events.

The Aileron Province includes numerous U-rich granites, such as the Wangala and Ennugan Mountains granites, and is regarded as highly prospective for basement-hosted mineralisation, as well as providing an excellent source for the uranium deposits in the Ngalia and Amadeus basins. In the central Aileron Province, basement-hosted uranium occurrences are typically associated with mineralised veins and shear zones within Palaeoproterozoic U-rich granites. Examples include Barrow Creek (Clarke 1978), Anomaly B (Uranium Exploration Australia, ASX Announcements, 27 August 2009 and 25 January 2010), and the Adnera prospect (Uramet Minerals, Quarterly Report to Shareholders, 30 September 2009). In the Wangala Granite, the Quartz Hill U-apatite prospect is characterised by uraniferous REE-rich biotite-apatite schists that appear to be related to metasomatic/igneous fluids derived from the granite or its associated pegmatites (Hussey 2003). In the Ennugan Mountains Granite, traces of uranium mineralisation associated with xenotime in narrow biotite-rich shear zones were reported in Kojan (1980). This granite is also considered to be prospective for REE mineralisation, as one or more of its phases are described as containing allanite (Stewart et al. 1980).

Wangala Granite

Overview

The Wangala Granite is an S-type composite batholith, comprising numerous phases of variably fractionated, crustally contaminated LREE-enriched granite. The batholith intrudes amphibolite-facies pelitic schist and associated metapsammite, calc-silicate rock, quartzofeldspathic schist and granitic orthogneiss of the Reynolds Range Group. The granite is intruded by dykes of pegmatite, amphibolite, felsic porphyry (restricted to the Hill Fault and is interpreted to be an anastomosing, transcurrent shear zone (Figure 1).

The 2012 exploration program aims to capitalise on this success and will include drill outs at Monitor and Goanna, to extend the high-grade copper mineralisation and also to investigate the gold at depth. Interestingly, the historical Gecko Mine was mostly a copper producer and, given the deeper gold encountered at either ends of the mine at Monitor and Goanna, it is possible that gold remains undiscovered at depth beneath the copper – particularly given the high bismuth grades. The exploration focus will also move out along the Gecko corridor into more regional targets, where similar alteration footprints to Goanna and Monitor have been detected (Figure 1).

These discoveries result from the execution of a bold strategy coupled with a strong technical program within a clear business framework. This long-term, systematic approach would not have been possible without the full support of the Emmerson Board. The code is being cracked! The authors wish to acknowledge the tremendous contribution from the entire Emmerson team in cracking the code.

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3 Names of 1:250 000 mapsheets are in capital letters, eg NAPPERBURY.
The Wangala Granite is comprised of four main phases. It is dominated by coarse-grained, porphyritic biotite-muscovite granite, but also contains other textural types including equigranular granite and medium-grained porphyritic granite. Equigranular leucogranite outcrops in the east and is characterised by abundant tourmaline and minor garnet. The presence of primary muscovite (±garnet) in the four main phases suggests that the intrusion, as a whole, is peraluminous, with high normative corundum (1.3–4.5%) in all phases. In the southwest, biotite granite with a distinctly I-type composition outcrops; however, it is currently not known if this is related to the Wangala Granite.

LA-ICPMS U-Pb zircon dating of coarse-grained porphyritic Wangala Granite yielded a weighted mean age of 1777 ± 6 Ma for zircon cores; this is interpreted as the magmatic crystallisation age of the granite and suggests emplacement during the 1780–1770 Ma Yambah Event. This event is characterised by widespread and abundant felsic and intermediate magmatism across the Aileron Province. Thick (>100 μm) U-rich overgrowths on cores yield a poorly-constrained age of 1565 ± 31 Ma, broadly consistent with new zircon growth during the 1590–1560 Ma Chewings Orogeny, a tectonothermal event that is restricted to the central Aileron and Warumpi provinces. The ca 1772 Ma Redhackle Granite, immediately north of the Wangala Granite on MOUNT PEAKE, has also yielded ca 1580 Ma ages from zircon overgrowths (Worden et al 2004).

Biotite-apatite schists

Biotite-apatite schists in the Wangala Granite are concentrated in a northeast-trending 2 km² belt in the southern part of the batholith. They occur as discrete, mesoscale linear bodies or as thin ‘carapaces’ on weathered surfaces (Figure 2a). The schists have unusual modes, containing up to 70% biotite and 25% apatite, with minor muscovite and quartz. The contact between schist and granite is gradational at the centimetre scale, and marked by increasing sericitation of feldspars, alteration of mica, and the presence of topaz and fluorite (Figure 2b). Relative to the enclosing granite, the schists are enriched in TiO₂, total Fe₂O₃, MnO, MgO and P₂O₅ and also display elevated abundances of elements such as U, Li, Co, Ni, Zn, Ag, Sn, W and REE, with total rare-earth oxides (TREO) as high as 1850 ppm. There is a positive correlation between many of these elements (including F, TREO, Th and U) and P₂O₅ content in the schists, suggesting that they are most likely hosted by apatite.

Previous workers have interpreted the schists as rafts of sheared and metasomatised phosphatic country rock, based on their unusual mineralogy (Davies 1979). However, new evidence from field relationships, petrography, geochemistry and geochronology does not support this interpretation. Firstly, the whole-rock geochemistry of the schists ranges widely in composition, but does not match any known country rock. Secondly, although the schists are referred to as biotite-rich shears, they preserve an apparent igneous texture with little evidence of strain foliation. In addition, the presence of fluorite and topaz in the diffuse schist–granite contact zone implies that there has been fluid interaction across the interface between the two rock types. The presence of fluorite and topaz in the diffuse schist–granite contact zone implies that there has been fluid interaction across the interface between the two rock types.
types. Whole-rock geochemical data suggests these fluids were rich in F, U, Th, and REE, as well as many other trace elements and metals. It therefore seems more likely that the schists represent discrete zones of Wangala Granite, or possibly pegmatite, which were hydrothermally altered or greisenised during a post-crystallisation metamorphic or metasomatic event. High-U zircon overgrowths in the host granite, which have yielded an age of 1565 ± 31 Ma, are interpreted to broadly constrain the timing of this event, and this age is mirrored in the schist, where LA-ICPMS U-Pb dating of zircon overgrowths and SHRIMP U-Pb dating of monazite have yielded ages of 1570 ± 30 Ma and 1574 ± 1.5 Ma respectively, strongly supporting an episode of accessory phase growth (or dissolution and reprecipitation) during the 1590–1560 Ma Chewings Orogeny. Magmatism of this age is quite rare in the Arunta Region; however, the 1570–1530 Ma Southwark Granite Suite, which outcrops in MOUNT DOREEN, the adjoining mapsheet to the west of NAPPERBY, raises the possibility of younger Chewings-aged granites intruding the Wangala Granite. These younger granites could have generated hydrothermal convection by providing a local radiogenic heat source and they could also have supplied the F, U, REE, trace elements and metals responsible for metasomatic enrichment in the schists and granite.

Uranium prospectivity

In the late 1970s, the Australia and New Zealand Exploration Company carried out an exploration survey across the southern Wangala Granite to determine its uranium potential. Secondary uranyl phosphates, tentatively identified as brannerite and bassetite (as well as traces of autunite), were identified in both the biotite-apatite schists and the host granite. However, despite an extensive field and petrographic investigation of the Wangala area, Davies (1979) concluded that “…although the rocks contain a generally anomalous amount of uranium, there is little evidence to indicate that concentration by magmatic processes to ore grade has occurred” and that although “uranium has accumulated in minor calcrete development… neither economic grade nor tonnage is indicated.”

More recent work by Callabonna Uranium Ltd is proving more promising. Rock chip samples of veined and altered granite, sampled during a first pass reconnaissance survey in 2010, returned uranium oxide results of between 268–979 ppm U\textsubscript{3}O\textsubscript{8} and elevated REEs (>2231 ppm TREO). Based on these results a Mobile Metal Ion (MMI) geochemical survey of drainage areas to the west of the main granite outcrop was carried out in October 2011, delineating what is now known as the ‘Five Mile Creek’ prospect, a 4000 m well attenuated uranium anomaly with a response ratio which is 150 times background. The source of the uranium is interpreted to be secondary uranium minerals, remobilised and reprecipitated in weathered surfaces of the granite. This is supported by HQ drill core that clearly shows fine-grained yellow uranium minerals in typical coarse-grained porphyritic Wangala Granite (Callabonna Uranium Ltd, Annual General Meeting presentation,

Figure 2. (a) Field photo of biotite-apatite schist enclosed in porphyritic Wangala Granite. Hammer is 32 cm long. (b) Photomicrograph of contact zone between Wangala Granite (far left) and biotite-apatite schist (right). Length of photo is 2 cm.
November 2011). Field scintillometer surveys carried out as part of the current NTGS survey also identified anomalous uranium readings in several different phases of the granite, with values typically between 20–40 ppm U, but in some instances greater than 250 ppm. Given that whole-rock uranium contents of fresh granite collected in the NTGS study are generally less than 20 ppm, it can be concluded that the high scintillometer readings are due to surficial concentrations of uranium (and thorium, which is also elevated in weathered granite).

Greisens and IOCG potential

The northern part of the batholith is distinguished by zones of discrete greisenisation, large roof pendants and smaller rafts of altered country rock, quartz-haematite veins, localised intrusion of dacitic porphyries, W mineralisation in pegmatites and trace occurrences of Cu and Ta in porphyritic granite. These characteristics tend to suggest that the current granite exposure in this area is close to the roof zone, where there has been extensive syn- to post-magmatic fluid flow.

In the field, the greisens are easily distinguished from unaltered granite as they are pink in colour and are often strongly silicified. They are comprised predominantly of quartz, pink K-feldspar, muscovite, leucoxene ± haematite, plagioclase, chlorite, opaque oxides and apatite. Feldspars are often clouded with sericite and haematite. Miarolitic cavities are uncommon, but are generally up to several cm across and partially infilled with haematite and fine-grained quartz. There is some evidence for argillic alteration in the form of very fine-grained chlorite and white mica in quartz. There is some evidence for argillic alteration in the form of very fine-grained chlorite and white mica in quartz. There is some evidence for argillic alteration in the form of very fine-grained chlorite and white mica in quartz.

Geochemically, the greisens are depleted in almost all the major oxides compared to unaltered granite, the exceptions being SiO₂ which ranges up to 80 wt% and is evidence for silicification, and K₂O which is a reflection of potassic alteration and associated high modal K-feldspar in these rocks. The greisens also show depletion in most minor and trace elements relative to unaltered granite, in particular the REE, Ba, Sr, Zr, Hf, Th and V. Redox calculations for the greisens suggest that they are strongly oxidised compared to unaltered granite.

A spatial correlation between 1780–1770 Ma felsic magmatism and IOCG mineralisation has been identified in an east–west-trending belt across the Aileron Province (Close and Scrimgeour 2009). The alteration style seen in the northern Wangala Granite shows some of the characteristics that define IOCG deposits, including large-scale hydrothermal fluid flow, oxidation of the host rock along with pervasive haematite-silica metasomatism, and extensive potassic alteration. However, the hydrothermal event has not caused significant fracturing or brecciation of the granite, and where alteration has been most intense, ie in the greisens, the granite has been largely stripped of any elements of interest. The only evidence of any anomalous Cu is in dacitic porphyry which has a Cu value of 131 ppm.

Ennugan Mountains Granite

Overview

The extensive Ennugan Mountains Granite is one of the most heat-producing granites in the Aileron Province. It forms the Ennugan Mountains, which lie predominantly in NAPPERBY, but also extend across the southern boundary of MOUNT PEAKE. The Ennugan Mountains Granite intrudes the Palaeoproterozoic Lander Rock Formation and is overlain by quartzites assigned to the Neoproterozoic Vaughan Springs Quartzite of the Ngala Basin. Field investigations have identified four main phases, three of which are porphyritic biotite ± hornblende granites and occur predominantly in the southern and central Ennugan Mountains, and an equigranular biotite granite that was only noted in the northern outcrops. Three of the main phases have an I-type composition and are leucocratic, with mafic mineral content generally less than 5%. In contrast, a porphyritic biotite granite in the south has high normative corundum (2.7%) and minor muscovite, indicating a more peraluminous composition. It is unknown if this granite is part of the Ennugan Mountains Granite or an unrelated intrusion.

Prospectivity

The Ennugan Mountains are relatively underexplored. Tanganyika Holdings Ltd conducted field surveys in the early 1970s looking for tin and uranium mineralisation. They found anomalous amounts of uranium in groundwater, which was attributed to leaching from the granite. They also detected small amounts of cassiterite in heavy mineral separates taken from drainages within granite outcrop. A similar study was carried out by Otter Exploration in the late 1970s, including a reconnaissance tin sampling program in the central and western Ennugan Mountains, which detected high concentrations of Sn (>2340 ppm) in creek sediments and also in metasedimentary rafts in the granite (1500 ppm Sn). Tin mineralisation is probably associated with a greisenous roof zone and with alluvial sediments shed from it; the greisen veins carry topaz, chrysoberyl and fluorite (Kojan 1980).

Several zones of biotite schist up to 2 m wide occur in porphyritic granite on top of a prominent ridge in the central part of the Ennugan Mountains Granite (Figure 3a). Unlike the biotite-apatite schists of the Wangala Granite, these are composed primarily of abundant strongly foliated biotite, large strained muscovite ‘fish’ and fine-grained polygonal quartz (Figure 3b). However, like the Wangala schists, they are variably enriched in a variety of major oxides including TiO₂, total Fe₂O₃, MgO, K₂O and P₂O₅, and numerous trace elements and metals such as F (ca 1 wt%), TREO₂ (2900 ppm), U (71 ppm) and Th (332 ppm), as well as Nb, Bi, Sn, W and Zn. Although there are some similarities with schists seen in the Wangala Granite, these deformed biotite-rich rocks are interpreted as rafts of sheared and metasomatized metaepilitic-Lander Rock Formation country rock, as opposed to altered granite. Similar rafts of biotite-rich metasedimentary rock have been noted elsewhere in
the intrusion, but they are generally less deformed and are not uraniferous.

The different granite phases show varying degrees of enrichment in elements such as F (897–4000 ppm), U (6–32 ppm), Th (22–100 ppm) and TREO (141–790 ppm). These anomalous values and the enrichment seen in the biotite schists suggest a hydrothermal fluid event similar in style to that seen in the Wangala Granite. It is likely these elements reside in accessory minerals such as zircon, monazite and xenotime (Kojan 1980). The timing of the event is harder to constrain. SHRIMP U-Pb zircon dating of porphyritic biotite ± hornblende granite yielded a magmatic crystallisation age of 1621 ± 5 Ma, confirming the original determination (1622 ± 7 Ma) by Smith (2001). This is an unusual age for a granite of the Aileron Province, and is more typical of felsic intrusive rocks from the Warumpi Province to the south. However, the proximity of the Ennugan Mountains Granite to the Reynolds Range raises the possibility that magmatism was a precursor to the 1590–1560 Ma Chewings Orogeny, which is the predominant tectonothermal event in the region. Many of the Ennugan Mountains granites display evidence for recrystallisation, and all are overprinted by a weak to moderate southwest-dipping foliation, which might point to low-grade metamorphism in the area. Hydrothermal activity could be either syn- or post-magmatic.

**Conclusions**

The Wangala Granite is a potential source for economic grades of calcrete-hosted and palaeochannel uranium, as

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**Figure 3.** (a) Field photos of biotite schist enclosed in porphyritic Ennugan Mountains Granite. Hammer is 32 cm long. (b) Photomicrograph of biotite schist. Field of view is 10 mm across.
has been borne out by recent successes for Callabonna Uranium Ltd. It is less prospective for basement-hosted uranium mineralisation as the bulk of the uranium appears to be present only as secondary minerals in weathered surfaces, or concentrated in narrow zones of metasomatiscated granite that are too small to be economically viable. This may also be the case for REE mineralisation. The alteration style seen in the northern part of the batholith shows some of the characteristics that define IOCG deposits, implying the Wangala Granite may also have potential for these commodities. The Ennughan Mountains Granite also shows evidence for hydrothermal alteration by high-F-U-REE fluids, possibly during the Chewings Orogeny. This granite is still vastly underexplored and may yet prove prospective for economic quantities of uranium and REE, though like the Wangala Granite, it would be considered a source region for calcrete-hosted or palaeochannel style (rather than basement-hosted) mineralisation. Although these two granites differ in age and composition, both provide evidence for a potentially widespread hydrothermal and mineralising event in the central Aileron Province, possibly related to the Chewings Orogeny.

References


Assessing the potential for uranium and geothermal systems in the southern Northern Territory

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Introduction

As part of the recently completed Onshore Energy Security Program, Geoscience Australia, in collaboration with State and Territory geoscience agencies, has undertaken geological framework studies to better understand the geodynamic and architectural controls on energy systems (including uranium, onshore petroleum and geothermal energy). A number of regional-scale studies have been conducted, based around the acquisition of deep crustal seismic and magnetotelluric data, such as the Georgina-Arunta survey (eg, Korsch et al 2011). A range of complimentary datasets and derivatives have been produced in conjunction with these data, including geochemical and geochronological data, 3D geophysical and geological models, and assessments of uranium and geothermal energy prospectivity (referred to from here on as energy assessments). During 2011–2012, an assessment of the potential for undiscovered or unrecognised uranium and geothermal systems in the southern Northern Territory is being undertaken.

Study area

The study area for the Northern Territory energy assessment incorporates the previously acquired 08GA-OM1 and 09GA-GA1 seismic lines (Korsch and Kositcin 2010, Korsch et al 2011). It extends from the Northern Territory–South Australia border in the south to the northern Aileron and Davenport provinces in the north (Figure 1). The region includes a number of geological features favourable for uranium and geothermal systems, including high heat-producing and uranium-rich granites (eg, Schofield 2009), recently recognised regional-scale haematite-fluorite alteration systems in the eastern Arunta Region (Whelan et al 2011) and thick sedimentary basin successions. These features suggest that the southern Northern Territory has considerable potential for uranium mineralisation and possibly geothermal energy.

Known uranium deposits and geothermal potential

A number of known uranium deposits and prospects occur within the southern Northern Territory (Figure 2). Known sandstone-hosted uranium mineralisation at the Angela and Pamela deposits occurs within the Neoproterozoic to Carboniferous Amadeus Basin (Figure 1, Borshoff and

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Faris 1990), and the similarly aged Ngalia Basin is host to the Bigrlyi and Walbiri deposits (Figure 1, Fidler et al 1990). Although unconformity-related uranium in the Northern Territory is mostly known from the Pine Creek Orogen, the Albarta Prospect, which underlies the unconformity between the Heavitree Quartzite and Palaeoproterozoic basement, may represent an example of this style of mineralisation in the study area (Figure 1).

Iron oxide-copper-gold (IOCG) mineralisation has been recognised at the Johnnies Reward prospect and at the Bellbird and Reward prospects in the Jervois district (Figure 1, Hussey et al 2005). In addition, IOCG mineralisation occurs just north of the study area in the Tennant Creek–Rover district. Although the IOCG prospects within the study area are not recognised as being uranium-rich, the deposits in the Tennant district are anomalous with respect to uranium. Further investigation is required to test the uranium potential of IOCG systems within the study area. A number of minor uranium occurrences related to igneous rocks have been identified in the Arunta Region at Adnera, Cockroach Dam and Crystal Creek (Figure 1, Beyer et al 2010, Dunster et al 2010). Uranium-rich rare earth element mineralisation is also known from within the study area, most notably at the Nolans REE deposit and in pegmatites in the Harts Range region (eg, Hussey 2003).

Geothermal potential is suggested by elevated temperatures interpreted at 5 km depth in the Georgina and Eromanga basins in the northeast and southeast of the study area, respectively (Gerner and Holgate 2010). Beardsmore (2007) suggested that areas of the Amadeus and Ngalia basins may have surface heat flow values exceeding 100 MW/m² and noted favourable geological conditions within the Eromanga and Pedirka basins. Although these results are inconclusive at present, they warrant additional investigation.

**Systems approach and methodology**

Although the southern Northern Territory is not an established uranium or geothermal province, the occurrence of uranium prospects within the study region, elevated temperatures in the Georgina and Eromanga basins, and the presence of favourable geological features (see above) suggests the potential for previously undiscovered or unrecognised uranium and geothermal systems. In recognition of this, the southern Northern Territory energy assessment will assess the potential for four styles of uranium mineral system: sandstone-hosted, unconformity-related, IOCG-U and magmatic-related. In addition, two separate geothermal systems will be investigated: hot rock geothermal and hot sedimentary aquifer.

**Figure 1.** Study area for the Northern Territory energy assessment showing recently acquired seismic lines and selected uranium mineral deposits and prospects.
Uranium systems methodology

Potential for uranium is assessed using a 2D GIS-based technique utilising a mineral systems approach, which focuses on key mineralising processes rather than empirical observations of known mineralisation (see Schofield 2011 for details). Using a mineral systems approach minimises the potential for bias towards local geological controls, which are significant only at the mine-scale, and allows the mineralising system to be mapped on a large scale, thus creating a greater ‘footprint’ of mineralisation.

Four key mineral system components are used in the assessment: (1) sources of metals and fluids, (2) drivers of fluid flow, (3) fluid pathways and architecture, and (4) depositional sites and mechanisms. Using these four components, favourable criteria are developed and translated into mappable geological proxies. These are then assigned weightings and combined into four equally-weighted intermediate maps (corresponding to the four system components, Figure 3). This approach is easy to implement, is transparent and objective, and is flexible enough to revisit if new information or datasets become available. Importantly, by focusing on mapping the geological proxies of processes rather than observations of known mineralisation, the potential of frontier or greenfields areas for unknown uranium mineralisation is able to be assessed more readily.

Geothermal systems methodology

The geothermal systems assessment is based on the results of thermal modelling on a 3D geological map. The 3D map was constructed using GoCad software and constrained using outcrop geology, drillhole data, seismic interpretations and magnetic modelling. Heat production and thermal conductivity values were assigned to geological volumes derived from the 3D map and

Figure 2. Selected uranium prospects and deposits plotted on the ternary uranium systems scheme of Skirrow et al (2009).

Figure 3. Schematic flowchart showing key steps in assessing the potential for uranium systems.
temperature predictions were calculated in 3D using the SHEMAT software package (Clauser 2003). Further details of the methodology used for the geothermal assessment are given in Meixner et al (2011).

Conclusions

The southern Northern Territory contains favourable geology for both uranium and geothermal systems. Together with previously recognised occurrences of uranium mineralisation and elevated temperatures in parts of the study area, this suggests that the southern Northern Territory has considerable potential for previously undiscovered uranium and possibly geothermal resources. The southern Northern Territory energy assessment seeks to better delineate regions of high uranium and geothermal potential, and enhance the prospectivity of this area. By employing a systems-based approach, prospectivity is able to be determined in greenfields areas.

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Introduction

The Jervois Base Metals Project is located about 380 km to the northeast of Alice Springs and comprises four main areas of economic interest, namely Marshall-Reward, Green Parrot, Bellbird and Bellbird North. Each area has received sufficient drilling for the identification of a mineral deposit. Reward (Cu-Ag) and Bellbird (Cu) are essentially copper (+silver) deposits, whereas the Green Parrot and Bellbird North deposits have a more polymetallic nature.

The base metals mineralisation in the Jervois area is hosted within a lower to middle amphibolite-facies meta-

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volcanosedimentary succession of the Bonya Schist. This unit is part of the Palaeoproterozoic eastern Arunta Region which reached peak metamorphic conditions during the regionally extensive high-T low-P Strangways Event at ca 1735–1690 Ma (Scrimgeour and Raith 2001, Scrimgeour 2003).

Neoproterozoic to Palaeozoic deposition of the Harts Range Group (Irindina Province) and the Georgina Basin was followed by granulite-facies metamorphism of the former and subsequent exhumation along a series of large transpressional to compressional generally E–W- to WNW–ESE-trending north-verging shear zones through the Ordovician to the Late Devonian (Scrimgeour and Raith 2001, Figure 1).

Figure 1. Jervois Project – regional geology.
Generalised mineralogy

Previous mapping of the regional geology and structure in the Jervois area was summarised in Thom (2004), who noted four primary lithological suites:

1. A gneissic suite comprising rhyolite and granitic gneiss with subordinate amphibolite.
2. A magnesium silicate suite, comprising cordierite-biotite schist, considered by Yates et al. (1989) to be of volcanic origin.
3. A mine sequence suite comprise andalusite-staurolite schist and quartz-sericite-feldspar schist and garnet-chlorite-magnetite rock, banded ironstone, quartz-tourmaline rock, banded epidote rock and calc-silicate rock of the ‘load sequence’.
4. An Fe-Mg-silicate suite, which transitions from suite 3 into quartz-magnetite-chlorite schist and quartz-chlorite schist.

The mineralogy of the metamorphic schists of the ore zone commonly comprises quartz-chlorite (biotite), ± muscovite ± cordierite ± garnet ± magnetite. Cordierite-rich (and occasional garnet-rich) bands are common within some units; these are coarser-grained with a subhedral to euhedral form and exhibit ‘speckled’ or ‘spotted’ textures.

Fine–coarse magnetite crystals are widespread (with associated strong magnetism) and are commonly associated with the occurrence of fine-coarse sulfides within the mineralised zones.

Silicified ‘metamorphic’ schist is the informal local lithological classification commonly applied to schists within one type of mineralised zone where the regional amphibolite-facies alteration has been heavily altered (usually by strong silica alteration) as a result of the sulfide emplacement. A remnant schistose fabric is retained, but in most cases, the fabric has been completely overprinted by silica and sulfides. Generally, this unit is intensely magnetised with fine-grained pervasive, colloidal and lensoidal sulfide replacement.

Structure

The regional close to tight folding of the succession which produced the J shape of the present outcrop is attributed to an F3 event. The J fold is a synform with a steep northerly plunge and a N–S- to NNE–SSW-trending axial trace (Yates et al. 1989). Structural mapping completed in 2011 by International Geoscience Pty Ltd was based on a Sub-Audio-Magnetic survey data, regional NTGS radiometric and magnetic data, and structural data collected during a field mapping program in 2011 (Figure 3). In addition to the previously interpreted data, a series of deformation events (D2) were identified as playing a major role in the mineralisation of the system. The early D2a shear zones are folded around the broad, steep north plunging, synform hinge of the regional fold that defines the J structure. D2b structures have been local reactivated and truncated by a set of structures designated as D2c which converge on the western side of the hinge zone and appear to ramp into a major bounding NNE–SSW-trending structural zone. The eastern limb of the regional fold is crosscut by a series of ENE–WSW-trending faults interpreted to be part of a D2c event (Crowe 2011, Figure 4).

Resource

Based on drill results from 3,740 1m composites from 177 drillholes, resource figures were determined by Hellman & Schofield Pty Ltd in 2011 and are presented in Table 1.
Figure 3. Imaged SAM data including (a) EQMMR, (b) first vertical derivative of EQMMR, (c) total magnetic intensity and (d) first vertical derivative of magnetic data.

Table 1. Jervois Project – inferred resource.

<table>
<thead>
<tr>
<th>Deposit</th>
<th>MTonnes</th>
<th>Cu %</th>
<th>Cu Tonnes</th>
<th>Ag g/t</th>
<th>Ag Moz</th>
<th>Cu Cut-off %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reward (+165mRL)</td>
<td>4.5</td>
<td>1.3</td>
<td>60 000</td>
<td>30.9</td>
<td>4.40</td>
<td>0.5</td>
</tr>
<tr>
<td>Reward (-165mRL)</td>
<td>2.5</td>
<td>1.4</td>
<td>35 000</td>
<td>23.2</td>
<td>1.90</td>
<td>0.5</td>
</tr>
<tr>
<td>Bellbird (+165mRL)</td>
<td>3.7</td>
<td>1.2</td>
<td>44 000</td>
<td>7.5</td>
<td>0.90</td>
<td>0.5</td>
</tr>
<tr>
<td>Bellbird (-165mRL)</td>
<td>0.2</td>
<td>1.1</td>
<td>2500</td>
<td>8.0</td>
<td>0.06</td>
<td>0.5</td>
</tr>
<tr>
<td>Green Parrot</td>
<td>0.7</td>
<td>1.0</td>
<td>7000</td>
<td>93.5</td>
<td>2.10</td>
<td>0.3</td>
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<tr>
<td>Bellbird North</td>
<td>0.3</td>
<td>0.7</td>
<td>2000</td>
<td>27.4</td>
<td>0.30</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>11.9</strong></td>
<td><strong>1.3</strong></td>
<td><strong>150 500</strong></td>
<td><strong>25.2</strong></td>
<td><strong>9.66</strong></td>
<td></td>
</tr>
</tbody>
</table>
Figure 4. Interpreted structural framework on imaged 1VD SAM TMI data. Background image is regional 1VD TMI magnetic data.

References

Crowe W, 2011. SAM data interpretation and field mapping within the Jervois tenements, Northern Territory, Australia. Kentor Gold Ltd, internal report.


New copper-gold discoveries in the eastern Arunta Region: Implications for Cu-Au mineralisation in the Arunta

Jo Whelan 1,2, Gordon Webb 3, Dorothy Close 1, Natalie Kositcin 4, Simon Bodorkos 4 and Roland Maas 3

The Arunta Region forms part of the southern portion of the North Australia Craton and has been divided into three provinces with distinct protolith ages and histories: the 1860–1700 Ma Aileron Province, the 1690–1600 Ma Warumpi Province and the Neoproterozoic to Cambrian Irindina Province (Scrimgeour 2003). The Arunta Region as a whole is characterised by a remarkably protracted history of episodic deformation, high-grade metamorphism and granitoid plutonism that sets it apart from many of the other Proterozoic provinces in northern Australia (Shaw et al 1984, Hoatson et al 2005, Scrimgeour in press a, b). The eastern Arunta Region (area east of the western boundary of HUCKITTA 5, ILLOGWA CREEK and HALE RIVER 1:250 000 map areas, Figure 1) has been affected by numerous tectonothermal events (eg Scrimgeour in press b), including the 1780–1770 Ma Yambah Event, 1735–1690 Ma Strangways Event, 480–460 Ma Larapinta Event and the 450–300 Ma Alice Springs Orogeny.

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Figure 1. (a) Schematic regional geological map of Arunta Region, showing locations of Cu-Au occurrences. Study area shown by red box (modified from Scrimgeour in press). (b) Schematic geological map of eastern Arunta Region, defined as area east of western boundaries of HUCKITTA, ILLOGWA CREEK and HALE RIVER. Map shows distribution of ca 1750–1740 Ma magmatism and locations of IOCG-style Cu-Au occurrences.
The Aileron Province has a relatively limited mining history and is underexplored in comparison to other Proterozoic regions in the Northern Territory such as the Pine Creek Orogen, and the Tanami and Tennant Creek regions (Scrimgeour in press b). Previous studies have highlighted a spatial correlation between ca 1770–1760 Ma felsic intrusive rocks and Cu-Au occurrences with Iron-oxide-Copper-Gold (IOCG) affinities in a broad, west-trending belt across the Aileron Province (eg Close et al 2007, Whelan et al 2009, Beyer et al 2012). However, in Limbla, recent exploration activity has been driven by the identification of large-scale fluorite-haematite alteration, hydrothermal brecciation and silicification that is associated with pyrite and copper sulfides and ca 1750–1740 Ma felsic magmatism. Such alteration is consistent with IOCG-style alteration systems (Whelan et al 2011). Subsequent discoveries of surface copper mineralisation (eg Bigglesworth, Austin, Powers, Figure 1) and highly anomalous gold values in assay results (rockchips up to 4.5% Cu, 0.2 g/t Au, 2.3 g/t Ag; Mithril Resources Ltd, ASX announcement 29th November 2011, Figure 1) suggests that this slightly younger suite of felsic, dominantly peraluminous intrusive rocks may also be prospective for IOCG-style mineralisation (Whelan et al 2011).

Regional geology

The Aileron Province of the eastern Arunta Region, as outlined in Figure 1 is a polydeformed, dominantly igneous terrane comprising metamorphosed felsic and mafic intrusive rocks, and amphibolite- to granulite-facies metasedimentary rocks. Magmatic rocks in the eastern Arunta Region are dominated by: ca 1810–1790 Ma metaluminous felsic and mafic magmatic rocks associated with the Stafford Event; the ca 1780–1760 Ma bimodal, metaluminous Ambulbinya Supersuite (new name; Whelan et al in prep) that were emplaced syn- to post-Yambah Event; ca 1755–1735 Ma peraluminous felsic intrusive rocks and lesser mafic magmatic rocks; ca 1730–1720 Ma felsic magmatic rocks, including high-level volatile-rich magmas in Limbla, emplaced during the onset of the Strangways Event and spatially associated with known uranium mineralisation (Huston et al 2011); and rare ca 1715 Ma alkaline (syenite) magmatic rocks (Whelan et al 2011).

In Limbla, outcrop in the northwest is dominated by the ca 1743 Ma Ateeqa Granite (Kositcin et al 2011) which intrudes and incorporates rafts of amphibolite- to granulite-facies metapelitic, metapsammopelite, metapsammitic, mafic amphibolite and, calc-silicate rock of the Albarta Metamorphics (Figure 2). In contrast, in Quartz, the Albarta Metamorphics are characterised by amphibolite-facies assemblages. The southeast comprises high-grade metapelitic, metapsammopelite and metabasalts of the Bluebush Metamorphics (new name Whelan et al in prep, Figure 2)

SHRIMP U-Pb zircon geochronology studies (Carson et al 2009, Kositcin et al in press) indicate that the sedimentary protolith to the Albarta Metamorphics was deposited <ca 1770 million years ago. A minimum age constraint on deposition is provided by the timing of metamorphism and the development of a pervasive north–south-trending amphibolite-facies fabric in the Albarta Metamorphics, exposed in Quartz, which has previously been constrained to the onset of the Strangways Event at ca 1729 Ma (U-Pb monazite; Carson et al 2009).

In contrast, the protilith to the granulite-facies Bluebush Metamorphics was deposited <ca 1830 Ma (Whelan et al 2011, Kositcin et al in press). U-Pb dating of low Th/U zircon rims in the Bluebush Metamorphics has yielded ages of ca 1745 Ma, indicating that new zircon growth was associated with emplacement of the Ateeqa Granite (Whelan et al 2011).

Timing of and nature of tectonothermal activity in Limbla

New in situ SHRIMP U-Pb monazite studies and PT-pseudosection analysis have been undertaken on the Albarta and Bluebush metamorphics in Limbla, in order to constrain the timing of high-grade metamorphism and fabric development in these units. Two populations of monazite were recognised in a sample of the Albarta Metamorphics collected in Limbla. Monazite occurring as inclusions in garnet, tend to have ages of ca 1770 Ma, while those in the matrix, which appear to sometimes truncate the fabric, yielded ages of ca 1750 Ma (Kositcin et al in prep). PT-pseudosection analysis of a sample collected from the same locality indicates that peak granulite-facies metamorphism occurred under conditions of 5.2–7.4 kbar and 730–810°C. These PT constraints vary from those recorded for peak assemblages from samples of the Albarta Metamorphics collected in Quartz to the north (ca 4.0 kbar and 625°C; Goscombe 2007).

Age data and PT constraints acquired in this study contrast with those of previous studies (Carson et al 2009 and Goscombe 2007, respectively) for the Albarta Metamorphics. However, there is a considerable strain gradient across a major east–west-trending structure located between the two sample localities (Figure 1). This likely Proterozoic structure, reactivated during Palaeozoic intra-platetectonism, may account for the observed differences in the metamorphic evolution of the Albarta Metamorphics.

In situ SHRIMP U-Pb monazite studies on a sample of the Bluebush Metamorphics have yielded a single age population at 1743 ± 7 Ma (Bodorkos et al in prep), consistent with zircon rim ages at ca 1745 Ma (Whelan et al 2011). PT-pseudosection analysis of the dated sample indicates that peak metamorphism occurred at minimum pressures of 3.5 kbar and temperatures of 650°C. There is no obvious fabric development associated with the metamorphism of the Bluebush Metamorphics and PT-t analysis indicates that, in this case, metamorphism was likely driven by the emplacement of the locally voluminous Ateeqa Granite and is consistent with advection of heat under near-isobaric conditions.

This new monazite-age data augments previous studies (eg Kositcin et al 2011, Kositcin et al in press), which have recorded new monazite growth or new metamorphic zircon rim growth at ca 1750 Ma throughout the eastern Arunta Region, including the central zone of the Casey Inlier and
in HUCKITTA (Kositcin et al in press). Coupled with field observations and the PT-t constraints described here, it appears that this event was regionally significant in the eastern Arunta Region.

**1750–1740 Ma magmatism in the eastern Arunta Region**

Ca 1750 Ma intrusive rocks have been increasingly recognised in the eastern Arunta Region. Named intrusions of this age include the Bruna Suite, Gidyea Granite (new name; Whelan et al in prep), Leaky Norite (new name; Donnellan in prep, Whelan et al in prep) and the Atneequa Granite, all of which are exposed in ILLOGWA CREEK and extend into eastern ALICE SPRINGS, and numerous unnamed intrusions in HUCKITTA and ILLOGWA CREEK. Although coeval mafic (gabbro, norite, diorite and rare pyroxenite) and felsic magmas were emplaced at this time, felsic, predominantly peraluminous compositions are dominant. Rock types include coarse-grained equigranular and porphyritic to megacrystic rapakivi granite and granodiorite. These are commonly garnet-biotite+muscovite-bearing and are rarely hornblende-bearing. This contrasts with the dominantly metaluminous bimodal plutons emplaced prior to 1760 Ma in the eastern Arunta Region.

Ca 1750 Ma intrusive rocks are characterised by a relatively narrow range in wholerock Nd isotope compositions (εNd +1.75 to -3.1) and a similarly narrow range in zircon Hf isotope compositions (εHf +5.2 to -2.8) that spread across CHUR. Such values are indicative of relatively immature sources that have not undergone large amounts of crustal recycling. Modelling of Hf-age data indicate that intrusive rocks of this age were derived from mixing between isotopically evolved, recycled Neoarchaean crust and a relatively juvenile component with a crustal residence age of ca 2.0 Ga.

**Fluorite in the eastern Arunta Region: implications for IOCG-style mineralisation**

Recent discoveries of Cu-Au mineralisation in the eastern Arunta Region are closely associated with fluorite-haematite...
breccia, potassic alteration, and in places, silicic alteration, hosted in the ca 1743 Ma Atneequa Granite (Figure 2). Fluorite in altered granitic rocks in LIMBLA occurs as both vein and disseminated types (Figure 2), with at least some of the vein fluorite predating the hydrothermal brecciation event, as is indicated by truncated fluorite veins occurring as angular fragments within the breccia. Petrographic studies indicate that this earlier fluorite veining appears to have little association with haematite. In contrast, disseminated fluorite is intimately associated with fine-grained, decussate and micaceous haematite, and silification appears to postdate the infiltration of hydrothermal fluids.

Fluorine is known as a powerful ligand for metal transport (eg McPhie et al 2011), as it is the most reactive and electronegative of all elements. However there are few geological settings where sufficient F is available to hydrothermal fluids. Recent studies (eg Agangi et al 2010) have focused on the correlation between fluorine-rich felsic magmas and large hydrothermal Cu-Au deposits, in particular the silicic large igneous province (SLIP) that hosts the supergiant IOCG Olympic Dam deposit. Like the felsic magmas that host this deposit, the ca 1743 Ma Atneequa Granite, which hosts Fe-oxide Cu-Au mineralisation in LIMBLA, is unusually enriched in F (between 1000–2000 ppm in unaltered granite and up to ca 20.9 wt% in altered granite) compared to Yambah-aged felsic intrusive rocks (ca 1770 Ma; <1000 ppm) in the eastern Arunta Region. Previous workers have suggested that a fluorine-rich setting is crucial in forming large hydrothermal ore deposits, such as Olympic Dam, as it provides an enhanced fluorine reservoir for any hydrothermal fluid, thus increasing its capacity to transport metals.

A number of Cu-Au and IOCG-style prospects have been recognised in the Aileron Province (Figure 1). These show a broad spatial correlation with a east–west-trending belt of Yambah-aged (ca 1770–1760 Ma) intrusive rocks (eg Close et al 2007, Whelan et al 2009, Beyer et al this volume) and include Johnnies Reward, Ginnatree, and deposits in the Jervois district (Huston et al 2006), Harding Springs and Hale River (Whelan et al 2009) in QUARTZ and the Perenti copper prospect (Scrimgeour in press b). The Perenti prospect, located in western HUCKITTA, is intimately associated with quartz-haematite-fluorite breccia (Scrimgeour in press b), a similar association to that seen at Bigglesworth, Austin and Powers in LIMBLA. Moreover, recent U-Pb zircon age data from the eastern Arunta Region (Figure 1, Kositcin et al 2011) has identified a greater abundance and extent of 1750–1740 Ma felsic intrusive rocks than previously recognised, including unnamed granite in the vicinity of the Jervois Cu-Au prospect. Like the Atneequa Granite, the unnamed ca 1750 Ma pluton exposed in the Jervois area is characterised by slightly elevated abundances of F (between 1000–2000 ppm; OZCHEM database).

In the eastern Arunta Region (as defined in Figure 1), it appears that the ca 1750–1740 Ma felsic plutons are characterised by elevated F and, at least in LIMBLA, are spatially associated with fluorite-haematite hydrothermal breccia and potassic and silicic alteration, consistent with an IOCG-style system. Recent Cu-Au discoveries in LIMBLA highlight the mineral potential of felsic intrusions of this age in the eastern Arunta Region.

Acknowledgements

Liz Webber, Bill Pappas and the Geoscience Australia geochemistry lab are thanked for their efforts in getting samples analysed for whole-rock geochemistry.

References


**Update on the Molyhil tungsten–molybdenum project**

*Richard S Bradey*1

**Overview**

Thor Mining PLC (Thor) is a junior exploration and resource development company with projects in the Northern Territory at Spring Hill in the Pine Creek Orogen and Molyhil in the eastern Arunta Region, and in Western Australia at Dundas in the southern Fraser Range (**Figure 1**). Spring Hill and Dundas are gold projects, whereas Molyhil is a tungsten, molybdenum and magnetite project.

First discovered by prospector Lindsay Johannsen in 1973, Molyhil has been subject to two phases of small-scale mining ending in 1982. Thor took control of the Molyhil project in 2005 and, after completing a Definitive Feasibility Study, commenced mine development in 2008. As a result of the GFC, the project was put on hold while awaiting a more favourable metal price outlook.

Molyhil is now once again on the cusp of mine development. Since May 2011, Thor has drilled a further 18 holes for 3838 m (**Figure 2**) and has completed a new resource estimate (**Table 1**). The new resource represents a tonnage increase from the previous 2009 estimate of 25% to 4.7 Mt to 220 m depth. An updated Ore Reserve and mine plan are pending to complete the updated project feasibility study. Environmental permitting has been refreshed and engagement resumed with Aboriginal custodians. Subject to a favourable feasibility outcome, commencement of mine development is anticipated in the third quarter of 2012.

**Geology**

The Molyhil tenement (EL22349) straddles the narrow east–west-trending area of the eastern Aileron Province. To the north, the province is unconformably overlain by the Georgina Basin and to the south, it is separated from the Irindina Province by the steeply south-dipping Entire Point Shear Zone. The area is subdivided by the east–to southeast-trending Delny Shear Zone, which separates Jinka Domain metasedimentary rocks to the north from the Kanandra Granulite to the south (Scrimgeour 2011).

The Molyhil mineralisation is hosted in Jinka Domain metasedimentary rocks comprising two adjacent outcropping iron-rich skarn bodies, marginal to a granite intrusion. Both lodes contain scheelite (CaWO₄) and...
molybdenite (MoS\textsubscript{2}) mineralisation. Although irregular in detail, the lode outlines and internal banding both strike approximately north–south and dip steeply to the east. The bodies are arranged in an en echelon manner, with the Yacht Club located northeast of the Southern. Molyhil is the only known occurrence of tungsten mineralisation in the eastern Arunta to be associated with magnetite.

Interpretation of mapping and drillhole logs suggest that the bodies may be two fault-displaced sections of an original single mineralised skarn unit. The mineralisation is coarse grained and its distribution is irregular (Barraclough 1979). Drilling has been focused on resources potentially recoverable from an open pit operation, and both bodies remain open at depth.

**Future work**

In 2012, the focus of exploration activity will turn from resource definition to exploration on both a tenement-wide and near-mine basis.

Near-mine opportunities have been identified in recent drilling. Two areas already identified include extensions of the mineralisation to the east and southeast that represent additional potential underground mining inventory, and an area at shallower depth to the west that represents potential additional open pit inventory. Follow-up drilling of these and any other identified areas will be integrated with the proposed mine development schedule.

Existing mapping and geophysical data will be fundamental to tenement-wide exploration efforts. The association of Molyhil mineralisation with magnetite and the high specific gravity of scheelite (ca 6) suggest that magnetics and gravity could be essential geophysical tools for continuing exploration efforts.

Significant opportunity exists for exploration success through consolidation and evaluation of the considerable body of existing data, such as two aeromagnetic surveys conducted in the 1980s at 150 m line spacing and 80 m terrain clearance. These surveys identified multiple possible Molyhil analogues, of which less than half were sparsely drill-tested. In addition, structural targeting, geochemical reconnaissance and prospect evaluation will comprise the broader exploration program for the coming year.

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**Table 1. Molyhil Resource estimate 2012**
(Thor Mining PLC, ASX announcement, 30 January 2012).

<table>
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<tr>
<th>Classification</th>
<th>Resource</th>
<th>MoS\textsubscript{2} Tonnes</th>
<th>Grade %</th>
<th>WO\textsubscript{3} Tonnes</th>
<th>Grade %</th>
<th>Fe tonnes</th>
<th>Grade %</th>
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<td>Measured</td>
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<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Indicated</td>
<td>3 820 000</td>
<td>0.22</td>
<td>8 200</td>
<td>0.29</td>
<td>10 900</td>
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<td>0.25</td>
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<td><strong>Total</strong></td>
<td><strong>4 710 000</strong></td>
<td><strong>0.22</strong></td>
<td><strong>10 400</strong></td>
<td><strong>0.28</strong></td>
<td><strong>13 100</strong></td>
<td><strong>18.1</strong></td>
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</tbody>
</table>

Mineral Resource reported at 0.1% combined Mo + WO\textsubscript{3}, Cut-off and above 200mRL only. Note: minor rounding errors may occur in compiled totals.
Use of NTGS magnetic data collection to estimate depths to basalts in the NT

Roger Clifton

Between 30 and 40% of the Northern Territory is underlain by flood basalts of the early Cambrian Kalkarindji Large Igneous Province, which attains a thickness of as much as several hundred meters. This voluminous mafic material provides a significant buffer of alkalinity. Where geological fluids of lower pH from underlying Precambrian sedimentary rocks meet this buffer, there is an increased likelihood of significant mineral deposits.

Because the basalts lie at various depths across the Territory, an explorer needs to know how deep they are before commencing exploration for any associated deposits. Although there are many boreholes intersecting the basalts, they tend to be in clusters, so that there are large areas of the Territory where there are relatively poor indications of basalt depths.

However, NTGS does provide an extensive coverage of magnetic data, with more than 80% of the Territory covered at high resolution. A geophysicist equipped with appropriate software is able to extract magnetic depths, which is of great benefit to understanding the settings for basalt-related deposits.

A classic method, proposed by Spector and Grant (1971), uses the radial power spectrum of a TMI anomaly to estimate the depth. The procedure requires repeated efforts to find a useful spectrum for the purpose. Further, it requires subjective judgment at picking the match that determines the depth. Several examples are demonstrated in the accompanying presentation.

A more modern method, using Euler’s homogeneity equations, is becoming more frequently used (Reid 1996). This method makes use of the increasing power of computers to allow the user to make repeated variations of parameters until satisfactory estimates are obtained. This technique is also demonstrated and shows a range of certainty in estimates, tested against intersection depths known from boreholes.

References


ASTER Geoscience Map of the Northern Territory

Thomas J Cudahy1,2, Michael Caccetta1, Simon Collings3, Matilda Thomas4 and Carsten Laukamp1

Introduction

A 3D mineral map of the Australian continent at high spatial resolution (suitable for deposit-scale mapping) is one of the 2020 project goals for CSIRO’s Minerals Down Under Flagship (MDU) and its C3DMM (WA Centre of Excellence for 3D Mineral Mapping (http://c3dmm.csiro.au). These digital maps should be publicly available and web accessible, in formats suitable for GIS and other spatial processing/modelling packages. It is planned that they be delivered by government geoscience agencies across Australia as a standard part of a precompetitive geoscience information suite. This vision is now achievable given developments in the last 10+ years that have led to a new generation of ‘geoscience-tuned’ spectral sensing systems operating from drill core (eg http://www.csiro.au/Portals/Publications/Brochures–Fact-Sheets/hylogging.aspx), field, airborne (eg www.hyvista.com) and space (eg www.isiswg.org) platforms. These emerging operational mineral mapping technologies measure natural electromagnetic radiation (from the sun) spanning visible light (0.4–0.7 µm) through to thermal infrared wavelengths (TIR; 7–12 µm) that is reflected or emitted from the top few microns of material on the Earth’s surface. Importantly, this wavelength range spans atmospheric windows that allow measurement of diagnostic spectral features for minerals that are key to characterising primary geology, metamorphic or metasomatic alteration, and weathering effects. However, these diagnostic mineral absorption features are often narrow, requiring hundreds of channels to measure the depth of available mineral information, including the abundances of specific minerals as well as their chemical and structural variations (eg Cudahy et al 2005, Cudahy et al 2008, Haest et al 2012).

Systems measuring hundreds of bands are often called ‘hyperspectral’. The ASTER satellite sensor (www.ersdac.or.jp; http://asterweb.jpl.nasa.gov) has a lower spectral resolution (called ‘multispectral’) and as a consequence, only broad mineral groups can be measured, such as the group of hydroxyl-bearing dioctahedral silicates (called AIOH Group), which includes minerals like kaolinite, dickite, nacrite, halloysite, muscovite, paragonite, illite, brammalite, beidellite and montmorillonite. At higher spectral resolution (eg HyLogger™), many of these AIOH group minerals can be distinguished, based on their diagnostic spectral features (http://speclab.cr.usgs.gov/spectral-lib.html).

The public release of the Northern Territory (NT) ASTER Geoscience maps in April 2012 follows earlier releases for Western Australia (November 2011) and South Australia (March 2012). This paper introduces a number of the sixteen ASTER products to be released for the NT,
including the ALOH Group Composition and Silica Index. One of the key messages for unlocking the value of these new mineral maps is the use of appropriate geological-mineralogical models to explain lithological, weathering and metasomatic phenomena.

ASTER

Japan's ASTER imaging system was launched onboard the USA's TERRA satellite platform in December 1999. ASTER was included on this multi-sensor platform in large part because it provided a 'zoom' optical lens with its 15–90 m pixel resolution (for 60 x 60 km-wide scenes) for the MODIS (Moderate Resolution Imaging Spectro-radiometer – http://modis.gsfc.nasa.gov) with its 250–1000 m pixel resolution (and a 2330 km-wide swath). ASTER and MODIS are multispectral systems with 14 and 36 bands respectively. MODIS was designed to globally measure parameters such as: atmospheric gases, like water vapour and ozone; chlorophyll absorption in photosynthesising biomass; and kinetic temperature. In contrast, ASTER was designed to globally map the Earth's land surface composition (below 80° latitude), especially its mineral group information, like 'aluminium clays', 'iron oxides', 'carbonates' and 'silica/quartz'.

CSIRO’s ASTER geoscience processing

In theory, only 15 independent parameters can be measured/mapped with ASTER’s 14 available spectral bands, although CSIRO’s processing methods, which are based on multiple parameters and masks for each geoscience product, allows additional geoscience products to be generated (more details below). The Version 1 ASTER geoscience product notes (http://c3dmm.csiro.au) provide details for each product, including how they are generated, their accuracy, what can complicate their information content, and how they can be used to extract geological information.

The NT ASTER mosaic used approximately 700 scenes selected from CSIRO’s archive (sourced from the USGS) of >30 000 scenes for Australia. CSIRO also has access to the National archive of satellite Hyperion hyperspectral (0.4–2.5 µm wavelength region) imagery (also sourced from the USGS), which enabled calibration/validation of the shorter-wavelength products, namely ASTER bands 1–9. No suitable independent validation data were available for ASTER’s five TIR bands (bands 10–14) and so, the associated derived products are not able to be similarly validated.

In brief, processing of ASTER bands 1–9 (L1B radiance-at-sensor) into geoscience products involved corrections for: errors in instrument calibration, solar irradiance, geometric deviations, atmospheric interference, inter-scene calibration, vegetation cover and overlapping mineral absorption effects. Processing of the ASTER bands 10–14 (L2 emissivity) involved corrections for geometric deviations and inter-scene calibration. The final digital NT ASTER geoscience mosaics were carved into 1:1M-scale mapshets (ca 100 Mbytes per map product) and converted to GIS-compatible formats for easy integration with other datasets. 'Version 1' comprises three types of ASTER geoscience products, namely: (a) mineral group content maps that are based on ratios of band/s outside the mineral absorption feature over the band that comprises the absorption feature of the mineral of interest; (b) mineral group composition maps that are function of the absorption feature geometry (wavelength); and (c) mineral group index maps, which are sensitive to the presence of material type, but not specifically its content or composition. Both dry and green vegetation complicate the accuracy of these mineral products, though future versions of the ASTER geoscience products are expected to reduce this error (Rodger and Cudahy 2009).

Geological synthesis

Figure 1 presents examples of the 1st-pass ASTER geoscience mosaics of the NT for combinations of VNIR (bands 1–3), SWIR (bands 5–7) and TIR (bands 10 and 13) bands. These 1st-pass processing mosaics have not been masked to remove water, clouds and green vegetation (Figure 1a). The normalised SWIR product (Figure 1b) shows column-striping, which often becomes apparent when the dominant, correlated ‘non-mineralogical’ information is removed. This striping is related to small calibration errors between each element of the sensor’s detector array and in theory can be removed. Also apparent in Figure 1b is a processing error in the lower left of the NT mosaic. Seasonal effects, such as fire scaring and green vegetation flushes, also impact on the seamless quality of the mosaic (Figure 1b). A number of these effects will be removed in the Version 1 products that are due for public released in April 2012, though errors from vegetation cover and detector line-striping will only be addressed in later product versions.

The ALOH Group Composition mosaic (Figure 1b) shows that the distribution and composition of Al-OH-bearing silicate minerals cover much of the orogenic domains (eg Arunta Region and Pine Creek Orogen), as well as the central Australian Neoproterozoic–Palaeozoic basin successions (eg Amadeus, Wiso and Georgina basins), presumably because of increased vegetation cover northwards, the northern Australian basin successions (eg McArthur, Victoria and Birrindudu basins). For the same reason, the onshore Carpentaria Basin appears to show relatively little mineralogical information in contrast to the Eromanga and Pedirka basins in the south. The Silica Index mosaic (Figure 1c) highlights both the central Australian Neoproterozoic–Palaeozoic and Mesozoic–Cenozoic basins, especially south of 18° latitude. For these same cover rocks, the ALOH Group Composition shows that there is a change in ALOH mineralogy from illite/muscovite/montmorillonite in the southeast to more kaolin-rich areas elsewhere. This may reflect the influence of major present-day in-land drainage networks affecting the southeast of the NT.

Figure 2 shows how the same ASTER maps can be used at scales suitable for mapping at <100K. The area shown covers the ca 140 Ma Gosse Bluff meteorite impact crater, highlighted by circular lines in the south, as well as a series of east–west-trending thrusts (including A–C in Figure 2a)
Figure 1. CSIRO’s 1st-pass ASTER geoscience products of the Northern Territory. (a) False colour mosaic image – note that this preliminary level of processing does not include any masks for water, cloud or green vegetation, which are to be corrected in the final Version 1 release. Also note areas affected by fire scars and green vegetation flush. (b) AIOH Group composition product based on ASTER SWIR bands, which has been masked to include only those pixels with sufficient AIOH Group content. Cooler colours are related to kaolin and Al-rich muscovite, paragonite and illite, whereas warmer colours are related to Si-rich muscovite (and illite) and montmorillonite. Note along-satellite-track striping, caused by small errors in calibration of ASTER’s detector array. Also note anomalous area in southeast caused by mis-calibration between scenes in CSIRO’s 1st pass batch processing. (c) Silica Index product based on ASTER’s TIR bands with warmer tones essentially related to more abundant, coarsely grained (>250 μm) SiO₂-rich minerals, such as quartz exposed in alluvium/colluvium.

Figure 2. Gosse Bluff area in the NT. (a) Geology from Hermannsburg 1:250 000-scale geology mapsheet. Note thrusts between A and B and near C, as well as the impact crater near D-G. (b) ASTER ‘AIOH Group Composition’ of same area shown in (a). Note more Si-rich AIOH group minerals in centre of impact crater [D–E in (a)] and with thrusts closest to A. (c) ‘Silica Index’ for area in (a). Note change in apparent silica-content along lithological-strike (yellow line), with lowest values (Si-poor) near A.
in metasedimentary rocks of the Amadeus Basin, where fluids have potentially been mobilised and deposited U and other commodities. The thrusts located between A and B are associated with a coincident Al-OH mineralogical pattern (Figure 2b), with both slightly cross-cutting the stratigraphy. That is, most of the metasedimentary rocks are characterised by ‘kaolinite’ (blue tones), whereas illite/muscovite is associated with the thrusts. Furthermore, the composition of illite/muscovite appears to become progressively Si-rich (phengitic) southward. The corresponding Silica Index product (Figure 2c) shows that for the same stratigraphic level within the metasedimentary rocks (yellow line/arrow), a progressive decrease is apparent in the silica content towards A. One possible geological interpretation of these patterns is that a fluid mobilised Si (presumably) from quartz and in part re-precipitated it as a more Si-rich illite/muscovite (eg phengite), with the area around ‘A’ being the most intense exposed part and thus, a possible exploration target. In theory, this interpretation should be further tested by also checking for other key attributes, such as looking for the presence of reduced rocks using the ASTER Opaque Index, as well as the presence of Fe²⁺-bearing chlorite (FeOH Group Content, MgOH Group Content and Ferrous in MgOH Group products).

The Gosse Bluff impact Crater also shows mineralogical zonation, namely: (D) an inner Al-clay-poor core, (E) a silica-poor, Si-bearing Al-clay-rich rim, and (F) an outer silica-rich, Al-clay-poor rim (Figure 2). The distal/background mineralogy is one of illite/muscovite and quartz. The Silica Index (Figure 2c) also shows that ‘quartz’ is more common on the southern side of the main ephemeral drainage system (ie alluvial/colluvial provenance control) with these Quaternary sediments gradually blanketing the original ca 25 km-wide impact crater (outer ellipse shown in Figure 2b).

A complete continental ASTER map, ‘The National ASTER Geoscience map’ is scheduled to be publicly released at the 34th International Geological Congress in August 2012 (www.34igc.org).

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References


ABM Resources: Finding roots in the final frontier

Rodney K Boucher¹,², Patrick M Smillie³, Rebecca E Richards¹ and Darren J Holden¹

ABM Resources NL explores in the Northern Territory, and is committing more than $10M annually on grass-roots, discovery-stage and resource delineation projects focused on gold in the Tanami-Arunta regions. The company is one of the largest exploration license holders in the NT (and Australia) and has a tiered approach to exploration.

The company began exploration in 2010, quickly focusing on the Buccaneer and Old Pirate prospects at the Twin Bonanza camp. A 1.67 Moz maiden gold inferred

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deep to quickly evaluate prospects with the aim to search for systems capable of delivering standalone mining operations.

**Twin Bonanza Gold Camp**

The Twin Bonanza Gold Camp is centred approximately 20 km south of the Tanami Road and 15 km east of the Northern Territory / Western Australia border. The area comprises over 30 targets including the IRGS at Buccaneer and the Old Pirate high-grade vein system.

The **Buccaneer** IRGS is an 1802 ± 8 Ma porphyritic syenogranite intruded into Wilson Formation sandy turbidites of the Ware Group. In February 2011, ABM Resources announced a maiden inferred resource of 65.8 Mt grading 0.79 g/t for a total contained metal of 1.67 Moz of gold (0.2 g/t cut-off). The resource extends over 600 x 400 m of the southern portion of the 2200 x 900 m stock (Figure 1). Drilling continued throughout 2011 for further resource delineation in addition to continued exploration. Five new mineralised zones were discovered: the higher-grade Caribbean and Cypress Zones, along with the West Sedimentary, Empress and Eastern Contact Zones.

Gold at Buccaneer occurs in stockwork quartz vein systems and is typically associated with enriched arsenic, antimony, bismuth, tungsten and copper. Zones of moderate to intense potassic and chlorite/sericite alteration are variably mineralised.

Three geophysically delineated grass-roots targets drill tested potential IRGS stocks to the west and north of Buccaneer; however, field mapping and drilling revealed iron-rich Wilson Formation turbidites. A fourth target to the east at Landlubber intersected a sulfide-rich, high-level acid intrusive rock. The best single metre assay result to date from Landlubber is 3.44 g/t.

![Figure 1](image-url). Location of Buccaneer IRGS deposit with adjacent Caribbean, Cypress, Empress, and Eastern contact discoveries.
The turbidite-hosted *Old Pirate* prospect contains high-grade, gold-bearing quartz veins. Quartz forms saddles in moderately-plunging, upright chevron folds. The host rock is sandy turbidites of the Killi Killi Formation of the Tanami Group. Two adjacent and parallel anticlinal sub-folds, approximately 50 m apart, occur at Old Pirate, both contain gold-bearing saddles. Bedding-parallel quartz veins form in thicker shale. The thickest shale with the best-developed quartz is 25 m true width. Mineralisation is continuous, with gold endowed in anticlinal and synclinal hinges, as well as along the entire length of the limbs. Longitudinal trenching along some of these veins has so far determined a combined strike length of 726 m at an average grade of 24.01 g/t (*Figure 2*). Although a sporadic, nuggetty assay

*Figure 2*. Old Pirate drilling, trenching, and surface sampling results.
response does occur, high- and low-grade zones can clearly be recognised. These have a periodicity of approximately 15 m along the length of the veins. Diorite and dolerite stocks and sills have been intersected beneath Old Pirate. Some of the better-grade drill results are on the margins of these igneous bodies. Twin Bananza generally has only 0.1% outcrop. However at Old Pirate, the quartz veins are some of the better-exposed rocks in the area and they can be followed for 3.5 km along the Old Pirate anticlinal trend before reaching cover of palaeochannel sediments.

The Corsair prospect is 2.5 km along strike from Old Pirate. Two mineralised zones were recognised from previous drilling and these were tested in 2011 with deeper RC drilling. Moderate gold results were returned in sandy turbidites. Diorite was intersected in the bottom of these holes.

Parallel to and 1.5 km east of Old Pirate and Corsair is the Bandit prospect. A belt of quartz over 2 km long outcrops in between palaeochannels. Holes into two structurally complex areas were drilled; one of these returned 5 m averaging 3.12 g/t.

Chert marker beds within the Killi Killi Formation and Wilson Formation provide good outcrop and assist to define the geometry of folds. Field mapping has revealed that Old Pirate and Bandit are just two anticlines that form part of a larger dome. The top of the dome is interpreted to be at Corsair and the northern closure near Buccaneer. Overall, this is a simple north–south-trending fold system. In contrast, the younger Wilson Formation to the west of Buccaneer contains refolded folds.

Additional grass-roots exploration to the east of Bandit revealed low-grade gold in sandy turbidites and dolerite.

**Base metals deposits of the Pine Creek Orogen: Types and prospectivity**

Mazhar Khan

The Palaeoproterozoic Pine Creek Orogen (PCO) consists of a thick (>4 km) succession of clastic, carbonate and carbonaceous sedimentary and volcanic rocks, unconformably overlying Neoarchaean (ca 2670–2500 Ma) granitic and gneissic basement. It is exposed over more than 47,500 km² in the northern part of the Northern Territory. The PCO is extensively mineralised and hosts over 1300 known mineral occurrences, which include uranium, gold, copper, lead, zinc, silver, tin, tantalum, iron ore, PGE, REE, magnesite, phosphate and a number of other commodities. There are more than 250 base metals occurrences in the PCO (Figure 1).

Copper mineralisation was discovered in the Rum Jungle area in 1869 and was followed by the discovery in 1872 of the Copperfield deposit near Pine Creek. There are 141 copper occurrences in the PCO. Most of these were discovered by the end of the nineteenth century. Uranium-copper deposits of the Rum Jungle area were discovered during 1949–1965 (eg Mount Fitch, Whites, Area 55), but currently, there is no operating copper mine in the PCO.

Major copper occurrences are located in the Rum Jungle and Mount Davis areas, and include Intermediate, Browns, Whites and Mount Fitch.

Lead-zinc-silver mineralisation was discovered in 1886 at the Evelyn mine. It was followed by the discovery of several other Pb-Zn-Ag occurrences in the PCO. The largest deposit in the PCO, now mined-out Woodcutters Pb-Zn-Ag deposit, was discovered in 1966 by the Bureau of Mineral Resources. Mining of this deposit started in 1985 and continued until 1999. During that time it produced 4.651 Mt at 12.78% Zn, 5.6% Pb, 87 g/t Ag and 0.73% Sb (MODAT).

**Base metals deposit styles**

Most of the base metals deposits of the PCO can be grouped into the following categories:

- Hydrothermal veins, eg Woodcutters, Mount Diamond, Waldens.
- Copper-lead-zinc occurrences of volcanogenic association, eg Daly River area deposits.
- Sediment-hosted stratiform deposits, eg Browns, Intermediate, Whites.

**Other prospects**

Mineralisation at Hyperion and Hyperion South in the northern Tanami Region is shear-hosted on the hangingwall of a granite dyke within dolerite. These ingredients are similar to the >1 Moz Au Groundrush deposit, 15 km to the south. Hyperion and Hyperion South have strike lengths of 400 m and 200 m, respectively, and mineralisation has been followed down to 250 m. ABM Resources have drilled multiple holes into Hyperion and Hyperion South and expect to release a maiden resource in 2012.

Drilling at the Kroda prospect, which is located near Barrow Creek in the northern Arunta Region, had yielded best results of 57 m averaging 3.83 g/t. Mineralisation occurs in plunging shoots along a west-northwestward-trending shear zone.

ABM Resources completed 16 holes into several targets in the Lake Mackay project area indicating the presence of both gold and copper. The Lake Mackay region will form part of the 2012 regional exploration program.

**2012 program**

ABM Resources will have a greatly expanded exploration program in 2012. Low-detection, deep-penetrating regional geochemical surveys will be conducted over granted tenements with the aim to delineate targets, particularly through transported cover. Additional targeted lines of pH measurements will assist to define prospective regions while in the field. Field mapping provides integral base data to delineate the depositional and structural template for the differing regions. The field mapping and geochemical data combine with geophysical data and tectonic models to generate drill targets.
• Polymetallic stratabound gold and base metals deposits, eg Mount Bonnie, Iron Blow.
• Skarn, eg Evelyn.

Hydrothermal vein-type occurrences are the most common base metals mineralisation style in the PCO. The Woodcutters Pb-Zn-Ag deposit is the largest known deposit of this type, and major copper deposits include Mount Diamond and Waldens. Most vein-type copper occurrences are related to intrusive granite and are mainly hosted by the Burrell Creek and Koolpin formations. Paragenetically, compared to other mineralised veins in the PCO, the copper (granite-related) veins appear to be younger than Au-quartz veins, overlap Sn-quartz veins and are probably earlier than, or synchronous with Pb-Zn-Ag-quartz veins. Most occurrences are associated with I-type granites of the Central Domain of the PCO, whereas the Litchfield Province, which is dominated by S-type granites, has mainly tin-tantalum occurrences (Ahmad et al. 1993). Most vein-type Pb-Zn-Ag occurrences are associated with the Pine Creek Shear Zone and the southern extension of the Mount Shoobridge Fault. However, the largest deposit, Woodcutters, is hosted within a north-trending fault system at the eastern flank of the Rum Jungle Dome. Mineralisation in the Woodcutters deposit is hosted by the Whites Formation of the Mount Partridge Group within the Woodcutters Fault Zone, which contains several north-trending, steeply dipping and subparallel faults. Some of these faults host a major portion of the mineralisation, while minor stratiform mineralisation is also found at deeper levels. The thicker ore bodies occur as replacement of dolomudstone within 25 m of faults.

Base metals (Cu, Pb, Zn) occurrences of the Daly River Mineral Field have volcanogenic affinities, as these deposits are hosted in chloritised shear zones within the Warrs Volcanic Member or adjacent schist and phyllite of the Burrell Creek Formation (Ahmad et al. 1993). The lodes usually trend north-northeast and appear to be relatively narrow and conformable with the cleavage or bedding of the enclosing strata (Ferenczi 1990). Disseminated magnetite is common within the chloritised zone. Quartz-carbonate-chlorite and sericite-chlorite alteration assemblages are prominent in some areas. Major primary ore minerals consist of pyrite, chalcopyrite, marcasite, arsenopyrite, and minor galena and sphalerite, while malachite, azurite and chalcocite are the main oxidised ores. About 1200 t of copper were mined from the oxidised ore of the Daly River deposit during 1884–1918.

Figure 1. Base metals occurrences of PCO. Geology simplified from 1:2.5M geological map of NT.
Sediment-hosted stratiform deposits of the Rum Jungle area (eg, Browns, Whites, Intermediate) are within the carbonaceous shale of the Whites Formation adjacent to the contact with the underlying Coomalie Dolostone (Ahmad et al 2006). The polymetallic Browns deposit is the largest copper resource in the PCO, and contains Ni and Co in addition to Pb, Zn and Cu. It contains a JORC-compliant resource of 9.4 Mt at 0.82% Cu, 0.14% Co and 0.14% Ni (oxide resource) and 45.1 Mt at 0.35% Cu, 3.74% Pb, 0.73% Zn, 0.09% Co and 0.07% Ni (sulfide resource). The Browns deposit was mined by Compass Resources Ltd briefly during 2008–2009 and is currently under care and maintenance. McCready et al (2004) interpreted these deposits as being diagenetic in origin with significant subsequent remobilisation. The Whites and Mount Fitch deposits also contain uranium in addition to base metals.

Polymetallic stratabound deposits of the Mount Bonnie area contain gold, silver, zinc, lead and copper. The Mount Bonnie deposit lies on the eastern limb of the Margaret Syncline, whereas the Iron Blow deposit lies on the western limb. Mineralisation in these deposits is hosted by the Paleoproterozoic Mount Bonnie Formation of the South Alligator Group. These deposits are contained as concordant lenses within interbedded pyritic shale, dolomitic siltstone and tuff (Ahmad et al 2009). Major sulfide minerals in the primary ore zone include sphalerite, galena, arsenopyrite, pyrite, chalcopyrite, pyrrhotite and tetrahedrite. Quartz veining is very rare in these deposits and zinc and gold are the dominant elements, followed by silver and lead. To date, only gold and silver have been produced from these deposits. Production was mainly from the oxidised zone and totalled about 0.035 Mt (Iron Blow) and 0.11 Mt (Mount Bonnie) of ore. The grade of gold in the oxidised zones of both of these deposits was about 7 g/t. Crocodile Gold Corporation calculated the NI43-101-compliant resource for the Iron Blow deposit as 3.175 Mt at 2.08 g/t Au, 101 g/t Ag, 3.28% Zn, 0.19% Cu and 0.76% Pb. The Mount Bonnie deposit contains 0.65 Mt at 1.7 g/t Au, 9% Zn, 280 g/t Ag, 2% Pb and 0.5% Cu.

Skarn mineralisation is not very common in PCO; it has only been reported from the Evelyn deposit of the PCO. This deposit was discovered in 1886 and was worked intermittently from 1886 to 1890. The mineralisation at Evelyn is hosted by several en echelon orebodies in thickly bedded marble of the Koolpin Formation. Nine small tabular lodes have been identified in the deposit and they strike roughly north–south and dip towards the east. The orebodies are commonly bounded by brecciated marble which is partially replaced by polycrystalline quartz and altered to tremolite, actinolite, anthophyllite, diopside, garnet and serpentine (Garth 1970).

**Prospectivity**

Granite-related, hydrothermal base metals veins were mined more than 100 years ago and have seen little exploration since then. The spatial distribution of the vein-type occurrences (Figure 1) shows that the margins of the granites of the Cullen Supersuite have significant potential for base metals mineralisation. Some large veins in the Mary River area have viable resources, but are now in Kakadu National Park. Deposits similar to the Mary River Gossan (Gubberah Gossan), which has a resource of 0.9 Mt at 9.7% Zn and 0.5% Pb, are possible in the area outside Kakadu National Park.

The basal PCO stratigraphy overlying Archaean granite in the Rum Jungle, Woolner and Alligator Rivers regions have significant potential for Browns-type polymetallic deposits. The 2670 Ma Woolner Granite consists of two domes that are concealed beneath 50–80 m of Cretaceous and Cenozoic cover, and the potential for base metals mineralization in the surrounding basal PCO stratigraphy remains largely untested. A number of small copper prospects and anomalies within carbonaceous strata in the vicinity of the Archaean domes remain virtually unexplored. These areas also have significant potential for Woodcutters-style hydrothermal vein-type deposits.

Base metals deposits with volcanic affinities in the Daly River area were explored nearly five decades ago and need fresh exploration efforts. Interbedded volcanic rocks in the southern Litchfield Province and elsewhere have moderately good potential for these types of deposits.

The potential for further copper discoveries in the PCO has been highlighted by recent exploration by Thundelarra Exploration Ltd at their Allamber project, which has intersected broad zones of anomalous copper, along a 20 km-long prospective horizon. Drilling intersections include 7 m at 9.69% Cu at the Lucas prospect and 19 m at 1.94% Cu at the Hatrick prospect. Thundelarra consider the mineralisation to be stratabound in nature, occurring as broad zones within dolomitic, pyritic and graphitic shale of the metapelitic succession in the Paleoproterozoic Masson Formation, close to the intrusive contact with the Cullen Supersuite (Thundelarra Exploration Ltd, ASX Announcement, 22 December 2011). The copper is locally also associated with uranium mineralization.

**References**


TUC Resources Ltd’s Stromberg heavy rare earth discovery (Figure 1), located on the Fish River Station in the northwestern NT, is one of the first deposits of its type found in the region.

Stromberg was initially drilled in 2009 as a uranium prospect after airborne radiometrics and subsequent geochemistry defined a highly coherent anomaly. In 2010, TUC noted some geological parallels with other rare earth prospects in the world and Stromberg drill chips were resampled for rare earths, with very positive results. Large amounts of high-demand heavy rare earths, such as dysprosium (Dy) and yttrium (Y) make Stromberg an important prospect. Supplementing this, preliminary mineralogical and metallurgical test work has highlighted some intriguing characteristics. The rare earths at Stromberg appear to be hosted within widely distributed clay bands, which include xenotime mineralogy. Importantly, concentrations of rare earths at Stromberg appear to exceed those of clays currently being mined in China, both in overall grade and HREE distribution. In addition, evidence exists of rare earths at Stromberg in a ‘roll front’ setting. This combination of deposit types, known for their low-cost processing and excellent recovery potential, could give Stromberg a significant competitive advantage over other heavy rare earth prospects. Additionally, the deposit is a near-surface, weathered tabular body. This means that drilling and potential development can progress more rapidly and lends positive economics to any future mining operation. Metallurgical test work is in progress to determine achievable rare earth concentration grades and extraction methods.

The current geological model suggests a large exploration upside associated with basinal development, stratigraphic repetition and enrichment by weathering processes. During the Palaeoproterozoic, an REE-enriched stratigraphic succession, likely sourced from an REE-rich granitic/volcanic Neoarchaean hinterland, was deposited as a part of the Tolmer Group, thickening around basinal growth faults. Subsequent remobilisation of REEs within the unit(s) and from the hinterland by meteoric waters (roll front mechanism) provided further concentration. Eventual uplift and basin extension has caused further fault movement; damming and trapping the REE-rich roll front fluids. A number of weathering events have overprinted the prospect, causing more concentration of heavy rare earths on a prospect scale.

TUC are planning a busy year ahead and are working on highlighting district potential, developing land access agreements, and of course, moving the current drill program towards the resource definition stage and perhaps even pre-feasibility. With multiple phases of metallurgical and exploration drilling planned over the next field season, it is sure to be an exciting year ahead for TUC, as the company continues to develop as a serious contender in the heavy rare earth space.

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Introduction

In 2007, Geoscience Australia, in collaboration with State and Northern Territory geoscience agencies, embarked on the National Geochemical Survey of Australia (NGSA) project, conducted under the Australian Government’s Onshore Security Program. The primary aim of this project was to provide data on the nationwide distribution of energy-related minerals, in particular uranium and thorium.

In total, 1186 catchments were sampled, including 202 catchments in the NT. About 200 catchments in WA and SA could not be sampled because of land access issues. All required catchments in the NT were sampled. The sampling was of ultra-low density, averaging 1 sample per 5500 km$^2$. It had been proved by earlier pilot studies that such low-density sampling can still provide meaningful geochemical information (de Caritat and Lech 2007, de Caritat et al 2007, 2008).

Wherever possible, sampling points were located on an overbank, transported floodplain sediment in the lower part of each river catchment, on the basis that such sediment should provide a geochemical signature of the entire catchment. At each sampling point, two samples were taken: from depths of 0–0.1 m (Top Outlet Sample – TOS) and 0.6–0.8 m (Bottom Outlet Sample – BOS). To reduce natural soil heterogeneity, every sample collected was a composite either from a shallow soil pit (TOS), or from at least three auger holes, or rarely, a pit (BOS) at a given site. An average of 9 kg of sediment was collected per sample (Figures 1, 2). At every ten sites, a duplicate sample was taken within a maximum distance of 200 m from the original sample site for quality control.

Field observations included measurements of pH, grain size, and the dry and wet colour of every sample. Before chemical analysis, each sample was divided into two fractions (<2 mm and <75 µm), which were analysed separately.

Sample analysis was carried out for 68 elements using X-ray fluorescence (XRF) and (reaction cell) inductively coupled plasma-mass spectrometry (ICP-MS) at Geoscience Australia. Analyses for selected elements (e.g., F, Se, Au, Pt and Pd) that could not be completed at Geoscience Australia were undertaken externally. Geometric means were used to provide background values for each element.

NTGS has undertaken a project to interpret the geochemical distribution of economically important elements in the NT as a guide to regional-scale prospectivity. Brief descriptions related to the anomalism of 14 selected elements within the NT are outlined below and associated geochemical maps are shown in the accompanying presentation. Figure 3 is an example of one such map. Extended descriptions of anomalies for more elements, as well as the Excel spreadsheet with complete analytical results for all 68 elements, is available as an NTGS product on CD.

This first-pass analysis of selected element anomalism in the NT illustrates a catchment-scale geochemical fingerprinting method that could be used as a broad prospectivity indicator.

Description of selected elements

Zinc

Zinc is highly mobile in oxidised and neutral conditions, however, it is less mobile in carbonate-rich environments. Its concentration can be significantly affected by adsorption and co-precipitation on clays and Fe-Mn oxides, and by adsorption on organic matter.

The majority of catchments enriched in zinc (>60 ppm, ca 5 times background) are clustered in catchments draining the Amadeus and Georgina basins. However, the strongest...
anomaly of 113.5 ppm Zn was located in the King River catchment (KATHERINE) which drains Cambrian carbonate rocks of the Daly Basin.

**Manganese**

Elevated manganese values are usually associated with carbonate rocks and their metamorphic equivalents, and with surface enrichment processes. During weathering, manganese is released from its host minerals such as Mn\(^{2+}\) bicarbonate, chloride and sulfate, and is readily re-precipitated as manganese oxides and hydroxides. These scavenge a range of metal cations and can cause false anomalies in target elements.

The strongest anomaly of 3222 ppm Mn was detected at the junction of the Flying Fox Creek and the Jalboi River (URAPUNGA). Manganese enrichment at this locality is likely to be associated with the hydrothermally enriched part of extensive iron deposits hosted by Roper Group sedimentary rocks of the McArthur Basin.

Six other anomalies of >1000 ppm Mn (ca 5 times background) were detected. The most interesting is an anomaly in the catchment of Newcastle Creek (BEETALOO), which drains the Cretaceous Mullaman Beds, as well as soft Cenozoic sediments. The lithology of Cretaceous sedimentary rocks there is similar to those containing large manganese deposits in Albian shoreline facies sedimentary rocks in Groote Eylandt. This locality therefore may be a good target for more detailed investigations.

**Nickel**

Nickel is both a siderophile and a chalcophile, and therefore is a good indicator element in geochemical surveys. Nickel occurs as a substitution in olivine, Mg-pyroxenes, amphiboles, mica and sulfides. It is less mobile in high pH environments, but is subject to scavenging by organic matter over a wide range of pH.

Thirteen anomalies >50 ppm Ni (ca 3.5 times background) were located. The strongest anomaly of 103.3 ppm Ni was located in an unnamed catchment with poorly defined drainage in the Davenport Province of the Tennant Region. The sample was taken at the lowest point of this internally drained catchment on FREW RIVER. The most likely source for this anomaly is the Kudinga Basalt and Wauchope Subgroup dolerite and gabbro of the Palaeoproterozoic Hatches Creek Group.

**Cobalt**

The distribution of cobalt is closely associated with nickel in both oxidised and primary zones. There is usually a degree of substitution between these two elements. Cobalt is relatively mobile under most weathering conditions and is a good indicator of a range of mineral deposits, even those in which it is only a minor constituent. It is readily scavenged by manganese.

Four anomalies of >30 ppm Co (ca 5 times background) were located. The strongest anomaly of 41.5 ppm Co was detected at the junction of the Flying Fox Creek and the Jalboi River (URAPUNGA). Cobalt enrichment at this locality is likely to be associated with the hydrothermally enriched portion of extensive iron deposits hosted by Roper Group sedimentary rocks of the McArthur Basin.

**Chromium**

Chromium is a siderophile element. It is present in most rocks and is particularly common in ultrabasic rocks. The only commercial mineral – chromite – is practically insoluble except under low pH, high Eh conditions. As a result, it commonly occurs as a mechanical concentrate in the heavy mineral fraction. Chromium also occurs in limonite, mica and garnet, and can also be substituted for other elements in pyroxene and magnetite in mafic rocks.

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1 Names of 1:250 000 mapsheets are shown in large capital letters, eg KATHERINE.
Figure 3. Example of geochemical map showing antimony (Sb) anomalies.
Two samples registered values >200 ppm Cr (ca 6 times background). The strongest anomaly of 247.9 ppm Cr was recorded in the catchment of the Reynolds River (PINE CREEK), which drains Palaeoproterozoic units of the Pine Creek Orogen, including the Burrell Creek Formation and Wangi Basics, the Mesoproterozoic Tolmer Group of the Birrindudu Basin, and Cambrian sedimentary rocks of the Daly Basin. The most likely sources of the chromium anomaly are small outcrops of Wangi Basics.

The second strongest anomaly (201.4 ppm Cr) was recorded in the catchment of the West Alligator river (ALLIGATOR RIVER), which drains several Palaeoproterozoic units of the Namoona, Mount Partridge, South Alligator and Finniss River groups of the Pine Creek Orogen. The source of the chromium anomaly in this catchment is unclear. It may be sourced from concealed dykes of the Zamu Dolerite.

Tungsten

Tungsten is widely dispersed in most rocks. It occurs as many primary and secondary minerals, but the most common are scheelite and wolframite, which are transported as detrital minerals. Anomalously high tungsten is normally an excellent indicator of its deposits.

Weak tungsten anomalies are widespread throughout the Northern Territory. The strongest anomaly of 12.2 ppm W (ca 12 times background) was located in HENBURY, in the catchment of Quandong Creek, which drains several detrital and carbonate Neoproterozoic and Palaeozoic rock units of the Amadeus Basin. The existence of such a strong tungsten anomaly is enigmatic, as there appears to be no obvious source rocks in this area.

Antimony (Sb)

Antimony is widely distributed in many geological environments. Boyle (1974) distinguished 13 types and 10 sub-types of Sb mineralisation. The element is not confined to any particular metallogenic province or epoch.

Certain gold deposits in greywacke-slate-graphitic schist assemblages (similar to gold deposits in the Pine Creek Orogen) are often enriched in antimony. Antimony is also enriched in most of the lead-zinc-silver deposits. Most of the large economic stibnite deposits worldwide occur in Phanerozoic sedimentary terranes containing phyllite, limestone and black shale (Boyle 1974).

The strongest anomalies (>3 ppm; 3 times background, Figure 3) occur in four catchments: (i) Sturt Creek catchment (BIRRINDUDU/LIMBUNYA), which drains the early Cambrian Antrim Plateau Volcanics of the Kalkarindji Province; (ii) an unnamed internally drained creek (TENNANT CREEK), which drains the Cambrian Montejinni Limestone, as well as several Palaeoproterozoic units; (iii) Boree Creek catchment (BRUNETTE DOWNS), which drains Cambrian limestone of the Anthony Lagoon Formation (Georgina Basin) and Cenozoic Brunette Limestone; (iv) an interdunal soak in LAKE MACKAY (Arunta Region).

Uranium

Uranium is widely distributed in sedimentary, igneous and metamorphic rocks. It is particularly enriched in more acidic igneous and metamorphic rocks, in carbonaceous shale and in phosphorite. It is very mobile in supergene environments with high pH and Eh. It is also readily adsorbed by organic matter, clays, and various oxides and hydroxides. On the other hand, considerable amounts of uranium are also locked in resistive minerals such as monazite, zircon and xenotime.

A number of strong uranium anomalies (>10 times background) were located in catchment samples from the eastern part of the Aileron Province of the Arunta Region.

The strongest anomaly of 31.2 ppm U was detected in a sample collected from a minor internally drained creek in HIGHLAND ROCKS. Another sample taken from an adjacent internally drained catchment in LAKE MACKAY returned the second-highest value of 30.23 ppm U. The likely source of uranium anomalies in the above two catchments are Palaeoproterozoic granites of the Carrington Suite, Rapide Granite and unnamed granites (Eg) dated at 1810–1770 Ma.

Most of the remaining anomalies of >10 ppm U are located in catchments draining the Arunta Region, eastern part of the Pine Creek Orogen (Nimbuwah Province) and Arnhem Province.

Cerium (Ce)

Cerium, along with other REE, is widely distributed in all types of igneous, sedimentary and metamorphic rocks. However, economic concentrations are limited to pegmatites, skarns, quartz-pebble conglomerates, carbonatites and placer deposits. This element was used as a proxy for determining the concentrations of light REE.

As many as 40 catchments returned cerium concentration of >100 ppm (ca 3 times background). The majority of the enriched catchments drain the Arunta Region. The highest concentration of 422 ppm Ce was recorded in a sample taken from Illogwa Creek (HALE HILLS) also returned a cerium anomaly >100 ppm.

Dysprosium

Dysprosium is one of the heavy REE and occurs in several minerals including xenotime, monazite, fergusonite, gadolinite, euxenite, polycrase, blomstrandine and bastnäsite.

The strongest anomaly of 20.8 ppm Dy (ca 4 times background) was detected in the catchment of the Giddy River (GOVE), which drains Palaeoproterozoic granitic rocks of the Arnhem Province (Mirarrmina Complex), as well as detrital Cretaceous sedimentary rocks of the Walker River and Yirrkala formations. Dysprosium enrichment...
probably developed in alluvial sediments, derived from weathering of the Mirarrmina Complex.

Nineteen other catchments contain Dy values >10 ppm (ca 2 times background), with the majority draining the Arunta Region and Pine Creek Orogen.

An interesting enrichment of dysprosium was detected in two adjacent catchments of the McArthur River (BAUHINIA DOWNS) and Wearyan River (ROBINSON RIVER). Both catchments drain the Karns Dolomite, sandstone of the Roper Group and the Palaeozoic Bukalara Sandstone. The source of dysprosium enrichment is unknown. One possibility is heavy mineral concentrations in sandstone. However, it is worth noting that these two catchments lie in the vicinity of two major crustal structures – the Calvert and Emu faults, and are also located in the vicinity of the Merlin kimerlites and Copperado breccia pipes (which have increased phosphorus and REE contents and may have carbonatitic affinities). Hence, it is possible that the source of the dysprosium anomalism could be an undetected carbonatite.

**Yttrium**

Most commonly, yttrium concentrations occur in pegmatites, skarns, rare-earth carbonate veins associated with carbonatites, and placer deposits. The three most important minerals containing yttrium are bastnäsite, monazite and xenotime.

The strongest anomaly of 166.6 ppm Y (ca 5 times background) was detected in the catchment of the previously described (Dy anomaly) Giddy River (GOVE). However, of particular interest is the catchment of the McArthur River (BAUHINIA DOWNS), which was also anomalous in Dy. The source of yttrium enrichment is unknown (see comments related to dysprosium enrichment in McArthur and Wearyan rivers above).

**Indium**

Indium is a highly volatile chalcophile element, primarily found in ores of zinc, copper and tin. The major hosts of indium mineralisation relevant to the NT include vein stockwork tin and tungsten deposits, skarns and polymetallic vein-type mineralisation (Schwartz-Schampera and Herzig 2002).

The strongest anomaly of 0.11 ppm In (ca 4 times background) was detected in the catchment of the Giddy River (GOVE), which is also enriched in Dy and Y, as described above.

**Gold**

Gold is only mobile mechanically as a detrital mineral. In general, gold anomalism did not reflect known gold provinces such as Pine Creek Orogen, Tanami Province and Tennant Creek Province. This is most likely due to the fact that the sampling points were located in drainage overbanks that are covered with water only during periods of flooding, and detrital gold, as one of the heaviest metals, would not be expected to be present in a fine-grained suspended flood sediments.

**Thallium**

Thallium is a rare metal that may occur as a slight enrichment in some potassic feldspars in pegmatites, and in galena, in a number of sulfides, in a range of sulfosalts in various polymetallic deposits, and in potassium salts. An important feature of thallium is that it is enriched in the sericite of the wall-rock alteration zones of various deposits, especially gold-quartz veins and lodes. Hence, it can be used as a proxy for orogenic gold.

Two of the strongest anomalies of 0.47 ppm Tl (ca 4 times background) occur in NAPPERBY, in the catchment of Napery Creek and in an adjacent internally drained catchment. Both catchments drain an area covered by small outcrops (or subcrops) of unnamed and undated granite marked on the map as Pg. No known gold mineralisation occurs in these catchments.

Anomalous levels of 0.41 ppm Tl were located in two adjacent and internally drained catchments in TANAMI and TANAMI EAST. Both catchments are located within areas covered by Palaeoproterozoic metasedimentary rocks (outcropping or under shallow cover) of the Tanami Group, which contains economic gold mineralisation.

A similar anomaly of 0.41 ppm Tl was located in CAPE SCOTT in the catchment of Door and Hermit creeks. This catchment drains S-type granites of the Litchfield Province, as well as the Burrell Creek Formation, which hosts quartz vein-style gold mineralisation (eg Fletchers Gully and Bubbles prospect).

Thallium did not form strong anomalies in the Tennant Creek gold province, which is consistent with the fact that Tennant Creek-style deposits are not auriferous quartz veins and lodes.

**References**


Roper Bar iron mineralisation

Andrew P Bennett

Overview

The Roper Bar iron ore project is located in the ‘Gulf Country’ of the Northern Territory, only 50 km inland from the Gulf of Carpentaria (Figure 1). The project comprises eight exploration licences covering an area of 1919 km². Western Desert Resources Ltd (WDR) has identified total Indicated and Inferred Mineral Resources to date of 321 Mt at 40% Fe, including a direct shipping ore component of 20.2 Mt at 58.6% Fe. WDR is contemplating a two-stage operation commencing in 2013; firstly, direct shipping ore will be exported via a truck and barging operation, and secondly, lower-grade ore will be processed and transported via a slurry pipeline.

Mineralisation

Mineralisation occurs as haematite in oolite within the Sherwin Iron Formation of the Maiwok Subgroup in the Mesoproterozoic Roper Group of the McArthur Basin. Analysis of the stratigraphy and palaeodepositional environments indicates that the Sherwin Iron Formation oolite was deposited during a marine transgression. The most plausible source for the oolitic iron is that it was contained within the sea water, having originated from subsea volcanism or hydrothermal discharges, and was precipitated as a result of changes in pH conditions.

Thin sections have shown that siderite and rarer chamosite ooids occur at depth, with varied oxidation to pulverulent haematite near surface. The ooids show an internal zonation that includes micro-platy haematite alternating with pulverulent red haematite or silica. The matrix is composed of varied silica, haematite or goethite. There is no textural evidence for a hydrothermal origin of the haematite matrix.

The presence of high-grade ores in some areas of the deposit may be linked to the presence of micro-platy haematite. It has been suggested, based on data from the Hamersley Iron Province, that the most important factor in microplaty haematite growth may be elevated temperature and pressure resulting from low-grade regional metamorphism during the early stages of diagenesis, which induces haematite growth in goethite and creates microvoids within which the microplaty haematite nucleates (Morris 2012). It is postulated that this is the mechanism by which DSO mineralisation at Area F was formed, the critical factor being regional metamorphism in proximity to the regional Hells Gate Hingeline.

Reference

The following results have emerged from the 18-month JSU (Joint Survey Uranium) Ngalia Basin Uranium Mineral System Project, which is a collaboration between CSIRO MDU (Minerals Down Under), NTGS, Thundelarra Exploration Ltd, Energy Metals Ltd and Cauldron Energy Ltd. The project aim was broadly to build upon existing knowledge of uranium mineralisation in the Ngalia Basin and contribute to: (1) the understanding of uranium fluid pathways and mechanisms of mineralisation at deposit scale; and (2) the understanding of the basin architecture.

Ngalia Basin overview

The Ngalia Basin covers an area of 16 000 km² between latitudes 22°00’ to 23°00’S and longitudes 129°00’ to 133°45’E in the southern part of the Northern Territory, Australia. Knowledge of the basin architecture and sedimentological record is derived mainly from studies and mineral exploration between 1970 and 1983. Geophysical data were acquired up to the mid-1990s, mainly for hydrocarbon exploration. The Ngalia Basin sedimentary succession is up to 6 km deep. There are only 3 deep drillholes (New Haven-1, Davis-1 and Dav-1) that penetrate a kilometre or more in the basin. Outcrops are generally confined to a narrow ribbon of sparse, mostly west-trending ridges at the edges of the basin. These peripheral more resistant exposures are separated by wide sand plains that obscure the basin sediments (Wells and Moss 1983). The Ngalia Basin was initiated at about 850 Ma, with the deposition of the Vaughan Springs Quartzite. Overlying units of Cambrian to Carboniferous age are discontinuous and separated by unconformities, dividing the sedimentary succession into six distinct groups. Uplift and erosion of Arunta Region rocks underlying and bordering the Ngalia Basin marked the deposition of the Mount Eclipse Sandstone during the Alice Springs Orogeny. The Mount Eclipse Sandstone is the youngest preserved unit in the basin (apart from Cenozoic deposits) and consists dominantly of medium- to coarse-grained arkosic sandstone. Uranium exploration by Central Pacific Minerals NL commenced in the Ngalia Basin in the 1970s and resulted in the discovery of the Bigrlyi, Walbiri and Minerva deposits in the Mount Eclipse Sandstone.

Gravity and magnetics

Magnetic data over the basin provide an incomplete image of the basement topography because of the sparse magnetic signal from weakly to moderately magnetised basement rocks beneath the northern part of the basin. Existing seismic data provide uncertain and sparse imaging of the basement surface and there are only two wells providing basement intersections. The Ngalia Basin basement container model has therefore been developed primarily from the interpretation of gravity data, constrained where possible by geological mapping, magnetic field interpretations, and seismic and borehole information. Gravity variation across the Ngalia Basin is dominated by density contrasts between different basement units, with gravity variation due to
the density contrast across the basement/basin interface producing only a minor contribution to the measured gravity variation. These models now clearly demonstrate that the present Ngalia Basin overlies what were originally much smaller separated graben and half graben structures that were later concealed beneath much broader sedimentary deposits of the main basin (Figure 1).

3D architecture

A 3D model of the basin, derived from seismic interpretation and drillhole data, indicates that it has a very complex architecture. The main features are:

• A central high area cut by numerous east–west-oriented reverse faults. Many of these faults only affect the higher layers in the succession such as the base Mount Eclipse Sandstone, but not the base of the Vaughan Springs Quartzite).

• A western basin, which initially had two main depocentres, one related to the Yuendumu Fault and the other related to the Mount Doreen Faults (Figure 2). The Mount Doreen Faults appear to have been inactive during the deposition of the Mount Eclipse Sandstone. Overall, the western section of the basin forms a wedge shape that thickens considerably towards the north and is deepest around the junction of the Yuendumu and Waite Creek thrusts.

• An eastern basin dominated by a very distinct E–W structural trend. This includes the Bloodwood Trough and shallower troughs that lie along its northern and southern flanks.

Very large faults tend to be parallel to the margins of the basin and its sub-basins, whereas smaller faults appear to control the internal structure of the basin. The larger faults may be reactivated basement structures. The faults may have a complex history including early-stage normal faulting during extensional deformation, followed by reactivation as reverse faults during compression.

Outcrop observations: Bigrlyi

Coarse-grained vertically dipping sandstone is exposed as ridges, whereas mudstone is commonly eroded and forms depressions. Faults or fractures in sandstone are narrow and show local displacement of sedimentary rocks and mineralisation. Therefore, localised faulting occurred after mineralisation of the sandstone. Small-scale fining-upward successions occur laterally and stratigraphically beyond the mineralised interval. Sedimentary rocks below the mineralised zone tend to have a higher abundance of gravel and cobble-size rounded clasts at the bases of fluviatile channels. Carbonate-cemented sandstone intervals are distributed heterogeneously throughout the Mount Eclipse Sandstone. Faults within basement granite trend parallel to the basin margin and are highly mylonitic.

Depositional environment

The fluvial channel and floodplain deposits of the Mount Eclipse Sandstone in the northern Ngalia Basin suggest that deposition occurred in a high-relief continental basin characterised by episodic rainfall and drying cycles. The majority of the fluvial deposits were accumulated in the distal parts of alluvial fans in a semi-arid environment. The common occurrence of groundwater calcrite suggests that evaporation greatly exceeded precipitation. Episodic tectonic activity during the Alice Springs Orogeny led to thick, immature, stacked fluviatile channel deposits intercalated with floodplain-playa deposits during times of stagnation.

Mineralogy

Petrographic studies show that the immature sandstone was mainly derived from a granitic source and was carbonate cemented at an early stage. Uranium mineralisation occurred very early during sedimentation, prior to calcite cementation. Uranium is only present in samples that contain vanadium minerals (at Bigrlyi). Vanadium Xis mainly found in detrital degraded roscoelite (Figure 3a, b) and in Fe- and FeTi-oxides.

Oxidising conditions released vanadium out of the roscoelite and precipitated it as montroseite prior to and/or with the onset of calcite precipitation. Primary porosity is zero, due to compaction. However, K-feldspar dissolution and kaolinite precipitation has created a secondary porosity. Some of the uranium, preserved in strongly calcite-cemented zones, is potentially detrital in origin, and has been subsequently remobilised.
Isotopes

Stable isotope data indicate a groundwater source for calcite formed at the same time the Mount Eclipse Sandstone was deposited. Strontium isotopes show that strontium leaching was limited due to short residence time, and this element retains a granitic signature. There is no evidence for exotic fluids within the mineralised zone.

Geochemistry

The mainly sub-arkosic sandstone of the Mount Eclipse Sandstone has been derived from volcanic arc granite. Vanadium and uranium are closely associated, although vanadium extends beyond the uranium mineralised zone. Elements such as Ba, Li, W, Se and Be are elevated within the mineralised zones, whereas S is depleted. There is no indication of organic material in the samples. Heavy minerals above a density of 10 are more prominent in the mineralised zone. Heavy minerals, including barium, lithium, tungsten and vanadium, are commonly found in hydrothermal deposits within granite. Therefore, it is proposed that the mineralising fluids at Bigrlyi originated from the weathering of hydrothermally altered granite.

REE patterns observed in samples of the Mount Eclipse Sandstone confirm a source rock dominated by granites with an emplacement age of 1770–1780 Ma. The main source rock is interpreted to be the Carrington Granitic Suite to the north of the basin.

Hyperspectral data

No uranium has been detected when well ordered kaolinite is the only dominant mineral. Any kaolinite present in a mineralised zone is poorly ordered. The 2245 nm mica/clay (Mg-Fe degraded chloritic roscoelite) is always present in mineralised samples and was found to be on the interface between phengitic mica and kaolinite within the mica. The 1550 nm scalar (coffinite) only occurs in highly mineralised samples (more than 300 ppm U). Carbonate minerals commonly occur within phengitic mica intervals and on the interface between kaolinite and muscovite group mica. Zones that are dominated by carbonate minerals usually lack kaolinite. Carbonate minerals are marginal to, or within highly mineralised zones. Iron-oxide minerals occur mainly within muscovite group mica intervals and are generally absent in kaolinite-rich intervals. The hyperspectral data from the Bigrlyi deposit confirms that mineralisation was related to groundwater processes during deposition.

Interpreted mineralisation model

Uranium mineralisation occurred in fluvial sandstone with abundant iron-rich detrital clasts (roscoelite, heavy minerals and biotite), prior to carbonate cementation and compaction. Vanadium originated from vanadium-bearing detrital mica (roscoelite) that was transported as clasts and in suspension into the Bigrlyi channels. Oxidising conditions released vanadium from mica and precipitated it as montroseite prior to and/or during the onset of calcite precipitation. Compaction and the effects of the Alice Springs Orogeny reduced porosity and permeability to low or zero and caused soft clasts, such as roscoelite, to deform and alter to smectitic/illitic/chloritic roscoelite, and re-mobilised vanadium and uranium towards the grain contacts. Uranium re-precipitated along adjacent quartz grains and caused them to etch. Radiation damage in detrital quartz and K-feldspar possibly started with the initial mineralising event.

All evidence (geochemical trace elements, petrographic observations and SEM work) indicates that the uranium and vanadium are diagenetically related to a hydrothermal source within granite. Weathering and transport in meteoric/groundwater lead to the deposition of vanadium-rich micas and uranium.

First-stage uranium mineralisation (not secondary remobilisation) is most likely to have occurred in the lower slope and distal parts of an alluvial fan system where it is intercalated with floodplain deposits and flow rates are slow. Dispersion into overlying units or other parts of the depositional system may have occurred during secondary re-mobilisation (eg, Cenozoic uranium deposits).
Using HyLogger as a tool to determine mineralogical differences in drill core across the Ngalia Basin.

Belinda Smith

Introduction

As part of its participation in a collaborative infrastructure research project in the development of the National Virtual Core Library (NVCL), NTGS is selectively scanning drill core from its Darwin and Alice Springs Core Facilities. The NVCL's primary goal is to progressively build an Australia-wide drill core database comprising high-resolution imagery and mineralogical data from spectroscopic scanning. The HyLogger is a tool that improves the efficiency, productivity and objectivity of logging by using reflectance spectroscopy to log the mineralogy of drill cores and chips. Reflectance spectroscopy can identify various minerals common to many geological units and hydrothermal alteration assemblages. During 2011, the NTGS HyLogger was upgraded to include a Thermal Infra-Red (TIR) spectrometer capable of detecting reflectance spectra in the 6000–14000 nm range. This wavelength range can detect quartz, feldspar, olivine, pyroxene and garnet, and adds to the depth of information from each drillhole, particularly those drillholes that have little hydrous mineralogy (such as fresh igneous rocks).

In the past year, the HyLogger scanned 77 holes for 16,376 m (between February 2011 and January 2012), of which there are now 68 TSG datasets available upon request. Initial web-hosting of TSG data as part of the NVCL commenced during 2011, through the AuScope portal (http://portal.auscope.org/portal/gmap.html), which hosts TSG datasets from drillholes across Australia. During 2011, NTGS prioritised the scanning of drill core through the HyLogger as follows:

a. Ngalia Basin drill core, as part of a regional mineral system analysis (building upon the JSU Ngalia Basin Uranium Mineral System Project study completed in 2011).

b. Type examples of rocks from Tennant Creek, in order to build a Tennant Creek Spectral Library to assist explorers in understanding the range of rock types from different Tennant Creek deposits.

c. Petroleum drillholes from the Beetaloo Sub-basin of the McArthur Basin (requested by industry).

d. Drill core acquired through the NTGS Bringing Forward Discovery Geophysics and Drilling Collaboration program.

Most of these scans also have TIR spectra. The major focus of 2011 has been on the scanning and interpretation of results from Ngalia Basin drill core, with work still in progress.

Ngalia Basin regional scanning

The Joint Surveys Ngalia Basin Uranium Mineral System Project is a collaboration between CSIRO, industry and NTGS that aims to integrate geophysical, geochemical, geological, isotopic and hyperspectral data acquisition and interpretation as a contribution to the understanding of the uranium fluid pathways and basin architecture (Schmid et al. 2011). This study presented results from the hyperspectral characterisation of the Bigrlyi deposit (collected from the HyChips™ 6-4 system) that showed some distinct spectral responses correlating with known uranium/vanadium mineralisation. Key hyperspectral findings from Bigrlyi were presented in Schmid et al (2011) and include the following:

a. 1550 nm feature only occurs in highly mineralised samples.

b. 2245 nm feature (from mica/clay) is always present in mineralised samples.

c. Carbonate is found marginal to, or within mineralised zones.

d. No uranium has been found where kaolinite is the only dominant mineral. Any kaolinite present within a mineralised zone is poorly ordered (poorly crystalline).

Although the study also collected hyperspectral mineralogy data from other prospects in the Ngalia Basin (9 drill core holes and 5 RC chip holes), these datasets were not incorporated into the study findings. The hyperspectral data results only relate to holes from the Bigrlyi deposit.

The NTGS Ngalia Basin Regional Scanning project is adding to the framework of this original study by collecting and comparing mineralogical characteristics from drill core across the Ngalia Basin. This work aims to assess the mineralogy and increase the understanding of uranium mineralisation mechanisms in the Ngalia Basin by:

a. comparing the mineralogy and spectral signatures from regional uranium prospects to those of the Bigrlyi U-V deposit

b. characterising the mineralogy from regional uranium-bearing holes for comparison with non-mineralised holes in the same area

c. determining whether mineralogical differences reflect changes in depositional environment across the basin

d. determining the silicate content in the sedimentary rocks, particularly noting proportions of quartz in sandstone with that of feldspar, white mica and kaolinite. Note that TIR spectral data (giving information on silicate mineralogy) was unavailable for the JSU Ngalia Basin study.

The NTGS Core Facility holds drill core collected from historic uranium exploration across the Ngalia Basin. This drill core consists of regional reconnaissance drillholes, as well as drillholes in and around identified uranium prospects, such as Camel Flat, Dingos Rest, Walbiri and Minerva. Most of the drilling was carried out in the 1970s by a number of companies and most of the reported findings from those...
drillholes focused on prospect-scale features. The style of historic geological logging varied between exploration companies, resulting in no consistent method of compiling and comparing the geology and mineralisation between the various prospects. Using the HyLogger to acquire spectral datasets and high-resolution imagery allows for an objective approach to analysing these drillholes. The NTGS Ngalia Basin Regional Scanning project has scanned 51 holes for 6304 m through the HyLogger and is also incorporating 10 holes for 1347 m that were scanned by the HyChips machine. Figure 1 shows the location of the scanned drillholes plus some of the key prospects that are part of this study.

The focus of this work is the acquisition of spectral and imagery data from the scanning of drill core through the HyLogger. It does not include the relogging or re-assaying of the drill core. Ngalia Basin drill cores that are short or have incomplete intervals were not scanned. Some of the scanned drill core has small incomplete sections (eg, highly radioactive intervals may be missing), which may affect interpretations.

This study is still in progress, but initial findings include:

a. There are distinct spectral responses (at 1137 nm / 1500 nm / 1550 nm) that correlate with known intervals of uranium mineralisation at Biglyi, Minerva, Walbiri and Camel Flat.

b. The 2245 nm response, identified in the JSU Ngalia Basin Uranium Mineral System Project study as being characteristic of a vanadiferous mica (Schmid et al 2011) that is always present in the mineralised zone, has also been noted at Dingos Rest (DRDP4). However, this response is only occasionally and inconsistently associated with zones of mineralisation at Camel Flat, and at Minerva, the 2245 nm response is not exclusively associated with mineralisation and can occur throughout the drillhole.

c. Carbonate minerals were absent from scanned drillholes at the Walbiri prospect. Calcite is associated with mineralisation at Biglyi, suggesting that Walbiri uranium mineralisation is not a 'Biglyi lookalike'.

d. Dingos Rest drillholes (n = 4) appear to contain a significantly higher proportion of carbonate minerals than other prospects (excluding Biglyi) in the Ngalia Basin.

e. Imagery indicates that the Mount Eclipse Sandstone at Minerva may be of a coarser grain size than that noted at other prospects. There are also (non-mineralised) zones of conglomerate containing rounded chlorite-rich clasts. This may indicate a local variation in the depositional environment and provenance for the formation.

f. The proportion of feldspar in sandstone is variable, with variations noted between prospects (eg, between Walbiri and Minerva).

This project is providing the first consistent dataset across all known uranium deposits in the Ngalia Basin and is highlighting the potential variation in mineralisation styles between the various deposits. Work is still in progress, with initial findings subject to further validation, plus there are another 20 holes (mainly regional holes) that are yet to be processed. It is envisaged that the mineralogical data will be appended to the Leapfrog 3D model created in the JSU study, and TSG datasets from the Ngalia Basin will also be available via the AuScope Portal.

Acknowledgments

The NVCL Database Project is a collaborative research project that is being administered by AuScope. NCRIS (National Collaborative Research Infrastructure Strategy) has funded and supported the NVCL Project with co-investment by the Northern Territory Government for the NTGS Node. CSIRO built the HyLogger instrument and provides ongoing technical assistance. Darren Bowbridge’s attention to detail has ensured the highest quality spectral and imagery data from the NTGS HyLogger. The contributions and ongoing suggestions from Susanne Schmid, Melissa Quigley and the CSIRO JSU group are greatly valued. Jon Huntington (HyLogging Specialist) is thanked for his ongoing help, training and mentoring in all things related to the HyLogging world. Dot Close’s guidance has helped, when the way forward has not been linear.

Reference


Figure 1. Location of scanned drillholes and key prospects discussed in this study.
Identifying first-order controls on the metallogenic potential of the Amadeus Basin

Christine Edgoose

Introduction

The Amadeus Basin is a large (ca 170 000 km²) elongate intracratonic basin that extends for approximately 800 km east–west and a maximum of about 300 km north–south in central Australia (Figure 1). It overlies Palaeo–Mesoproterozoic basement of the Musgrave Province to the south and Arunta Region to the north, and is overlain by the late Palaeozoic Pedirka Basin and Mesozoic Eromanga Basin in the southeast, and by the Palaeozoic stratigraphy of the Canning Basin to the west. The Amadeus Basin has a depositional history spanning the Neoproterozoic to the Devonian/Carboniferous. It was initiated as part of the Neoproterozoic Centralian Superbasin, which formed in an intracratonic setting related to the breakup of Rodinia. Sedimentation in the superbasin continued with the assembly of Gondwana, which resulted in the fragmentation of the superbasin into separate intracratonic basins, including the Amadeus Basin.

The present-day Amadeus Basin is a structural remnant of a more extensive basin, and has been significantly tectonically modified during two major intracratonic orogenic events: the 580–540 Ma Petermann Orogeny and the 450–300 Ma Alice Springs Orogeny. The Petermann Orogeny was focused in the Musgrave Province and also substantially affected the southern part of the Amadeus Basin. It significantly transformed the basin architecture, with the development of major basin features that controlled subsequent sedimentation. Depositional loci subsequently shifted to the northern part of the basin, where Palaeozoic successions are largely concentrated in sub-basins and troughs and up to 14 km of sedimentary rocks are preserved. Several minor events or uplifts punctuated the Palaeozoic depositional history and account for local disconformities and absent sections. The Alice Springs Orogeny was a multi-phase, intracratonic event concentrated in the Arunta

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Figure 1. Generalised geology and major structures of Amadeus Basin, Northern Territory.
Region and the northern part of the Amadeus Basin. Like the earlier Petermann Orogeny, the Alice Springs Orogeny involved substantial structural interleaving of basin sedimentary rocks with the basement. Synorogenic sedimentation accompanied Mid to Late Devonian uplift, whereas Late Devonian to Carboniferous basin inversion terminated sedimentation, and resulted in folding of the youngest successions.

**Stratigraphic record**

The stratigraphic succession of the Amadeus Basin is shown in **Figure 2**. Neoproterozoic deposition began with fluvial to shallow marine clastic rocks and an overlying dominantly calcareous and fine clastic sequence, representing the initial sag phase (Supersequence 1 of Walter *et al.* 1995). This is overlain by sedimentary rocks related to both the Sturtian and Elatian Neoproterozoic glaciations, as well as varied glacio-fluvial, fluvial and shallow marine successions (Supersequences 2 and 3 of Walter *et al.* 1995). Sediment supply and depositional patterns during the very latest Neoproterozoic to early Cambrian were strongly influenced by exhumation of the Musgrave Province to the south during the Petermann Orogeny (Supersequence 4 of Walter *et al.* 1995). During the early–mid Palaeozoic (Stage 2 of Lindsay and Korsch 1991), Australia was located at low palaeo-latitudes, and at times of high sea level, transcontinental seaways may have existed (Walley *et al.* 1991, Lindsay 1993). During the Cambrian, the seaway axis lay across the Arunta Region to the north of the Amadeus Basin. Most palaeogeographic reconstructions of Ordovician Australia (eg Nicoll *et al.* 1988, Walley *et al.* 1991) show an open east–west seaway (Larapintine Seaway) across the continent that connected the Amadeus and Canning basins, although the evidence for this is poor and if the seaway existed, it is likely to have been either brief or very restricted (Haines and Wingate 2007). The Ordovician was a period of widespread deposition across Australia, with deeper water continental margin systems established in eastern Australia, and shallow marine to paralic conditions prevailing in several inland and northern basins. A thick succession accumulated in the Amadeus and Canning basins at this time. Marine sedimentation in the basin ceased at the end of the Ordovician in response to broad, regional uplift and from then until the Early Devonian, only limited deposition occurred in the basin, largely in aeolian and lesser fluvial systems. The Silurian was largely a period of hinterland erosion, followed by fluvio-lacustrine to paralic conditions in parts of the basin in the late Early Devonian. The middle to latest Devonian is characterised by an upward-coarsening fluviatile system, deposited in response to uplift related to the Alice Springs Orogeny, and sedimentation was terminated in the Late Devonian/Early Carboniferous as a result of final orogenic processes and basin inversion. Permian glaciation in the area suggests that highlands persisted until this time, and that the area was at relatively high palaeo-latitudes.

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**Figure 2.** Stratigraphy of Amadeus Basin (modified from Marshall *et al.* 2007, Haines *et al.* 2010). Supersequence scheme of Walter *et al.* (1995) is shown on right.
Mineral exploration and metallogenic potential

The Amadeus Basin has had comparatively little exploration for mineral commodities, with much of the western half of the basin having received no modern exploration. Mineral production in the Amadeus Basin is confined to gold extraction from the Arltunga and Winnecke goldfields (Supersequence 1), and very minor surficial copper workings. Mineral commodities present in the basin include gold, uranium, base metals, phosphate and manganese. The Amadeus Basin is highly prospective for both oil and gas, with five petroleum systems recognised, and are two production oil/gas fields. The potential for unconventional gas and oil is also substantial, particularly associated with organic-rich shale units (Tiem et al 2011).

Exploration that has occurred in the Amadeus Basin to date has largely consisted of sampling and shallow drilling of surface mineralisation to test the lateral and vertical extents of these occurrences. Very little exploration has been conceptual or model-derived, or based on assessments of potential metallogenic sources, sedimentary facies, fluid pathways and structure. At a basin-wide scale, a consideration of some of these first-order controls on mineral systems that may have operated in the basin assists with a first-pass assessment of the mineral potential. Some of the controls to consider include sediment sources and prospective lithostratigraphic successions, basement and basin interaction, and intra-basinal magmatism.

Sediment provenance

Information on sediment source areas provides information about basin architecture and the hinterland events that have influenced basin history. Provenance data can also be used to flag significant changes in sediment source areas, as well as give an indication of how much sediment has been recycled within the basin as opposed to being sourced from basement. These data can assist in determining basin metallogenic potential. Only limited data are available on the source areas for the sediments of the Amadeus Basin and that data has been acquired largely from the northeast of the basin (Maidment et al 2007), with lesser data from the north-central (Zhao et al 1992, Buick et al 2005) and southwestern areas (Camacho et al 2002).

Neoproterozoic to late Cambrian sediments were locally sourced from basement of the Arunta Region and Musgrave Province. Detritus from the Arunta Region (2.5 Ga, 1.9–1.8 Ga), dominates in older rocks, but the signature of the Musgrave Province (1.2–1.0 Ga) increases up-section during the Cambrian, particularly after the 580–540 Ma Petermann Orogeny. In the late Cambrian, a fundamental shift occurred in sediment source areas, when the basin became part of an epicontinental seaway, and significantly younger detritus (0.6–0.5 Ga) with no apparent local source became dominant. This is a similar signature to sediments of the Pacific Gondwana margin, which includes rocks from eastern Australia, New Zealand and Antarctica. The ca 1.1 Ga detritus in these rocks is also considered to have a distal source and was not derived from the Musg rave Province. Significant sediment recycling appears to begin after the onset of the very early stages of the 450–300 Ma Alice Springs Orogeny, where uplift exhumed older sedimentary rocks, but was not sufficient to expose the underlying basement. During the main phases of the Alice Springs Orogeny, there is no detrital data for the resultant sediments, but it is likely that significant intra-basin sediment recycling occurred initially, with later basement input as uplift progressed.

Very little whole-rock or isotope geochemistry data is available to provide further information on sediment source regions for the Amadeus Basin. A limited geochemistry and Nd isotope study of the Neoproterozoic Bitter Springs Formation indicates that it was derived from a relatively homogeneous source with a strong mafic component, interpreted to have been a now eroded, contemporaneous flood basalt province in southern and central Australia, the emplacement of which was possibly related to the breakup of Rodinia (Barovich and Foden 2000). A comprehensive geochemical and isotopic study of the major sedimentary packages of the basin could be very useful in defining potential mineral targets.

Prospective shale host rocks

There has been very little investigation of prospective shale intervals within the Amadeus Basin succession. Many formations contain shale/siltstone intervals, but they are generally poorly exposed and many are known from drill intersections only. Most of the known base metals occurrences are in shale intervals in the Neoproterozoic succession, especially in the northeast of the basin. The Neoproterozoic succession in this area, in particular, has been considerably affected by halotectonics (eg Dyson and Marshall 2007), where the migration of evaporites and brine-rich fluids has led to irregular depositional surfaces, mini basin development and local unconformities during deposition, all potential fluid paths and metal traps. Potential shale host targets that warrant attention include: dark, pyritic shales in the Aralka Formation, known from petroleum well intersections (eg Wallara-1); significant shale intervals that occur in the upper part of the Bitter Springs Formation; alternating reduced/oxidised shale in the Hugh River Shale and Deception Formation, which may indicate prospectivity as a Kupferschiefer-style copper target; and shale in the Pertatataka Formation, particularly close to the facies change to carbonate rocks in the overlying Julie Formation. Visible chalcopyrite occurs in dark shales intersected in the lower Pertatataka Formation in NTGS drillhole BR05DDH1, in the southwest of the basin. Useful information can be acquired from source rock petroleum studies, including TOC and other relevant data (for example Marshall 2004). For instance, the Aralka Formation has a TOC of 1%, and the Horn Valley Siltstone has intervals with TOC in excess of 6% (Burgess et al 2002), and as such could be a significant host if it interacted with mineralising fluids.
Basement/basin interaction

An understanding of the composition and structure of the basement to the basin is important in determining the nature and timing of any mineral systems sourced from basement rocks that may have interacted with the basin sedimentary succession.

Although many workers have recognised that the tectono-stratigraphic record has largely resulted from forces at plate margins well outside the region (eg Shaw 1991, Lindsay 2002), basement structures also appear to have placed long-term and repeated controls on subsidence patterns (eg Redbank Thrust Zone; Shaw 1991). The present-day basement topography has been interpreted to be a consequence of the reactivation of pre-existing Palaeo- and Mesoproterozoic basement fabrics (Munroe et al 2004), and reactivation of these basement structures beneath the Amadeus Basin, during both the Petermann and Alice Springs orogenies, has had a strong influence on the shape of the basin and the location of basement highs. Shaw (1991) describes at least nine tectono-stratigraphic intervals of basin history which strongly influenced basin shape and evolution, and Munroe et al (2004) identified eleven key basement terranes (phases) which they considered to have provided this first-order control on the evolution of the basin.

Although most of the major structures show similar trends in both the basement and the basin, a few workers (eg Wellman 1991, Marshall and Dyson 2007) have noted some disconnect between the orientation and timing of movement on pre-existing basement structures with the orientation and timing of movement on some structures in the overlying basin sedimentary rocks, which has implications for the timing and distribution of basement-generated fluid flow through the basin succession.

During the major orogenic events in the basin, a major décollement surface formed within the Bitter Springs Formation. This décollement separated the basal units of the basin, which were deformed together with the underlying basement, and the overlying sedimentary rocks which underwent thin-skinned deformation with a different structural style (eg Flottmann and Hand 2004). It is likely that any mineral systems operating at the time or subsequently, may also have been partitioned in the same way. Many of the major basement-penetrating structures, especially in the northern part of the Basin (Edgoose et al 1993, Marshall and Dyson 2007), sole out in salt intervals within the Bitter Springs Formation. This has implications for identifying the fluid pathways that were available to access higher levels of the succession in these areas.

The nature of the basement beneath the Amadeus Basin remains poorly understood. Near the eastern edge of the basin, magnetic images suggest that Musgrave Province basement may underlie the Amadeus Basin almost to its northern margin. However, this is inconsistent with interpretations of seismic data that suggests that much of the basin is underlain by rocks of the late Palaeoproterozoic Warumpi Province of the Arunta Region (Korsch et al 2010).

Intra-basinal magmatic rocks

Two phases of volcanism are recorded in the Amadeus Basin. In the southwest of the basin, a bimodal rift succession with intercalated sedimentary rocks, known as the Tjauwata Group within the Northern Territory (Close et al 2004), immediately underlies Supersequence 1 of the Amadeus Basin. However, the exact relationship of this rift succession to the initiation of the basin is equivocal, as there may be a time break of up to 200 million years between the Tjauwata Group and Supersequence 1. The rift succession is a supracrustal equivalent of the dominantly mafic ca 1080 Ma Giles Complex, which hosts the Babel and Nebo Ni-Cu-PGE deposits in Western Australia. Voluminous bimodal volcanics of the same age also occur in WA (Tollu Group), and these contain several Cu and Ni occurrences (eg Tollu, Michael Range). A number of Cu occurrences also occur in the basalt and associated sedimentary rocks in the NT, and high Au and Ag values have been obtained from quartz veins intruding the succession. The Tjauwata Group volcanic rocks comprise interlayered basalt and rhyolite, intercalated with quartzose sedimentary rocks. Analogies can be drawn between this rift succession and host rocks of the Zambian Copper System in Africa, including the presence of Neoproterozoic quartzose sedimentary rocks marginal to a rift setting, along with evaporites in the overlying strata.

Poorly exposed spilitic basalt flows occur in the Neoproterozoic Bitter Springs Formation (Supersequence 1). They mostly occur as scattered outcrops in the northeast of the basin (Figure 3), and are known from drillhole intersections in a few other locations. The spilites are tholeiites or flood basalts, and have been interpreted to represent part of a large mantle plume that affected central and southern Australia (Zhao et al 1994, Lindsay 2002; Nowland 2008) at about 820 Ma. Mafic dykes equivalent to the basalts are known to intrude the Pinyinna Beds (Bitter Springs Formation equivalent) in the southwest of the basin, the Musgrave Province (Amata Dolerite) and southern Australia (Gairdner Dykes).

The spilites were originally thought to be confined to the lower part of the upper member of the Bitter Springs Formation, but further investigation has shown they have been variably described from the lower, middle and upper parts of the upper unit, and have also been recorded from within the lower unit. They therefore may be much more extensive and long lived than previously described, and warrant detailed investigation to determine their stratigraphic range, geochemical variation, and base metals prospectivity. Cu is associated with the basalts to the east of Alice Springs (Undoolya Cu prospect). A distinct texture in the magnetics, observed in the south-central part of the basin, is interpreted to represent subsurface spilites in the Bitter Springs Formation (Figure 4). These features appear to be very shallow and have never been investigated.
Mineral endowment

Base metals

Pb Zn
Minor base metals occurrences are generally associated with the Neoproterozoic succession, particularly in the northeastern and central parts of the basin. Investigations into several of the occurrences have not been able to confirm any mineralisation at depth. Best grades occur at Blueys prospect in the northeast, which is hosted in dolostone and dolomitic siltstone of the Bitter Springs Formation, where rock chip sampling returning maximum values of 6.55 kg/t Ag, 18% Cu, 0.8 g/t Au and 27.5% Pb (Fabray 2010). The best drill intersections, although anomalous, were of sub-economic grade, with a best intersection of 1 m at 300 g/t Ag, 4.1% Pb and 0.13%Sb from 11 m.

Cu
Known copper occurrences in the Amadeus Basin are largely confined to Neoproterozoic and Cambrian successions in the northeast and north-central parts of the basin. Copper also occurs in the underlying Tjauwata Group in the Bloods Range area. The most intensive exploration has been in the Waterhouse Range area, and comprised soil, rock, chip and stream sediment sampling, followed-up by shallow drilling. Numerous small occurrences of secondary Cu mineralisation are present in the late Cambrian Goyder Formation, just below the contact with the Pacoota Sandstone where it is exposed on both flanks of an antcline. Drilling has confirmed Cu anomalism below the depth of oxidation. Visible hydrothermal Cu-Pb-Zn mineralisation has been identified within the Goyder Formation (not just at its upper contact) and in the underlying Jay Creek Limestone. Soil samples gave maximum assays of 5000 ppm Cu, 95 ppm Co, 1700 ppm Pb and 860 ppm Zn (McKay 1997). Nine areas with elevated responses for base metals were outlined. Rock chip samples had maximum assays of 11.6% Cu, 6100 ppm Pb, 2500 ppm Zn, 560 ppm Co and 210 ppm U. RAB drilling resulted in a best assay of 1.26% Cu, and a 3 km anomalous zone was identified. A number of factors, including the presence of uranium, indicate that this may be a suitable environment for a Cu-U system. Fluid inclusion studies by NTGS from the Goyder Formation indicate that high-temperature (200–250°C), high salinity (18–19 wt%...
NaCl eq) fluids, prospective for metals, were present in these rocks (A Wygralak, NTGS, unpublished data).
Cu sulfides (chalcopyrite/bornite) were observed in the Petermann Sandstone and basal Pacoota Sandstone in NTGS drillhole LA05DDH1 (Ambrose et al 2010). The sulfides occur in thin bands (cross-bedding) and along sub-vertical fractures, and are also finely disseminated in the host rock.

Gold
The Amadeus Basin has supported historic, and more recent, extraction of gold at White Range and Winnecke, east of Alice Springs. The gold occurs in pyrite in quartz veins within the Heavitree Quartzite, and also in the Bitter Springs Formation at Winnecke, and most likely has been sourced from basement rocks of the adjacent Arunta Region, which host gold in the Arltunga and Winnecke fields. The model for ore genesis of Burlinson and Mackie (1985), suggests that gold was hydrothermally leached from volcanic assemblages in basement rocks by fluids associated with a greenschist-facies retrograde metamorphic event during the Alice Springs Orogeny. It was then deposited in structurally favourable sites associated with regional thrusts and nappes generated during the orogeny.

Uranium
The Amadeus Basin has known reserves of uranium at the Angela-Pamela group of deposits south of Alice Springs, which have been interpreted as roll-front-style sandstone-hosted deposits. The uranium is hosted in Late Devonian clastic sedimentary rocks deposited in a foreland setting during the Alice Springs Orogeny. Mineralisation is associated with upper and lower redox boundaries, within lithic sandstone. Currently the deposit has a JORC-compliant resource of 10.7 Mt at 1310 ppm UO₂, for a total of 13 980 t of UO₂. This makes it the Territory’s largest uranium resource outside the deposit has a JORC-compliant resource of 10.7 Mt at 1310 ppm UO₂, for a total of 13 980 t of UO₂. This makes it the Territory’s largest uranium resource outside the Pine Creek Orogen. The host stratigraphy is very extensive along strike, with significant potential for additional redox traps, and large areas of prospective stratigraphy have not been adequately explored. Stratigraphy of the same age and depositional setting also occurs in the southwest of the basin.

Phosphate
Sedimentary rocks within the Amadeus Basin contain pelletal phosphate rocks in a number of Neoproterozoic to Cambrian-Ordovician units. The most prospective stratigraphic unit is the Ordovician Stairway Sandstone, which records six occurrences that range in grade from 5 to 27% P₂O₅. The phosphate is predominantly pelletal, although nodular phosphate also occurs within a succession of interbedded shale and sandstone with minor carbonate rocks and phosphorite. Phosphate trap settings, such as those that host phosphate in the Georgina Basin, are present, including shallowing waters on basement highs in the southern part of the basin (Cook 1972).

Manganese
The Amadeus Basin has significant potential for sedimentary and hydrothermal manganese mineralisation. Manganese occurs in the Bitter Springs Formation, in a zone several kilometres long, with values that averaged 39% to a maximum of 50.9%. At the Wangatinya prospect in the northwest of the basin, Mn occurs in the Pacoota Sandstone, where nine grab samples averaged 44.3% Mn, with a range of 13.6–55.0%. The lenses and pods are confined to two beds that total about 30 m in thickness and can be traced for 260 m along strike (Ferenczi 2001). Minor occurrences have also been recorded from the Winnall beds in the southwest, where a grab sample assayed 52.54% Mn, 0.8% Fe and 0.068% P (MODAT). In the Jay Creek Limestone in the central part of the basin, sampling of poorly exposed rocks at the Camel prospect by Northern Mining Ltd in 2010 yielded assay results of 45.6% and 28.6% (Jay Creek Limestone).

Summary
The Amadeus Basin has significant known uranium endowment, and numerous occurrences of manganese and phosphate. Base metals mineralisation is known in shale, carbonate rocks and basalt in the early Neoproterozoic succession, and there is significant potential for Zambian-style Cu in association with the Tjauwata Group rift succession and overlying basal Amadeus Basin strata in the southwest, and for Kupferschiefer Cu in Cambrian clastic sedimentary rocks. The basin has a number of elements that make it highly prospective, including the localised presence of an underlying rift succession, the presence of basalt and evaporites in the lower parts of the basin, the existence of a number of significant shale units, and a large number of basement-penetrating structures. However, despite this prospectivity, the metallogenic potential of the Amadeus Basin has not yet been investigated in any detail and most exploration to date has investigated surface occurrences only. Developing an understanding of first-order controls on mineral systems that may have operated in the basin is a first step to developing metallogenic concepts and models, and subsequently exploration targets, in a systematic way.

References


