NEWS AND COMMENTARY

2014 Tour: SEG Pacific HL S. Chandola
23rd IGC: undercover workshop recap
24th IGC: conference themes
GGSSA: overview and update
23rd IGC: a student perspective

FEATURE ARTICLE

Impact structures in the Eastern Yilgarn
Introduction

The minerals exploration industry over the past decade has come to realise that future significant mineral discoveries are most likely going to be found at depths or under cover material, that makes recognition of deposits, with the historically very successful boots and hammer type exploration approaches increasingly problematic. The term ‘boots and hammer’ in this context is defined as the geological recognition of outcropping or shallow mineralisation, and the use of simple ‘bump finding’ geophysical techniques, or the application of basic geochemical approaches, which were designed to detect shallow mineral systems.

Considerable efforts are being expended to define new exploration strategies and technologies in the two leading countries where most of the world’s exploration technology is derived: Australia and Canada. These two countries also account for 28% of global exploration investment in 2012 conducted by publically traded companies according to the SNL-MEG, and so they would be major end users of any new exploration technologies as well.

Concurrent with the increased focus on exploration undercover is recognition of major changes in the commercial aspects of how companies search for new resources. Major producing companies have tended to pull back from supporting broad commodity and geographical programmes to much more focused efforts to support their current operations, most often in mature and politically safe settings. Intermediate producers appear to have greater risk tolerance regarding geography, but still shun greenfield-type exploration. This leaves greenfield-type settings, regarded by many as the best locations for new major discoveries, largely the focus of equity-funded junior companies that rely primarily on the vagaries of speculative investors to support their programmes. Whilst the markets made billions available for exploration over the past decade (Doggett 2013), few new major deposits have been located and the current funding drought has brought all but advanced exploration projects to a halt for the majority of juniors.

To help bring issues into sharper focus for the geophysical community, a workshop was organised as part of the recently held 23rd ASEG-PESA International Conference in Melbourne in early August. This workshop brought together senior representatives of state and federal geoscience groups, universities and industry to review the challenges and opportunities that are faced with ‘going undercover’. While the primary focus was on undercover exploration in Australia, technology examples were drawn from the global community as well as oil and gas exploration.

Ken Witherly
Condor Consulting Inc., Lakewood, CO, USA
ken@condorconsult.com

Graham Ascough
Mithril Resources, Adelaide SA

The economic need to explore undercover

Graham Ascough
Mithril Resources, Adelaide

Graham outlined that, over time, there has been a steady decline in the number and quality of near surface resources, meaning there is a greater requirement to find replacement deposits at depth. This task is arguably neither easy nor inexpensive and often takes longer to achieve, so major changes in how the discovery and development risk is managed are required. The commercial environment is challenging as well; while junior companies have seen significant increases in funding over the past decade, most investors are still reluctant to support long-term, high risk greenfield-type exploration. Graham cited an innovative approach whereby six juniors pooled their projects in a remote, but prospective part of South Australia into a new company and were then able to raise $20m to support exploration that individually would not have been possible.

The geophysical tool kit to map the upper 3 km

Ken Witherly
Condor Consulting, USA

Ken reviewed the roster of geophysical techniques available to support undercover exploration. There were no surprises overall in this assessment as the industry has a comprehensive suite of:

- well understood applications covering potential fields, EM, electric and acoustic methods;
- a good service industry capable of supporting delivery of techniques to end users; and
- a wide range of readily available processing and analysis techniques to manipulate data.
Examples of techniques reaching several kilometres into the Earth were presented. However, as we go deeper overall the resulting images of what would be called targets at a shallow depth become inevitably ‘fuzzy’. Consequently, we have more chance of defining the likely environment that would host a deposit rather than the deposit per se. There appears to be no technological ‘silver bullet’ on the horizon to deal with this ambiguity of exploring at depth. The best means to manage this risk has been to have a group of explorers work as an interactive team on such problems, thereby allowing the overall risk to be defined and where possible, managed. While this style of exploration model was historically popular with major companies, it has proven difficult to translate to the junior exploration sector. A ‘score card’ of the various techniques available to explore at depth was presented.

Exploring undercover: building and testing geological models

Andy Barnicoat
Geoscience Australia (GA), Canberra

Andy started by pointing out that approximately 80% of Australia has some form of cover including extensive areas of relatively thin transported cover. Consequentially, almost all exploration and discoveries has focused to date on those remaining areas with easily accessible bedrock. To help coordinate Australia’s efforts to develop the technology and skills needed to explore effectively undercover, the Uncover Initiative was started several years ago. Four themes define rallying points for the efforts of research groups, government surveys, service providers and explorers:

1. character and depth of Australia’s cover;
2. investigating Australia’s lithospheric architecture;
3. 4-D geodynamic and metallogenic evolution of Australia; and
4. characterising and detecting the distal footprints.

Andy then provided examples of work on each of these themes that is being carried out. One major effort involving GA and CSIRO is to adapt airborne electromagnetic (AEM) technology to help in the remote mapping of the composition and thickness of cover material. This is a change from the traditional focus AEM has been used for which is to define generally confined bodies of high conductance (targets). With high-powered AEM systems now available as well as rapid inversion software to produce 1-D, 2-D and 3-D conductivity outcomes, AEM can be used to help model palaeosurfaces, alteration zones and allow for the better design and interpretation of geochemical surveys.

One of the most exciting projects is focused on building continental scale 3-D models of the earth in 4-D and use to try and predict how ore systems came into being and deposit were then derived from these large scale crustal events.
the depth of investigation the client required. When the survey was completed, new targets at depths of approximately 1 km were revealed. At Santa Cecelia, understanding of the deposit, its geology, alteration and mineralisation built up over a 20-year period, culminated in the use of deep penetrating induced polarisation (IP) and magnetotellurics (MT) to define what is thought to be the overall system geometry. One of challenges with large systems was revealed in that, given their size (often several kilometres for the actual deposit), getting to background response using ground techniques can be challenging.

**First Quantum’s deep exploration: reasons and results**

Chris Wijns
*First Quantum, Perth*

Chris started by giving his take on the importance of differentiating undercover from deep exploration and indicated that the challenges and opportunities were somewhat different. Areas that could be defined as undercover are arguably easier to explore, but likely need well-integrated use of technologies, especially geochemistry with geophysics. Deep exploration is seen as more the realm of conceptual geology and geophysics.

Chris then outlined that his company preferred not to see itself as seeking deep resources as a priority, but did see the value in obtaining geological knowledge from depth so as to better understand deposits near surface. He then provided two examples of using deep exploration techniques: a Ni–Cu deposit in Finland; and, a Cu deposit in Zambia Copper Belt. In Finland, a seismic survey suggested a potential target area at a depth which would not otherwise been considered as ‘attractive’ to explore. However, deep drilling failed to define the presence of mineralisation at depth, but the geological results have allowed for what is believed to be a much better understanding of the ore system. In the Cu example, deep drilling was used to help better constrain the overall geometry of the mineralised system at depth.

**SEAM: the challenge of modelling seismic exploration at full scale**

Yaoguo Li
*Colorado School of Mines, USA*

Yaoguo described the Society of Exploration Geophysicists (SEG) SEAM programme, a very successful research programme being run on behalf of a consortium of oil and gas producers and oil industry service companies. The programme builds computer models that replicate real-earth attributes with such accuracy that they can be used as an inexpensive means to:

- provide datasets to test algorithms for imaging and inversion, that is, datasets for models that represent realistic (complex) earth structures and physical parameters, where the true inversion result is known;
- better understand features and artefacts in real images;
- explore trade-offs in acquisition methodologies; and
- train next generation of seismic processing and imaging experts.

In the present context the SEAM approach could have value for the minerals industry to develop the capabilities to explore cost-effectively at great depths.

**Geochemical techniques for undercover exploration: the ‘new geophysics’?**

James Cleverley
*CSIRO, Perth*

James gave us a ‘tour de force’ of the state of the art of geochemistry as it relates to building capabilities around concepts that come out of mineral systems frame work. Understanding distal footprints of deposits becomes critical, but
also the need to much better understand the various settings
that surround ore deposits at depth, as this ‘geo-setting’ can
have an enormous influence on the geochemical outcomes. He
examined new technology and how breakthrough opportunities
exist if applied in the right settings. Innovation is critical and
he cited fields as diverse as oil and gas technology to planetary
exploration as areas of study that offer opportunities that can
be applied to the minerals exploration problem. He suggests
that a closer merging of traditional geophysical approaches and
geochemistry has much to offer industry as well. In closing
he pointed out that exploration in general and geochemistry
in particular has entered in the domain of Big Data and new
approaches as to how we view and interpret information are
required.

Model building to support exploration undercover
John McGaughey
MIRA, Canada

John outlined how model building to support exploration
undercover has made significant progress with the addition of
adding constraints during the inversion process. He provided a
suite of examples that included several gravity data sets and a
number of airborne EM data sets where constrained inversion
had provided a superior outcome to traditional unconstrained
approaches.

Carrapateena: discovery and early exploration
Lisa Vella
Southern Geoscience, Perth

Lisa’s presentation looked at the early stages of exploration for
new IOCG style deposits that could be hosted in the Gawler
Craton, home of the world-class Olympic Dam deposit. Starting
in the late 1970s, explorers found encouraging alteration while
testing aeromagnetic highs. However, as many have found,
IOCG systems often have extensive alteration systems and to
make an actual discovery of significance can take a considerable
amount of patience, money and (often) serendipity. In 2005,
using a variety of geophysical data sets but mainly Direct
Current (DC) resistivity and gravity, two drill holes were
designed to test the geophysical features: whilst the first hole
failed to intersect mineralisation of interest, the second hole
encountered 68 m @ 3% Cu + 0.4 g/T Au. This was a huge
success for the property owner and the government of South
Australia who were co-supporting the drilling programme.
Lisa then reviewed the ongoing exploration programme and
research started on the deposit so as to try to better vector what
were thought to be other possible similar systems in the area.
Deeper penetrating induced polarisation (IP) resistivity was used,
along with the extensive use of 3-D modelling of the magnetic
and gravity results. In the end, the geophysical signature was
defined as a low order magnetic and gravity high that showed
a DC conductivity response (but, nothing definitive with
electromagnetics).

Carrapateena project
Charles Funk
Oz Minerals, Melbourne

Charles provided an update on the recent exploration and
geotechnical work around the Carrapateena deposit. The
challenges of defining a major complex ore body at depth were
discussed and he noted that the main mineralised zone was not
encountered until 30 holes after the discovery hole. The likely
mining plan was discussed including the incredible machinery
required to provide access to the deposit approximately 500
m below the ground surface. So as to better understand the
geotechnical challenges with building such a deep underground
mine, an extensive seismic survey was carried out over the
deposit. Charles provided some information on two other IOCG
systems in the vicinity; Khamsin and Fremantle Doctor. As
well, he provided a set of comparison images showing the cover
thickness and geophysical responses for Carrapateena and the
Prominent Hill deposit located about 300 km to the NW.
What role for government in pre-competitive R&D?

Ted Tyne
SADM, Adelaide

Ted first laid out the challenges explorers and governments face in keeping a strong and successful minerals industry present in Australia. He outlined how the South Australian (SA) government looks at a combination of pre-competitive R&D (including providing state-of-the-art geoscience data sets) as well as co-investment in high-risk drilling, much of it channelled through SA government’s PACE programme. He also touched on various international initiatives whereby SADM is working with overseas groups under collaborative projects so as to enhance the understanding of important deposit models which could be present in SA. The Carrapateena discovery discussed earlier in the workshop was cited as one of successful outcomes of the PACE programme.

Mapping igneous activity associated with mantle plumes and rifts to target mineral deposits

Peter Gunn
Bohuon Resources, Sydney

Peter provided what could be best termed a ‘left-lateral leap’ in how to think about exploration targeting, providing a range of examples of using often quite basic regional data sets to show how major mineral system events could have taken place. While most of Peter’s examples had a minerals flavour, his dual career in having worked both in minerals as well as for a major international oil company showed through frequently as he is as comfortable with seismic data as he is potential fields and clearly sees them as complimentary when both are available. Mantle plumes are a favourite topic both given their size (geophysical footprint) and the sorts of major mineral deposits that can be associated with such events. He populated the talk with a number of examples from Australia and around the world that he has examined over his extensive career.

How to exploit recent and current undercover initiatives?

Richard Hillis
DETCRC, Adelaide

Richard spoke about the major collaborative R&D project on-going in Australia - the Deep Exploration Technologies (DETCRC). The primary purpose of the DETCRC is to develop and facilitate the successful commercial implementation of new technology to assist explorers to work undercover. A major focus of the programme is to adapt oil field technology termed coil tube drilling to minerals exploration. A technology testing and development and training facility has been established at the Brukunga site north of Adelaide so as to provide a ‘real world’ setting for new techniques to be trialled. In addition to the improved drilling of holes, the DETCRC is working a range of in-hole measuring technologies, some operated in real time (whilst drilling) which will provide multi-parameter feedback on geology, alteration, mineralisation and rock quality never-before available to explorers. Had Jules Verne written about minerals exploration, the DETCRC programme would have had a chapter in this book.
The speakers are thanked for their excellent presentations. Portable Document Format (PDF) files of the talks (most speakers were able to release without any restriction) and the full oral presentations will soon be available on the ASEG website. Thanks are also expressed to the workshop sponsors: the CSIRO National Flagship Minerals Down Under; and First Quantum Minerals.

References

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Electrical geophysical solutions
Resource exploration, environmental and geotechnical applications
Workshop on exploration undercover; challenges and opportunities for industry, academia and government

CSIRO

FIRST QUANTUM MINERALS LTD.

ASEG-PESA 2013
'THE EURiKA MONEr'T
13-14 AUGUST 2013 • MELOBORNE, AUSTRALIA
<table>
<thead>
<tr>
<th>Time</th>
<th>Title</th>
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<tr>
<td>8:00</td>
<td>Introduction</td>
<td>Ken Witherly-Condor Consulting</td>
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<tr>
<td>8:10</td>
<td>The economic need to explore undercover</td>
<td>Graham Ascough-Mithril Resources</td>
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<tr>
<td>8:30</td>
<td>The geophysical tool kit to map the upper 3 km</td>
<td>Ken Witherly</td>
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<td>9:10</td>
<td>Exploring undercover – building and testing the geological models</td>
<td>Andy Barnicoat-Geoscience Australia</td>
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<td>Deep exploration for porphyry coppers in the western cordillera</td>
<td>Jonathan Rudd-Quantaec Ltd</td>
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<td>10:45</td>
<td>First Quantum’s deep exploration: reasons and results</td>
<td>Chris Wijns-First Quantum</td>
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<td>11:30</td>
<td>SEAM-An Introduction to a program and concept for exploration undercover</td>
<td>Yaoguo Li-Colorado School of Mines</td>
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<td>11:45</td>
<td>SEAM discussion</td>
<td>Ken Witherly-moderator</td>
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<td>Geochemical techniques for undercover exploration; the 'new geophysics'?</td>
<td>James Cleverly -CSIRO</td>
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<td>Model building to support exploration undercover</td>
<td>John McGaughey-Mira</td>
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<td>Carrapateena-Discovery</td>
<td>Lisa Vella-Southern Geoscience</td>
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<td>3:00</td>
<td>Carrapateena-Development</td>
<td>Charles Funk-Oz Minerals</td>
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<td>3:45</td>
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<td>Ted Tyne-SADMC</td>
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<td>4:15</td>
<td>How to exploit recent and current undercover initiatives?</td>
<td>Richard Hillis-DETCRC</td>
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<td>Mapping Igneous Activity Associated with Mantle Plumes and Rifts to Target Mineral Deposits</td>
<td>Peter Gunn-Bohuon Resources Pty Ltd.</td>
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<td>5:15</td>
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The Economic Need to Explore Undercover

ASEG 2013 August 15 Melbourne

Workshop on Exploration Undercover; challenges and opportunities for industry, academia and government
Nova Discovery

- ~1M Cash
- Market Cap of ~8.5M
- "Insufficient funds to be effective"

Bollinger Discovery

- Market Cap of ~600M
- Fully Funded

Drilling Targeting Delineation

~4000%
~8600%

EM survey outlines 3 priority conductors and recce drilling confirms Ni-Cu anomalies

Sirius Resources Ltd

- Nova discovery results in massive re-rating
- 14.6Mt grading 2.2%Ni, 0.9%Cu and 0.08%Co
The Imperative to Explore Undercover

- Ensure resource inventory matches demand
- Readily identifiable resources (outcropping) discovered
- Next tier of major deposits will come from greenfield areas – areas that have been considered too deep, too remote or too difficult to explore
- Style of exploration will need to change (empirical and conceptual)
Discoveries are getting deeper,....

- Readily identifiable resources have been discovered
- Fewer, near surface discoveries
- Technology advances required to identify and delineate resources at depth
..there are fewer of them,...
....and they cost more to find!

Discovery rate versus spend
Western World non-ferrous exploration spend and discoveries

Between 2002 & 2012 WW spend went up 8x and discovery rate up ~3x

Even after adjusting for unreported discoveries, in the last 5 years a large gap has opened up between expenditures and number of deposits found.

...Gap due to higher input costs (labour, drilling and admin)

MinEx Consulting
Strategic advice on mineral economics & exploration
Resource depletion outstrips replenishment of supply

Exploration expenditures and amount of copper found
Primary copper deposits >0.5 Mt Cu-eq found in Western World: 1950-2012

Expenditures (2012 US$B)

Note: Estimate includes adjustments for deposits with no discovery year and deposits missing from the database

FORECAST TO 2014

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Refined Production - Usage Balance

Source: MiEx Consulting © June 2015
**Copper Market**

- **Copper Price**
  - Source: Bloomberg
  - $US/lb vs. $A$/lb

- **Chinese GDP & Copper Consumption 1980-2010**
  - Source: Global Insight, AME, McKinsey Global Institute, Wood Mackenzie, EIU, J.P. Morgan
  - Chinese GDP vs. Copper Consumption

- **Global Consumption & Mine Supply**
  - Source: Wood Mackenzie
  - Mt Cu

- Key Points:
  - Requirement for 6.3Mt of new mine production capability by 2022.
  - On average an additional 1 million tonnes of production is required per year to keep up with demand.
  - New production to come on at a higher cost in jurisdictions that may be new to mining with deposits being deeper – underground mining will become the future.

Source: OZ Minerals Presentation to BMO Conference Feb 2013
Not all discoveries make the cut....

- Gold in Australia (from MCA)
  - More than 2000 active gold exploration projects in Australia alone
  - ~10% (198) are at the scoping to feasibility stage
  - Majority are small, near surface and low grade

- Copper Globally (SNL Metals)
  - 1998 to 2012 there 100 significant new copper discoveries (>500kt Cu each)
    - Generated ~395Mt of Copper in resources
  - 15 of these projects have reached production
    - Only 1/10th of the resources were converted to reserves
  - The average “replacement” needs of the 22 Major Producers is approximately 500,000t per year. Most of this comes from brownfields but this is unsustainable — need for new world class deposits
Exploration Funding has grown long term but...

- “cyclical” (near term) exploration expenditure fell 18.4% to $672.2m
- Exploration on areas of new deposits fell 33.1% (or −$87.1m) and expenditure on areas of existing deposits fell 11.5% (or −$64.7m)
- Current trend towards lower exploration spend in base metals & gold:
  - decreasing discovery rates;
  - a focus on brownfield exploration;
  - difficulty raising equity!
Costs are on the Rise

- Spend is up but drill metres are flat
- Deposits are difficult to find and delineate undercover
- Looking at greater depths
- Larger tonnages and lower grades
Greenfield Exploration required to deliver the big deposits

Major mineral deposits in Australia

- Incremental discoveries are insufficient to sustain inventories
- General trend of decreasing size of discovery with maturity of terrain
- Large scale discoveries required – new camps/provinces not just single deposits
- Greenfield (undercover) exploration in less explored areas is the best opportunity to deliver the Tier 1 deposits
Reluctance to explore undercover

- Long lead times
- Highest risk
- Limited technology to rapidly screen large areas
- Lack of Investor Support
- Juniors often first movers in covered terrain
- Reality is that most investors in juniors are not interested in backing long-term exploration in unproven, high-risk areas
- Most juniors are “forced” to explore in brownfields areas where shorter term (and more modest) outcomes are likely to be found
A Junior’s Perspective

- Juniors account for over half of all the exploration spend in Australia
- Difficulties in raising finance directly translate into reduced exploration activity particularly greenfield exploration
- 100’s of Junior Resource Companies with less than $1M cash
  - Junior Companies need ~$500,000 per annum to stay afloat (compliance costs)
- When sentiment is good, Investors will tolerate high risk but when sentiment turns investors seek lower risk sectors
- Need to lower risk of greenfield exploration by increasing success rates
  - Targeting Technologies
  - Drilling Innovation
- Shorten the time between targeting and drilling
Industry can drive sentiment by making better, faster and more profitable decisions

- Fiscal return on exploration has declined – need to lift our game
  - Demonstrate significant return on Invested Capital
  - Lower risk and shorten time frames
- Enterprise Value must grow at a faster rate than Invested Capital
- No (or limited) growth of EV during the targeting stage is an issue for investors
- Need to build confidence in the targets prior to drill testing
We explore to add value....

Sirius Resources Ltd
- Nova discovery results in massive re-rating
- 14.6Mt grading 2.2%Ni, 0.9%Cu and 0.08%Co

- Nova Discovery
  - Market Cap of ~600M
  - Fully Funded

- Bollinger Discovery
  - ~1M Cash
  - Market Cap of $8.5M
  - “Insufficient funds to be effective”

- EM survey outlines 3 priority conductors and recce drilling confirms Ni-Cu anomalies

Drilling

Delineation

Targeting

~8600%

~4000%
**ASX ANNOUNCEMENT**

**26 JULY 2012**

**SIRIUS RESOURCES NL**
ASX: SIR
ABN: 46 009 150 083

**Major Nickel-Copper Discovery**

New deposit style, new nickel province, first of three EM targets to be tested at the Eye

Sirus Resources (ASX:SIR) advises that it has discovered significant nickel and copper sulphide mineralisation in the first reverse circulation (RC) drill holes at its 70% owned Fraser Range project in Western Australia.

The discovery has been named the Nova deposit.

The Nova deposit is located in a previously unexplored and inaccessible area, beneath transported overburden, and was discovered with the first drill hole designed to test a very large electromagnetic (EM) conductor – one of three EM conductors at the Eye prospect.
- 14.6Mt grading 2.2%Ni, 0.9%Cu and 0.08%Co
- Conceptual Studies Underway
- Tropicana also in Albany-Fraser province
- Discovered in 2005 through follow-up of gold-in-soil anomaly in data collected in the 1990’s
Challenge of Greenfield Exploration - Mithril

- New IOCG Area – 50km x 15Km
- 95% of the area is undercover
- $2.2M Cash
Explorers also need to be innovative to attract funding

- Musgrave Minerals Limited
  - 6 companies agree to vend their SA Musgrave tenure to new entity
  - Creates dedicated exploration company and investment vehicle
  - Successful $20M IPO in 2011
  - 55,000km² Land Holding in the “Greenfield” Musgrave Province
Deep discoveries continue in SA

CARRAPATEENA: NEW DISCOVERY KHAMSIN PROSPECT

Khamsin
DD12KMS003
440.6m @ 0.43% Cu, 0.08 g/t Au from 1,005.4m
(including 26.7m @ 1.48% Cu, 0.13 Au g/t from 1,005.4m)

Carrapateena
(Indicated + Inferred Resources)

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<th>COG % Cu</th>
<th>Tonnage</th>
<th>Cu %</th>
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<td>0.5</td>
<td>475</td>
<td>1.02</td>
<td>0.39</td>
</tr>
<tr>
<td>0.3</td>
<td>760</td>
<td>0.78</td>
<td>0.30</td>
</tr>
</tbody>
</table>

- New regional discovery made at the Khamsin prospect.
- Khamsin prospect approximately 10kms northwest of Carrapateena.
- Geophysical signature is similar in size to Carrapateena.
- First drill hole with 440.6m @ 0.43% Cu.

Source: OZ Minerals Presentation to BMO Conference Feb 2013
Majors still active in greenfield exploration

- Rox Resources Ltd in JV with Teck – Teena, NT
The Economic Need to Explore Undercover

- Success stories of exploration “undercover” demonstrate value
- Shallow or Deep - cover is an impediment to success
- The cost of exploration is rising
- Fewer discoveries
- Resource depletion outstrips replenishment in Brownfield Camps
- Small % of “discoveries” convert to “production”
- Market appetite for risk is in decline
- Industry can drive sentiment by making better, faster and more profitable decisions
Need to fill the technology gap

**Historical AEM Performance**

*Best Case prospected ground coverage*

- 1975 = 10%
- 1990 = 46%
- 2000 = 100%

![Diagram showing historical AEM performance and ground coverage improvements over time.](image)
Government and Academia have a role to play

- Incentives for greenfield exploration
- Pre-competitive data
- Support drilling programs to test new concepts
- New exploration models / search techniques
The Geophysical Tool Kit to Map the Upper 3 km
“we can see deep but its blurry...”

Joel Jansen-Teck
Undercover Toolkit
The Roster

• Potential fields
  • Magnetics
  • Gravity
• Electromagnetics
  • Active
  • Passive
• Seismic
  • Surface
  • VSP
• DC resistivity/IP
• Radiometrics
• Other
Understanding Inversion: Non-Uniqueness

An Infinity of Models have the same Gravity Tensor Response
Undercover Toolkit
Unconstrained inversion

Three dimensional density and susceptibility distribution from non constrained inversion

3D density

3D susceptibility

Cheng et al. 2010
Undercover Toolkit
Getting more sophisticated

© Condor Consulting 2013

Duffett et al. 2013
How might such alteration systems appear in this data?

In the next slide we consider the effect of adding the response from silicification / or desilicification zones above the unconformity.

The simplistic geometry and the six different density contrasts used are shown below.
Inverted Density Model

... with “Alteration Chimneys” added to data before inversion
Undercover Toolkit Simulations

Noranda Camp Quebec

[Model from Holtham & Oldenburg 2012]
Undercover Toolkit
Limits of certainty

Athabasca Basin
Virgin Trend

[Data used with permission of Titan Uranium Inc.]
Undercover Toolkit
Uncertainty in modeling

3-D, Siripunvaraporn

3-D, Mackie

3-D, Farquharson

Craven et al. 2006
Undercover Toolkit
Seeing deep

Conductive shale

ZTEM 2D inversion

1.8 km

ZTEM 3D inversion
Case study — Neves Corvo

Exploration Challenge in Portuguese Iberian Pyrite Belt
(www.lundinmining.com)

- Complex structural geology with thrusting
  - Surface geology does not always represent subsurface

- Mature terrain = deep targeting >500m
  - 30 years of exploration focused within upper 500m

- Economic mineralization is difficult to target with conventional methods
  - All geophysical and many geochemical surveys tried with limited significant success
Case study – Neves Corvo
Case study – Neves Corvo

Courtesy Lundin Mining

High Resolution
Rx  90 x 15m
Tx  90 x 45

Survey Block
6.4 x 4.6 km

Note faults cutting Lombador into segments

Lombador
Semblana
Tailings Dam
Neves Corvo
Case study – Neves Corvo
"A high-resolution 3D seismic survey has now been completed over a 21 square kilometer area surrounding the Neves-Corvo mine. Preliminary results have clearly imaged the major Semblana deposit, verifying the effectiveness of this new tool in the search for blind massive sulphide deposits"

Undercover Toolkit
The Big Bite

Magnetotelluric Section through Olympic Dam
Undercover Toolkit
3D models; primitive but *understood*
Undercover Toolkit
Merging geology & geophysics-hypothesis testing

Steinberger et al Econ.
Geology
2013 Vol 108
Undercover Toolkit
Merging geology & geophysics-hypothesis testing
Undercover Toolkit
Geological mapping with geophysics
Undercover Toolkit
Undercover Toolkit

- RIDGEWAY
- CADIA QUARRY
- CADIA HILL
- CADIA EAST/CADIA FAR EAST
- NW
- SE
- Weemala Formation sediments
- Forest Reefs Volcanics
- Monzonite

1 km

© Condor Consulting 2013

Wood 2012
Undercover Toolkit
“The IP survey did not find Ridgeway but Ridgeway was found because of the IP survey”

Dan Wood-ASEG Aug 13 2013
Undercover Toolkit
Is it enough??

Weemala Formation sediments

1 km

????

© Condor Consulting 2013
Undercover Toolkit
See deep and fuzzy
The reprocessing by CD3D clearly demonstrated two electrically conductive beds with the deep bed, which had previously been mapped by electromagnetic surveys to depths of 400 metres, now interpreted as extending up to 1,500 metres deep.
### Undercover Toolkit

**A ranking**

<table>
<thead>
<tr>
<th>Task</th>
<th>Potential Fields</th>
<th>EM Active</th>
<th>EM Passive</th>
<th>Seismic</th>
<th>DC Res/IP</th>
<th>Radiometrics</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Targeting</td>
<td>M-H</td>
<td>M-H</td>
<td>L-M</td>
<td>L-M</td>
<td>M</td>
<td>L-M</td>
<td>?</td>
</tr>
<tr>
<td>Mapping</td>
<td>M-H</td>
<td>M</td>
<td>M-H</td>
<td>M-H</td>
<td>M</td>
<td>M</td>
<td>L?</td>
</tr>
<tr>
<td>Cost</td>
<td>L</td>
<td>M-H</td>
<td>M-H</td>
<td>H</td>
<td>M-H</td>
<td>L</td>
<td>??</td>
</tr>
<tr>
<td>Rank</td>
<td>H</td>
<td>M</td>
<td>M-H</td>
<td>M</td>
<td>M</td>
<td>L-M</td>
<td>NA</td>
</tr>
</tbody>
</table>

**H= high**

**M= medium**

**L= low**
Undercover Toolkit
A ranking

<table>
<thead>
<tr>
<th>Terrain</th>
<th>District</th>
<th>Project</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>10</td>
<td>1</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Exploring undercover: building and testing geological models

Andy Barnicoat
Chief of Minerals & Natural Hazards Division
Challenges and opportunities

- ~80% covered
Australia’s undercover mineral potential

Surface geology (1:1 M)
Australia’s undercover mineral potential

Australia’s potential for new discoveries. A common perception of Australia as ‘mature’ in relation to mineral exploration and discovery

Vast areas of basement rock are concealed by relatively thin transported cover, shown in yellows and pale browns in this image of the 1:1 million scale Surface Geology

Huge potential for discovery under and within this cover
Australia’s undercover mineral potential
Australia’s undercover mineral potential

Generalised surface geology (from 1:5 million scale map) exaggerates the amount of outcrop but shows the extent of exposed geological provinces
Australia’s undercover mineral potential
Australia’s undercover mineral potential

Major known mineral deposits (coloured dots) are clearly mostly located within areas of outcrop
Australia’s undercover mineral potential

When we superimposed the aeromagnetic data, shown as a greyscale transparency here, we can see that many of the well known and world class mineral provinces actually extend for considerable distances beneath the cover of transported sediments – good examples are south of Mt Isa, Albany-Fraser province, northern Gawler Craton.

Those areas of basement concealed by shallow cover represent major greenfields exploration opportunities

Australia is not as mature as commonly perceived!
Standing Council Energy & Resources (SCER)

VISION:
Unlocking Australia’s hidden resource potential.

MISSION:
To address greenfield exploration challenges, stimulate new discoveries, ensure continuity of the pipeline of mineral resource investments, and the longevity of Australia’s mineral resources industry.
UNCOVER vision

• nationally-coordinated and strategic people and sector network
• Science based on mineral systems concepts
• Four “themes” for research groups, Government surveys, service providers and explorers:
  1. Character & depth of Australia’s cover
  2. Investigating Australia’s lithospheric architecture
  3. 4D geodynamic and metallogenic evolution of Australia
  4. Characterising and detecting the distal footprints
Character & depth of Australia’s cover
Modelling cover character: ASTER

Cudahy et al.,
Several known gold-rich regions (eg Kalgoorlie, Charters Towers, Ballarat) show up as anomalous in gold in the surface regolith material. Other gold anomalies elsewhere may be pointers to undiscovered gold enrichment in the basement.

Testing the NGSA with infill ME geochemistry in southern Thomson (2013–14)
Modelling cover character: regolith geochemistry

Regional regolith geochemistry GSWA (Paul Morris)

Modelling makes predictions of Cr values between points and in large areas of no points.

Cr ppm

800
0

30 km

J Wilford
Modelling is not interpolation between points but a model prediction based on multivariate correlation.
Modelling cover character: regolith geochemistry

Ultramafic & mafic rocks (white polygons)

Elevated Cr in shallow cover

Cr ppm

0

800

J Wilford
Depth of Cover: AEM valuable tool

- Model palaeosurfaces
- More precise depth to target information
- Map alteration zones

Roach et al. 2013
Depth of Cover: AEM valuable tool

3D mode of the entire Frome AEM survey showing combined depth to resistive basement models in the NW Murray-Darling Basin, Benagerie Ridge at Honeymoon and the northern Flinders Ranges at MacDonnell Creek. The model combines the digital elevation model (DEM), conductivity sections and a depth slice to highlight the ability of AEM to map cover in 3D over a wide region. This model appears on the front cover of the Frome AEM Survey GA Record.
Depth of cover

• Cover depth predictions difficult
• Range of magnetic methods with mixed terrane-specific success
• Possible national AEM survey (like AWAGS)?
  • good for <500 m regions
• Terrane-specific experiments needed with shallow MT, seismic, plus potential fields
  • What works best and how much?
  • What scale?
• UNCOVER workshop to tackle the depth challenge

Meixner, 2010
Looking a bit deeper: towards a 3D map of Australia

GA working on harmonising and integrating these 25 regional and provincial maps into a national 3D geological map/model

T Brennan
Building continental-scale 3D models/maps

M Nicoll
Building province-scale 3D models/maps

Henson et al., 2006
Building camp-scale 3D models/maps

Mt Margaret Dome

Wallaby

Granny Smith

Dome

Kirgella Dome

Celia Fault penetrates crust

Henson et al., 2006
Building deposit-scale 3D models/maps
Building deposit-scale 3D models/maps

This slide shows the calibration of the grade shells (generated by John Miller in Leapfrog) and favourably oriented regions on the Sunrise Shear (blue spheres). The correlation is very good and deeper extensions that are favourably oriented are highlighted down dip and along strike. Unrealised potential?
Model building advances: 3D inversion codes on NCI

Milligan et al., 2013
Model building advances: 3D inversion in spherical on NCI

- Continental Scale 3D density model of crust
- Australian national Gravity database + satellite data
- in true spherical co-ordinate space
Building a mineral systems model

Schofield, 2013
IOCG conceptual criteria

Sources
- Uranium
- Volatiles
- Brines
- Cu/Au

Pathways
- Fluid flow
- Crustal margins

Drivers
- High-T crustal melts
- Mantle melts
- Iron oxide alteration
- Fe-rich rocks

Deposition

Schofield, 2013
IOCG mappable criteria

- Sources
  - Basins, magmas
  - U-rich igneous
  - F-rich igneous
- Pathways
  - Mafic igneous
- Drivers
  - A- to I-type granites
  - Mafic magmatism
  - Geophysical inversions
- Deposition
  - Solid geology

Schofield, 2013
Integrating geochemical modelling

Modelling Cu solubility

Cu deposited near magnetite-hematite gradient

- Map magnetite-hematite gradient in susceptibility (mag) & density (gravity) space
- Take into map space via 3D inversion of mag and gravity

From Huston et al., 2012
Integrating geochemical modelling

A water-rock interaction model for Cu and Au precipitation in IOCG systems. Copper precipitates by reduction of a copper-gold-bearing oxidized (hematite-stable) fluid infiltrating a magnetite-bearing assemblage. The slide shows a dramatic drop in copper solubility and development of best copper grades next to the hematite-magnetite alteration interface. The example is provided for 300°C but the principle would apply outside of this temperature range.
Integrating geochemical modelling in 3D space

- 3D magnetic and gravity inversions volumes hematite & magnetite alteration
- Filtered by geology to minimise lithological influences
- Favourable gradient near magnetite to hematite mapped in 3D
- Take result into spatial model analysis

Hematite: green; magnetite: pink
Integrating geochemical modelling in 3D space

• First step: perform 3D magnetic and gravity inversions to derive density and magnetic susceptibility models for the study area

• Cross-plots of density vs susceptibility generated
  • Filtered using solid geology to minimise lithological influences (e.g., don’t want mafic rocks coming up consistently as mgt)

• From this, volumes of potential mgt or hem alteration are identified, from which we identify the transition from mgt to hem as the most favourable
Building a geological (architecture) model

Southern Aileron Province

Reliable ‘solid geology’ (architecture) maps vital

Schofield, 2013
Building a mineral system model

Schofield, 2013
Building a testable hypothesis

Aileron IOCG potential

Schofield, 2013
Testing the geological–mineral system models: regional-scale pre-competitive drilling

Considerations for area selection:

- Mineral systems potential
- Relatively poorly known geology
- Greenfields – make a material difference
- Potential to collaborate (co-invest)
- Suitable access and infrastructure

Some drilling parameters:

- Depth to target limit at <500 m.
- ~5–15 holes within ~1:250,000 map sheet area (~150 km x 115 km); or
- ~300 km long transect
Delamarian
(600–490 Ma)

- Margin of Proterozoic Australia with interpreted west-dipping subduction
  - Began with Rodinia break-up
  - Ended with Delamerian Orogeny (ca. 520-490 Ma)
- Extensive felsic and mafic volcanics and associated sediments
- Deep marine turbiditic sediments
- Restricted granites

Huston et al. 2010 after Collins and Richards (2008)
Delamarian (600–490 Ma)

- Geological model building generates a range of mineral system concepts
  - many under shallow cover e.g., western Victoria
- Drilling to test geological models
Pre-competitive drilling project 1

- Victoria drilling project (2013–15)
  - geophysical data acquisition
  - **Drilling in < 12 months**
  - 10+ diamond holes
  - Develop our workflows for sample handling and analysis
  - Partnership of GA, GSV and DET CRC
  - DET CRC research projects access (e.g. carbon fibre rods, new downhole tools, lab at rig)
Benambran Cycle (490-430 Ma)

- Widespread non-volcanic deep water sediments, and
- Calc-alkaline to shoshonitic magmatic arcs
- Ended with Benambran Orogeny (ca. 450-430 Ma)
- Subduction environment, complex configuration, modified by subsequent tectonism
- Geological model building generate a range of mineral system opportunities
- E.g., Southern Thomson
- Drilling to test geological models
Pre-competitive drilling project 2

- Southern Thomson Orogen drilling project (2013–16)
  - GA–GSQ–GSNSW project
    - Scoping and compilation (GA-GSQ-GSNSW data harmonisation)
    - Define problem and select drill sites
    - Depth and character of cover (2013–14)
      - broad-spaced AEM survey
      - pre-drilling MT or passive seismic survey
      - pre-competitive surface geochemical survey
  - Drilling in 2014–15
  - Much to still scope on this project
...possible **regional drilling** in the out years?

Possible future areas include:

- Carpentaria Basin in NT seismic/MT and drilling
- Southern Isa in Qld seismic/MT and drilling
- Eucla to northwest Gawler in SA drilling
- Ideas in from Vic, Tas to consider
Australia Minerals: ‘open at depth’ for business under cover

• Vast undercover opportunities
  • extensions to known provinces
  • true greenfields

• World-class precompetitive data holdings, which are FREE

• Highly skilled knowledge base in terms of:
  • technology to manipulate & interrogate data
  • geology of Australia

• Networks both physical and intellectual

• Supportive government at all levels

• Skilled explorers to Australian conditions
Thank you

Dr Andy Barnicoat  andrew.barnicoat@ga.gov.au
Chief: Minerals and Natural Hazards Division
Geoscience Australia
Porphyry Exploration in the Americas

2D Synthetic and field resistivity data modeling

Jonathan Rudd, P.Eng.
Quantec Geoscience

Workshop on Exploration Undercover
August 15, 2013
Kemess North - Case Study

2D Synthetic and field resistivity data modeling

Mehran Gharibi, Ph.D., P.Geo
Quantec Geoscience

Workshop on Exploration Undercover
August 15, 2013

Results shown courtesy of:
Northgate Minerals Corporation
Objectives

• Demonstrate the use of physical properties and synthetic model tests to survey design and planning

• Show Results from Titan 24 Survey at Kemess, Northern BC
Kemess North Case Study

• Survey design based on initial synthetic model testing using physical property estimates from previous geophysical surveys (useful approach)

• Final results agreed with initial synthetic models (proof of concept)

• Drilling of Titan DC/IP targets led directly to new discovery of “Ora” and “Altus” Zones at Kemess North
Titan-24 Distributed Acquisition System

- Line Length - 2400 m
- 24 $E_x$ 100m dipoles
- 12 $E_y$ 100m dipoles
- 25 current stations
- 2 $B_x/B_y$ magnetometer sites

Remote Magnetometer site

>20 km

LAN Link to Logging Truck

2 Channel AM

Battery

Typical Station Set-up

Base magnetometer Site

current electrode (mobile)

cross-line potential electrode (fixed)
in-line potential electrode (fixed)
infinity current electrode (fixed)

1 channel AM

2 channel AM

>5-10 km

>20 km

2 Channel

AM

Battery
This slide presents a schematic of the typical Titan DCIP & MT configuration in the field – with 24 in-line dipoles, 12 cross-line dipoles and current injections in-between receiver stations. For the dcip, each current injection, spanning 10, 20 or more cycles, is recorded in each acquisition module (AM), at the end, the “event” is harvested back to the recording truck along a LAN. The data are then qc’d by the operator before a decision is made to proceed to the next current injection or to repeat. A Titan spread typically takes a day to undertake, starting with the set-up, and the dcip acquisition in the daytime, followed by the mt acquisition at night. The entire data record is then brought to the processing office in camp, and the final results are available the following day to determine whether the line can be moved or repeated. This process is repeated until all the lines are completed.
Titan single spread

Titan extensions - extra injection points beyond ends of line

Larger receiver dipoles (150 m or 200 m) plus current extensions has provided DC and IP information to 900 metres.

Standard Titan spread
N=0.5 to 23.5, a= 100m

Line Length 2.4 km
Extensions are added to provide depth coverage under the ends of the lines which improves the accuracy of the model at the edges – minimize geometrical edge effects
Survey Objectives

• Find more ore

• Kemess North mineralization is a typical Copper-Gold Porphyry Target, occurring at the surface in the favourable Takla volcanic host rocks.

• However, Kemess stratigraphy becomes progressively buried and block-faulted below 300 m to 600 m thick, younger Hazleton Volcanic and talus cover, and intruded by post-mineralization Black Lake intrusives.

• Challenges include rugged topography and contact issues due to talus, and snow cover.
Original Deposit, Kemess North outcrops, but block faulting has dropped the mineralization to depth as you go northeast
Tough terrain – poor ground contact due to talus and snow cover
Survey Objectives

• The Titan-24 DAS surveys were proposed based on their deep penetration and multi-parameter capability, with emphasis on detecting the primary mineralization using IP and providing additional alteration and geologic mapping using DC + MT resistivity.

• Titan field surveys were preceded by a 2D synthetic modeling study to determine optimal array parameters (dipole size) and detection limits/sensitivity of the proposed survey.
IP is the main parameter for detecting the mineralization – resistivity for structural control and mapping
Procedures:

• Create 2D synthetic DCIP model for the Kemess Deposit, using pole-dipole data (1991) or physical property estimates and sketch geologic section.

• Calculate synthetic 2D DC & IP data for Titan lines across
  • deposit (approx. 5 km survey line - Assume 100m dipoles, with 2 x end-on 2.4km Titan Spreads), and also for
  • “Barren” geologic model (for comparison).

• Create 2D resistivity and chargeability inversion models.

• Compare Inversion Results with original Geologic Model to evaluate accuracy and capability of Titan to resolve Buried Kemess-style Porphyry Copper Deposits.
Now I describe the procedure that we employed for the synthetic model analysis. Two models are created – one for barren geology, one including the mineralization –. The reason we do this is for sensitivity analysis to establish the degree to which we can detect and delineate the mineralization.

Forward modeling to create the 2D synthetic data. Invert these synthetic data to understand how accurate and resolvable the deposit mineralization is. Error floor – 5%
Legacy geophysical data (1991) to estimate Physical Properties

TOTAL CHARGEABILITY PLAN

DC APPARENT RESISTIVITY PLAN

TDIP Pole-dipole Array
(A=50m / N=1-6)

Results shown courtesy of Northgate Minerals

A total of 201 kilometres of IP data was collected during this time. Approximately 60% of the property showed a strong IP (chargeability) response. This response has been interpreted to indicate the presence of a significant sulphide system.

Extensive drilling of a portion of this large sulphide system has led to the discovery of the Kemess South and Kemess North deposits.

Whilst geophysics did not lead to the original discovery of the Kemess deposits, the application of geophysics in outlining the interpreted sulphide system and in support of the drilling programme was of significant value.
Legacy data acquired in early 1990’s includes conventional IP – 50 m dipole spacing – over known mineralization in the near surface. These data were used to establish the physical properties for the model study.
These are the two models generated for the barren and mineralized cases. Good contrast between the host and mineralized zones.
KEMESS NORTH PORPHYRY COPPER – DC RESISTIVITY MODEL

2d DC Resistivity Forward Model
(Titan Pole-dipole Array – A=100m / N=0.5-32.5)

Calculated Response from Geologic Model Below - used as data for 2d Inversion Bottom

2D DC Resistivity Inversion
(Titan Pole-dipole Array – A=100m / N=0.5-32.5)

Calculated Response from 2d Inversion Model Below – using data from 2d Forward Above

Notice:

a) Similarity between Fwd & Inverse Models, but Cu vs. Py Zones Not Differentiated,

b) Moderate contrasts in Fwd Data, but Targets Well Resolved in 2d
Forward data in pseudosection format on top with the model. On the bottom, the inversion model and the inversion response in pseudosection format – you can see that the data has been recovered very well. But you can see that there is no clear discrimination between the cap and economic mineralization.
KEMESS NORTH PORPHYRY COPPER – CHARGEABILITY MODEL

2d Chargeability Forward Model
(Titan Pole-dipole Array – A=100m / N=0.5-32.5)

Calculated Response from Geologic Model Below - used as data for 2d Inversion Bottom

Notice:

a) similarity between Fwd & inverse models, but Cu vs. Py zones not differentiated,
b) moderate contrasts in fwd data, but targets well resolved in 2d

2D Chargeability Inversion
(Titan Pole-dipole Array – A=100m / N=0.5-32.5)

Calculated Response from 2d Inversion Model Below – using data from 2d Forward Above
Same for chargeability – pyrite zone has been well-resolved, copper zone not so much
Used a DC reference model
Barren vs. Mineralized - resistivity

**BARREN - 2D DC Resistivity Forward Model**

- Calculated Response from Geologic Model Below - used as data for 2d Inversion Bottom
- Host Volcanic
- Intrusive
- Late Volcanic

**MINERALIZED - 2D DC Resistivity Forward Model**

- Calculated Response from Geologic Model Below - used as data for 2d Inversion Bottom
- Host Volcanic
- Intrusive
- Late Volcanic

- **2D DC Resistivity Inversion**
  - Excellent Similarity between Fwd & Inverse Models
  - Marked Difference between Barren & Mineralized

- Calculated Response from 2d Inversion Model Below – using data from 2d Forward Above
- 100-10k ohm-m Range

(Titan Pole-dipole Array – A=100m / N=0.5-32.5)
Here are the two resistivity results together indicating that the proposed survey design is sensitive to the mineralization and is a very viable approach to mapping the porphyry systems.
Barren vs. Mineralized - chargeability

**BARREN - 2D Chargeability Forward Model**

- Excellent Similarity between Fwd & Inverse Models
- Marked Difference between Barren & Mineralized

**MINERALIZED - 2D Chargeability Forward Model**

- Excellent Similarity between Fwd & Inverse Models
- Marked Difference between Barren & Mineralized

(Titan Pole-dipole Array – A=100m / N=0.5-32.5)
Same for IP
Synthetic Modeling Summary

- Proposed 2D Titan survey will require 2 separate 2.4 km receiver spreads, with 200m overlap, and 600m-1km current extensions – Total length 4.2km with $a=100m$, $n=0.5-33.5$ separations.

- Titan surveys should be able to penetrate and resolve Porphyry bodies below 300-600m of Takla volcanic cover.

- Titan results should be able to image top and possibly bottom of Porphyry mineralization, but may not be able to distinguish between Pyrite-only and Cp+Py Phase in Ore zones at depth.

- The results show that chargeability model could be a primary data for interpretation because it shows a higher resolution due to stronger contrasts, when compared with resistivity.

- DC resistivity image will nevertheless assist in mapping alteration & structure – Titan MT will provide additional support and improved resolution.

- 2D Titan DCIP survey imaging could be improved by using 3d Inversion tools (better image along NS strike) - provided 3 or more lines are surveyed (300-400m spaced).
Case History: Kemess North

Titan-24 DC resistivity & IP and Tensor MT Results
This is where the survey was completed – looking from the SE – single line, 4.2 km in length
This is a plan map of the three lines that we will be discussing as completed with TITAN 24. More lines were recorded.
Line TA – 2D DCIP Inversion Results

Line TA Sp1+2 - Smooth UBC 2d DC Resistivity
(using 5% error floor w 15x error misfits removed)

Line TA Sp1+2 - Smooth UBC 2d IP Chargeability
(using 3.0mrad error floor w 15x error misfits removed)

Observed Data
Calculated Data
2d Inversion

Note: Excellent Model Fits to Observed Data
Note: Subcropping + Depth-Limited Source: Consistent with Observed Data

Note: Weaker but Persistent DC Low/IP High Feature Visible East of Kemess North
Note: Layer-like IP High Coincides with Py Halo Lying Above Cu-rich Zone?

View Looking Northwest
This is the actual data in pseudosection format and inversion below along the long NE trending TA line. Resistivity on left and IP on right. Even without inversion, we can see several geologic points of interest. Kemess North mineralization at surface is clearly mapped with the limited depth extent. Unknown potential mineralization to depth at the northeast is clearly mapped, and further potential target at greater depth and the far NE. Chargeability response is depth limited and may only be representing the pyritic cap. DC referenced chargeability model.
Line TA – 2D Multiparameter Inversions

2d Smooth Chargeability
(Titan Pole-dipole Array – A=100m / N=0.5-32.5)

2d Smooth DC Resistivity
(Titan Pole-dipole Array – A=100m / N=0.5-32.5)

2d Smooth IP (Null Resistivity Reference Model)
(Titan Pole-dipole Array – A=100m / N=0.5-32.5)

2d PW MT Resistivity (Topo-Corrected TM-TE Phase)
(Titan Tensor MT Array – A=100m / f=0.1-10,000Hz)

Note: Deeper Vertical Extent of “Null Res” vs. Default IP Model

Note: Graben-like Deep Resistivity Low Structure, i.e. Alteration System?

View Looking Northwest
Note the clear fault offset between the Kemess Noth zone and the previously unknown Altus zone at depth – no surface expression. The resistivity model on the bottom left uses a HHS (null) reference model and shows additional chargeability at depth which could represent copper mineralization zones at great depth. It is important to run several IP inversion models to remove any bias in the results caused by the initial model. At right is the resistivity – DC at top and MT at bottom. MT sees to a depth of 1.5 km, and indicates a graben-like structure which may reflect alteration.
Line TB – 2D Multiparameter Inversions

Note Similarity Between “Null Res” vs. Default IP Model

Note: Graben-like Deep Resistivity Low Structure, i.e. Alteration System?
Moving to another line, this east-west line show very similar IP model using the two different starting models. Highly conductive, high chargeable zone at the west is the Ora zone MT shows the same graben-like structure on the previous line.
Line TC – 2D Multi-parameter Inversions + DDH Results

Note: Graben-like Deep Resistivity Low Structure, i.e., Alteration System?
Now we are looking at a N-S line which intersects the TB line at the end. So we are crossing the Ora zone directly. The null resistivity IP model show a depth extent to the anomaly, and the MT confirms this depth extension.
Putting these three lines together. Ora zone, Offset zone, Altus Zone
KEMESS CLAIMS EXPLORATION RESULTS

During the summer exploration season, a deep penetrating IP survey was conducted in the area surrounding the Kemess North deposit. This survey outlined several previously unknown exploration targets which are shown in pink in Figure 2. Northgate plans to drill several diamond drill holes to test the largest of these targets to the east of Kemess North during November, prior to the end of the 2006 exploration season. While the large target to the east of Kemess North Offset looks to be quite deep on the section view provided, the proposed drill holes will be collared at much lower elevations to the north and south of the plane of the section. Assay results from these holes are expected towards the end of December.

Figure 2: Kemess North Area (Vertical, North Looking, Longitudinal Section)
Kemess North

Titan 24 (2 spreads) IP results

TITAN-24 2D CHARGEABILITY INVERSION
(from Pole-Dipole Array DCIP Survey - $a=100m / n=0.5$ to $32.5$)

Colour Scale
0-75mrad

View Looking South

Kemess Camp Exploration
Isometric View of Kemess North Region

- Chargeability (sulphide) anomaly located beneath cover east of KN
- Altus
- Ora
- Pit Area

TITAN-24 SMOOTH 2D CHARGEABILITY INVERSION

View Looking North

From Northgate Minerals Press Release May-2007
NORTHGATE REPORTS STRONG QUARTERLY CASH FLOW OF $43.7 MILLION
A THIRD LARGE GOLD-COPPER PORPHYRY SYSTEM DISCOVERED AT KEMESS

VANCOUVER, July 26, 2007 – (All figures in US dollars except where noted) – Northgate Minerals Corporation (TSX: NGX; AMEX: NXG) today reported cash flow from operations of $43,685,000 or $0.17 per diluted common share and net earnings of $8,647,000 or $0.03 per diluted common share for the second quarter of 2007.

SECOND QUARTER HIGHLIGHTS

- Production of 65,999 ounces of gold and 14.8 million pounds of copper
- Net cash cost of production of $35 per ounce of gold
- Exploration drilling on targets identified in a deep penetrating induced polarization (IP) survey in 2006 has discovered two new zones of mineralization east of the Kemess North deposit
  - Ora Zone: Hole KH-07-04 returned 441 metres (m) of 0.38 grams per metric tonne (g/t) gold and 0.39% copper
  - Altus Zone: Holes KH-07-03 and KH-07-05 returned 155 m and 128 m, respectively, averaging 0.23 g/t gold and 0.3% copper

Ken Stowe, President and CEO, stated, “The discovery of another large mineralized system in the Kemess camp is very exciting. Equally important is the success of the Titan® deep penetrating IP survey technique, which has proven itself to be an excellent predictive tool for spotting drill holes on the Kemess property in areas where there is no surface expression of mineralization. Over the next two months, we plan to follow up with further drilling of the Ora and Altus zones while conducting additional IP surveys at both Kemess North and Kemess South. From a financial
Field surveys corroborated our initial 2-D DC synthetic modeling studies, plus the discovery of new mineralized zones.

Initial inversion results suggest that deeper Cu-rich zone is not differentiated from shallower Pyrite Halo – the use of Null-Conductivity IP model proposes deeper chargeability signature consistent with Cu-zone.

Kemess North and Ora signatures coincide with Resistivity Low/IP High features – consistent with previous geophysics.

Mineralized zones defined below >350m cover, extending to >1km – confirmed by drilling of deepest mineralization in Kemess camp, Cu-Au at 855-1296m
• Mineralized zones also indicated to subcrop (Ora), but remained previously undetected/hidden below talus cover – proves shallow to deep resolution capability of Titan DAS surveys.

• Deeper DC + MT Resistivity Low signatures suggest source is deeply rooted hydrothermal clay-chlorite alteration system.

• More detailed coverage recommended (e.g. Orion 3D survey), supported by 3D inversion, to better determine geometry and potential continuity between Kemess North and Ora-Altus zones, as well as nature of apparent deeply altered/mineralized system.
• **Availability of Physical Property Data (from previous geophysics)** Critical for Success of Synthetic Model Study.

• **Although Titan Survey Results Led to New Discovery adjacent to Kemess North, Arguably Success is Attributed to Strategically Designed Survey.**

• **However, Knowledge Gained from Synthetic Modeling Provided Confidence in Capability of Geophysics to Be Successfully Applied in These Areas.**

• **Titan Surveys Able to Prove that Mineralized System Extended >1.5km Beyond Previously Known.**
Delineation of a Porphyry Copper-Gold system using ORION 3D DCIP- MT and CSAMT surveys—Case history, the Santa Cecilia Deposit, Chile

Nasreddine Bournas* (1) and David Thomson (2)
(1) Quantec Geoscience, (2) Cerro Grande Mining Corporation

KEGS-PDAC Symposium, Toronto March 2nd 2013
Introduction

- Location, High Western Cordillera, Maricunga Belt.
- Intensive Hydrothermal alteration
- Magnetic, CSAMT and ORION 3D DCIP/MT
SC project area is located in the High Western Cordillera of Chile’s “3rd Region” within the Maricunga Mining Belt. Intensive Hydrothermal alteration with Cu-Au-Ag mineralization occurs within an area of ≈ 10 km² at elevations of 3600 to 4600m ASL. CSAMT and ORION 3D DCIP/MT results are presented and discussed.
History

- 1984-1990- Anglo American Chile
- 2009- Ground magnetic survey
- 2010- CSAMT and Mobile Metal Ion (MMI)
- 2011-2012- CSAMT coverage and drilling
- 2012- QUANTEC ORION 3D DCIP/MT
Regional settings

- Maricunga Mining Belt (Mining District).
- Folded Formations of Upper Triassic Caspiche
- Oligocene to Lower Miocene Aguas Blancas and Rio Nevado Formations
- Porphyry intrusives, diorites and Qz-diorites & alteration zones
On regional scale SC lies within the Maricunga Belt (Mining District). Basement rocks are Folded Formations of Upper Triassic Caspiche (volcanics and sediments) unconformably overlain by Oligocene to Lower Miocene Aguas Blancas and Rio Nevado Formations (Volcano-sedimentary rocks). Mineralization is found in Porphyry intrusives, diorites and Qz-diorites located in alteration zones.
Intense hydrothermal alteration

Peripheral propylitic

Silicification

Intermediate argillic

Mz-intrusion

Qz-alunite-clay-Py

Advanced argillic

1km

Intense hydrothermal alteration
Intense hydrothermal alteration, which has affected all rocks at Santa Cecilia, comprises a peripheral propylitic zone with an inner shell of quartz-alunite-sericite-chlorite, clay-pyrite. Intensity is indicative of mineralization that includes stockwork intrusives, porphyry-type intrusives and silicified structures. Alteration is 3km wide and centered on Cerro Del Medio, and extends along the ridge to the ESE where it narrows to approximately one kilometre.
Widespread silicification
There is a widespread silicification associated with argillic alteration, disseminated sulphides, pyrite and alunite. Main mineralization includes gold, silver, and copper in Stockworks and siliceous veins associated with Qz-diorite and microdiorite including pyrite, chalcopyrite within altered breccias.
A detailed ground magnetic survey with east west traverse lines of 100 meters apart was run by Quantec over the entire SC altered zone in 2009. The RTP image draped on the topography, shows a broad circular feature of low-magnetic relief closely outlining the SC alteration zone probably reflecting magnetite destruction. The strong short wavelength lineament observed in the SE coincides with diorites and microdiorites.
Enhanced filtering technique such as the 2\textsuperscript{nd} VD, better highlights the near-surface feature and particularly provides with a precise delineation of the altered zone the response of which is very well marked by the low-gradient area as shown in this slide.
The transition between low and high gradient area marks the outline of the Peripheral alteration zone.
In addition, the magnetic interpretation suggests that the area has been subjected to several faulting systems (NW, NE).
Blue = low mag susceptibility and red = high mag susceptibility. The blue areas appear to be indicative of advanced alteration due to destruction of magnetite.
• Source dipole (3.5 km length)
• Current = 2-13 A
• Acq. Bandwidth = 2-9000 Hz
• Inv. Bandwidth = 24-9000 Hz
• Bostick depth ≈ 750m

CSAMT

• Source dipole (3.5 km length)
• Current = 2-13 A
• Acq. Bandwidth = 2-9000 Hz
• Inv. Bandwidth = 24-9000 Hz
• Bostick depth ≈ 750m

CSAMT Survey 2010

Horse-shoe shaped conductor

Slice at 3800m ASL
A CSAMT was conducted in 2010 to test the MMI anomalies and to detect anomalous zones associated with mineralization and alteration. This slide shows the 2D MT inversion results along the CSAMT lines.
MMI (Mobile Metal Ion) 2010 survey (SGS)
A Geochemical tool for deeply buried Mineralization

Copper anomaly

CSAMT Conductor
Following the successful results of the Mobile Metal Ion (MMI) survey over the nearby Caspiche Mine, a MMI survey was carried out over the SC property by SGS. This slide shows the strong Cu-geochemical anomaly, occurring in coincidence with the CSAMT conductor.
Discovery holes (2011)

Mineralization over 1000m
Au ≈ 0.2 g/t
Cu ≈ 0.25%
Mo ≈ 80 ppm

Discovery holes (1400 and 1700 m)
In 2011 two deep holes have been drilled by CEG to test the CSAMT and the MMI anomalies (CDM03=1400m and CDM02=1700m). Both holes were successful and intercepted Cu-Au and Ag mineralization which is still persistent down to level 2800 ASL.
Drill testing the CSAMT conductor
A CSAMT section looking NW. It highlights a flat lying conductor with limited depth extension. The deep part of the CSAMT model section does not however, support the DH results.
ORION 3D Survey (Fall 2012)

Objective: 3D imaging of mineralization and alteration
In Fall 2012 an Orion 3D survey was carried out by Quantec covering the SC alteration zone with the objective of 3D imaging and investigating of deep-seated mineralization and alteration.
Orion 3D DCIP Survey

- 539 Current injections (Transmits)
- 300 (⊥∥) receiver dipoles (150m)
- 50 DAUs (loggers)
539 current injections and 300 receiver dipoles were deployed along with loggers that collect the data from neighbouring dipoles.
Remove the current ext.
Orion 3D MT Survey

- 100 MT sites
- Bandwidth=250-0.001 Hz
- Bostick depth>3km
539 current injections and 300 receiver dipoles were deployed along with loggers that collect the data from neighbouring dipoles.
Remove the current ext.
ORION 3D Survey

150,000 DC data points collected
Pseudo-plot of apparent resistivity data
Orion 3D Survey

150,000 IP data points collected
Pseudo-plot of apparent chargeability data
3D DC Resistivity Model
A sensitivity analysis has been applied to the Model data to determine the areas of confidence (areas that are sensitive to the survey).

Show the model with sensitivity
3D DC Resistivity Model

1 km
3D DC Resistivity Model

1 km
3D IP Model

1 km
3D IP Model
3D IP Model

1 km
DC Res Horizontal Slice
(3775m ASL) \( \approx \) 700m depth
IP Horizontal Slice (3775m ASL) ≈ 700m depth
IP Horizontal Slice (3775m ASL) ≈ 700m depth
DC Res Horizontal Slice
(3550 m ASL) ≈ 900m depth
DC Res Horizontal Slice
(3550 m ASL) ≈ 900m depth
IP Horizontal Slice (3550 m ASL) ≈ 900 m depth
IP Horizontal Slice (3550 m ASL) ≈ 900m depth
3D MT Model

3 km
3D MT inversion code (WS and Egbert) using half space and 1D models and topo., 15 freq. 250Hz-1000 s. 99 sites
3D MT vertical slices
3D MT Model

DC Resistivity

Deep-seated Conductor

1 km
The MT model suggests a down-dip extension of the conductive zone
3D MT

CSAMT Conductor

Feeding Zone?
The CSAMT conductors appears as of limited depth extension. The MT suggests a vertical conductive zone featuring a possible feeding zone.
3D MT

< 10 Ohm-m

3D MT
MT isosurfaces of < 10 Ohm-m
Conclusions

- Accurate delineation of the outer alteration with the magnetic data.

- Strong CSAMT conductor in coincidence with MMI anomalies.

- Accurate delineation of alteration and stockwork intrusives (up to 1km) with the ORION 3D DCIP

- Significant conductive zone, increasing the size and depth extension of the alteration zone and related mineralization to depth of 2km in the down dip direction with the ORION 3D MT
Acknowledgments

- KEGS
- Cerro Grande
- Quantec Geoscience
THANK YOU

QUESTIONS?
Deep exploration: reasons and results

15 August 2013

Chris Wijns
Group Geophysicist, First Quantum Minerals
What is “undercover”?

- **Is not lack of outcrop**
  - Deeply weathered in-situ regolith is usually amenable to soil geochemistry for geological and alteration mapping

- **Is not leached regolith (leached of target metal)**
  - still usually holds other geochemical indicators (Chile=Mo, Kamoa=Zn,Pb)

- **Is transported overburden that masks or displaces surface geochemical expression of mineralisation**
  - e.g., windblown sand, transported gravel, young surface volcanic flows
Reasons for looking deep

- Junior purpose: get an intersection, doesn’t matter if it will ever be economic
- Top end of town: have $$, will probably mine it (more concerned with tonnes than profit)
- “Research hole”: geological understanding will let us explore better near the surface
Do we really need to look deep?

• As an industry ... maybe
• As individual companies ... no
• Do we need to look under cover? ... Yes
First Quantum deep exploration examples

- NiS deep drilling on seismic + concept
- Sed Cu deep drilling on concept alone
Kevitsa Ni-Cu

- Mafic/UM intrusion into interlayered metavolcanic/metased country rock
- Grades 0.3% Ni, 0.4% Cu, 275 M tonnes
Kevitsa Ni-Cu

- Mafic/UM intrusion into interlayered metavolcanic/metased country rock
- Grades 0.3% Ni, 0.4% Cu, 275 M tonnes

Where’s the good stuff?
Defining base of intrusion

- Base of intrusion interpretation to constrain exploration for contact style ore
Base of intrusion

- Drill pierce points + 2D and 3D seismic
Extension of intrusion?
Extension of intrusion?

- Deep drill hole 1.7 km
Gravity and magnetics

Gravity (Bouguer)

Magnetics (RTP)
Sediment-hosted Cu

- African Copperbelt = Lufilian Arc
Copperbelt deposit settings

- Schematic stratigraphy, fluid/metal sources, and traps

Hitzman et al, 2010
Copperbelt deposit settings

- Simple structural/chemical trap model
Copperbelt deposit settings - ores

- predominantly in clastic (less commonly carbonate) sediments; (1) large tonnage deposits in dark shales and carbonates above thick red bed sequence

1. SHALE HOSTED
Copperbelt deposit settings - ores

- predominantly in clastic (less commonly carbonate) sediments; (2) small/large deposits in sandstone or arkose lenses within interbedded sandstone/shale redbed
Kansanshi Cu(-Au)

- Kansanshi domes - mineralisation at each local apex
Kansanshi Cu(-Au)

- Kansanshi domes - mineralisation at each local apex
Reductant horizon control

- “Middle mixed clastics” ore host
Drilling result

- Nil
Mapping basement domes with AMT

- AMT conductivity, 16 - 8192 Hz, 1+ km depth resolution

- Control line mapping basement in the west, dominated by Mwashia shale to east
Mapping basement domes with AMT

- AMT conductivity, 16 - 8192 Hz, 1+ km depth resolution
Mapping basement domes with AMT

- Long regional lines < 40 km for detection of hidden basement domes

Depth extent 1.4 km
Conclusions

• For First Quantum, deep drilling is about geology and not metal
  - improving stratigraphic and structural understanding to help shallow targeting

• Seeing deep is a fight against physics
  - seismic = $$ vs objectives
  - geologically constrained inversions of various data sets

• Explorability depends on deposit style
  - Drill deep for hydrothermal systems with huge alteration footprints
  - NiS cannot afford exploration by deep drilling
• What is “under cover”?
• Do we need to look deep?
Pyhasalmi

- 2012 production: 12,600 t Cu, 25,600 t Zn, 891,700 Py
- home of the world's deepest sauna at 1440 metres
SEAM – THE CHALLENGE OF MODELING SEISMIC EXPLORATION AT FULL SCALE

Overview
SEAM—Modeling seismic exploration at full scale

Outline

- Introduction to SEAM
- Review of SEAM Phase I – Modeling modern 3D marine seismic acquisition
- Overview of SEAM Phase II – Modeling the future of land seismic acquisition
- Candidates for SEAM Phase III
What is SEAM?

SEG Advanced Modeling Corporation

The SEG Advanced Modeling Corporation

On 14 February 2007, the SEG Advanced Modeling (SEAM) Corporation was incorporated as a not-for-profit organization in the state of Oklahoma, with SEG as sole member, for the purpose of literary, policy, and management oversight of the SEAM projects ("Phases"). SEAM is an industrial consortium dedicated to large-scale leading-edge geophysical numerical modeling.

The SEAM projects will provide the geophysical exploration community with geophysical model data for subsurface geological models at a level of complexity and size that cannot be practically computed by any single company or small number of companies. A general introduction to the SEAM initiative can be found in TLE's June 2007 issue (44th PDF).

The SEAM mission is to advance the science and technology of applied geophysics through a cooperative industry effort focused on subsurface model construction and generation of synthetic data sets for geophysical problems of importance to the resource extraction industry. Data sets, after an initial two-year period of confidentiality, will enter the public domain.

The primary goals of SEAM are to:

- design and generate synthetic model 3D and 2D seismic data
- share the high cost of substantial model design and generation
- provide a forum to discuss geophysical problems of interest
- advance the art of modeling and computation
- provide data sets for industry benchmarks and educational purposes

FROM THE BYLAWS:

To this end, the corporation shall advance the science and technology of applied geophysics by...

(1) designing and generating synthetic model 3D and 2D geophysical data that represent challenges to the geophysical community;

(2) providing a forum to discuss geophysical problems of interest;

(3) advancing the art of modeling and computation by testing and comparing modeling code for accuracy and efficiency;

(4) providing data sets for industry benchmarks and educational purposes; and

(5) furthering the science of seismology for the public benefit.

www.seg.org/resources/research/seam
Motivation for SEAM

- Provide datasets to test algorithms for imaging and inversion – i.e., datasets for models that represent realistic (complex) earth structures and physical parameters, where the true inversion result is known.
- Better understand features and artifacts in real images.
- Explore trade-offs in acquisition methodologies.
- Train next generation of seismic processing and imaging experts.
SEAM Corporation
Board of Directors

Management Committee
one representative from each participant

Technical Committee 1
Technical Committee 2
Technical Committee 3

SEG Support Staff
Project Manager

Two concurrent projects
SEAM Phase I – Marine seismic (2007)
SEAM Phase II – Land seismic (2011)

Projects have an initial 3-year lifetime (with possible extensions)
Member fees are $60k/year (with late fees)
SEAM Advanced Modeling Corporation
Board of Directors

Manik Talwani, Chair
Kevin Bishop, Vice Chair
Jesse Perez, Treasurer
Kamal Al-Yahya
Sheldon Breiner
Steve Danbom
Henri Houllevigue
Yaoguo Li
Scott Morton
SEAM Phase I

Challenges of Sub-salt Imaging in Tertiary Basins, with Emphasis on Deepwater Gulf of Mexico
SEAM I Results

- Phase I finished acoustic simulations in 2011
  - 62,478 shots, 450 K traces/shot
  - Full data (220 TB) distributed to members
  - Classic data sets corresponding to conventional 2D and 3D acquisition geometries also available

- Phase I extension through a RPSEA proposal (www.rpsea.org)
  - Reduced set of pseudo-acoustic TTI and full isotropic elastic simulations
  - Simulations of non-seismic exploration methods: CSEM, MT, and gravity gradiometry

- Papers at SEG 2011 using Phase I results available at SEG SEAM web site

www.seg.org/resources/research/seam/seamsuccess011012
SEAM Phase II (launched March 2011)

Understanding the Challenges of Land Seismic through advanced 3D elastic modeling
Goals for SEAM Phase II – Land Seismic Challenges

Use 3D elastic-wave modeling to better define

- Trade-offs in next-generation land-seismic acquisition ("million-channel" systems)
- Challenges in land-seismic data-processing, imaging, and inversion
  - Near-surface complexity: topography, strong velocity contrast, heterogeneity at all scales
  - Complex reservoirs: fractured, unconventional, complex structure

- Modeling challenges
  - Accurate representation of surface-wave scattering with extreme topography
  - Fully anisotropic modeling of fractured reservoirs: HTI, VTI, TTI, general anisotropy
  - Accurate modeling of Q (visco-elastic effects) to mimic the balance of surface and body-wave energy seen in real data
Arid near-surface model  
(Saudi Aramco, Chevron, Sinopec)

Foothills near-surface model (extreme topography)  
(Total, Repsol, Shell)

Unconventional model  
(fractured shale gas reservoirs + overburden)  
(BP, Chevron)

Thrust model (complex tectonic structure)  
(Repsol, Total)
SEAM Approach to Model Building

Build generic structural models as much as possible from real geologic formations, including information, such as structure and reflectivity, from 3D seismic data.

Populate the model with elastic properties derived from petrophysical models based on cores and well logs.

Elastic Inversion Models from seismograms to rock/reservoir properties

Elastic Parameter Models from rock properties to elastic properties

Rock Properties
\( V_{\text{shale}} \), Porosity, Pressure, Fluid Saturations, ...

Geophysical Parameters
\( V_p, V_s, \rho, C_{ij}, Q, \sigma, ... \)
Candidate for SEAM Phase III: One possibility

- Mineral exploration?

- Goal?
  - Facilitate inversion and or interpretation?
  - Understanding data acquisition in mineral systems?

- Data types?
  - Electrical, induced polarization, and Electromagnetic
  - Potential field
  - 3D seismic

- Geologic models?
  - Deposit types?
  - Deposit systems/footprints?

- Synergy with non-seismic in oil and gas exploration and production?

- Potential funding base?
Possible opportunities

- Similar to SEAM Phase-I and II approach
  - Mineral related simulation program consisting of model building and simulation focused on EM
  - “Integrated” simulation focusing on 3D seismic, potential-field, and EM in hard rock environment
  - General non-seismic (gravity, magnetic, and EM) covering needs in hydrocarbon and mineral industries

- A modular approach
  - Perform model building and simulation, then deliver the results in packages

- A broader approach to include a near-surface hazard in oil and gas and other similar fields
Example model types

- Deposit systems for understanding the response of entire footprint
- Porphyry systems with multiple alteration phases
- Deposits under cover and at depth

Purpose of simulation projects

- Trials of acquisition systems, and processing and interpretation methods
- Understanding geophysical signatures of deposit systems
- Verification of simulation/interpretation algorithms
- Education of next generation geophysicists
Deliverable/product (?)

- Models
- Simulated data
- Verification of simulation/interpretation algorithms

Expertise/vendors

- Enough vendors in industry and academia to construct models with sufficient complexity with relevant geological features
- Several groups with the expertise, codes, and facility to carry out simulations
For further discussion regarding SEAM Phase-III candidate, please contact

- Yaoguo Li, ygli@mines.edu
- Ken Witherly, ken@condorconsulting.com
# SEAM II Management & Technical Committees

## Management

**Gladys Gonzalez, Repsol**

One representative from each member company

## Near-Surface Modeling

**Tim Keho, Saudi Aramco**

- Shon Bourgeois, Marathon
- Scott Burns, OXY
- Maria Donati, Repsol
- Constantin Gerea, Total
- Stefan Kaculini, CGGVeritas

Chris Krohn, ExxonMobil
- Pedro Munoz, Repsol
- Carl Regone, BP
- Joseph Stefani, Chevron

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- Elizabeth L'Heureux, BP

**Charles Sicking, Global**

- Jimmy Muskaj, Repsol
- David Stathopoulos, Repsol
- Joseph Stefani, Chevron
- Qunshan Zhang, Repsol

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- Scott Burns, OXY
- Tim Brice, WesternGeco
- Maria Donati, Repsol

**Carl Regone, BP**

- George El-Kaseeh, WesternGeco
- Tom Fleure, Global Geophysical
- Steve Knapp, Hess
- Jimmy Muskaj, Repsol

## Numerical Design

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- Gladys Gonzalez, Repsol
- Scott Morton, Hess
- Joseph Stefani, Chevron

- Igor Terentyev, Hess
- Tetyana Vdovina, ExxonMobil
- Qunshan Zhang, Repsol

- Corey Morgan, BHP Billiton
- Jean-Marc Mougenot, Total
- Pedro Munoz, Repsol
- Gerry Wilbourn, Anadarko

Administrative support
- Peter Pangman, SEG
- Jan Madole, SEG
- Barbara Cartwright, SEG

Oversight
- SEAM Board of Directors
- Project Manager
  - Michael Oristaglio, Yale/SEG

Administrative support
- Peter Pangman, SEG
- Jan Madole, SEG
- Barbara Cartwright, SEG

Oversight
- SEAM Board of Directors
- Project Manager
  - Michael Oristaglio, Yale/SEG
SEAM Phase II Summary [From 2012 briefing]

- SEAM Phase II started in March 2012, with 20 participants since June.

- Goal is to build a suite of near-surface and subsurface models and perform full elastic-wave simulations to advance the state of the art in land-seismic acquisition, processing and imaging, including studies of future high-channel land systems.
  - **Near-surface**: topography, strong scattering (karsts, voids), rapid velocity variations
  - **Subsurface**: subtle reservoir features (unconventional plays), fractures (anisotropy), complex structures

- Four models are under construction by technical committees.
  - **Arid model** (near-surface): strong velocity contrasts, dipping refractors, karsts, buried topography
  - **Unconventional model** (near-surface and subsurface): shale gas reservoirs
  - **Foothills model**: extreme topography and highly heterogeneous velocity
  - **Thrust-zone** reservoir model: complex structural geology

- Several geologic models will be completed by the spring of 2012, which will be followed by QC tests on the model and a series of benchmark numerical simulations.

- Request for bid (RFB) for elastic simulations will be issued in summer 2012.
Arid Model

*Expected final model parameters*
- 10 km x 10 km x 2 km
- 500 m near-surface region
- $V_p$ (min) = 1000 m/s (600 m/s)
- $V_s$ (min) = 500 m/s (300 m/s)
- $f_{max}$ = 60 Hz
Foothills Model: Extreme topography

Elevation differences up to 1000 m
Depth = 0 m $\rightarrow$ SRD = 2000 m above MSL

courtesy of Constantin Gerea, Total
Foothills Model: Strong near-surface heterogeneity
courtesy of Constantin Gerea, Total
Foothills Model: Strong near-surface heterogeneity

Geology: Mountainous valleys filled with alluvial deposits, quartz conglomerates, dry river beds
Rock properties: Low velocities (< 1100 m/s), strong vertical gradients, lateral velocity variation and inversions

Vp range: 1100 – 4500 (m/s)

courtesy of Constantin Gerea, Total
SEAM
Are we ready for a SEAM thread in the Undercover Journey?
<table>
<thead>
<tr>
<th></th>
<th>Deposit</th>
<th>Deposit Type</th>
<th>Number of Model Variations</th>
<th>Contributing Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Synthetic Kimberlites</td>
<td>Kimberlite</td>
<td>13</td>
<td>Anglo American and Rio Tinto</td>
</tr>
<tr>
<td>2</td>
<td>Brunswick Mining and Smelting #12 Mine</td>
<td>VMS</td>
<td>12</td>
<td>Noranda</td>
</tr>
<tr>
<td>3</td>
<td>San Nicolas</td>
<td>VMS</td>
<td>13</td>
<td>Teck-Cominco</td>
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<td>4</td>
<td>Spence</td>
<td>Cu Porphyry</td>
<td>14</td>
<td>BHP-Billiton</td>
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<tr>
<td>5</td>
<td>Gamsberg</td>
<td>Sedex</td>
<td>13</td>
<td>Anglo American</td>
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<td>6</td>
<td>Red Dog</td>
<td>Sedex</td>
<td>5</td>
<td>Teck-Cominco</td>
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Gravity Gradiometry-2001
IP-2005
<table>
<thead>
<tr>
<th>Lithology</th>
<th>Base density</th>
<th>Relative density</th>
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<tbody>
<tr>
<td>ore</td>
<td>4.31</td>
<td>1.73</td>
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<tr>
<td>volcbreccia</td>
<td>2.85</td>
<td>0.27</td>
</tr>
<tr>
<td>mafflowsed &amp; volcseds</td>
<td>2.87</td>
<td>0.29</td>
</tr>
<tr>
<td>rhyoflows breccia &amp; mvt</td>
<td>2.85</td>
<td>0.27</td>
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<tr>
<td>graphmudstone</td>
<td>2.58</td>
<td>0</td>
</tr>
<tr>
<td>rhyolite intrusions</td>
<td>2.75</td>
<td>0.17</td>
</tr>
<tr>
<td>overburden</td>
<td>2.00</td>
<td>-0.58</td>
</tr>
</tbody>
</table>

Figure 6. San Nicolas structural model.
CMIC-Foot Prints

- Canadian Malarctic-QE
- Millennium SK
- Highland Valley-BC
Role of SEAM Models-Value

- Exploration targeting-planning; synthetic/predictive
- Exploration targeting-tactical; real-time data analysis
- Educational
Undercover Toolkit

Magnetotelluric Section through Olympic Dam

OD Density Inversion Anomaly

Areas of Textureless Seismic Response

© Condor Consulting 2013
Density model
Conductivity model
Velocity model
Role of SEAM Models-Challenges

- Oil & gas model is high dependent on internal R&D groups supporting/using SEAM results

- Service component supporting minerals of limited technical depth/resources.

- Cost
Geochemical techniques for undercover exploration: The 'new geophysics'?

James S. Cleverley | Principal Geochemist
How do I explore for a mineral system?

Undercover, ASEG Workshop – Melbourne, August 2013

ALL THE GOLD IS GONE
The Exploration Challenge

Deep Exploration Targeting

A New Search Space
As a result of this complex history, we can have profiles which are quite distinct from other environments such as Chile and Canada. First, our cover is generally weathered and mature compared to Chile and Canada where much younger. Many regions are tectonially stable and have not experience much neotectonic activity. Because of present arid climate, upper soil Profile development is very poor and lack development of strong A and B horizons because of low leaching environments. We have silicified and calcareous B horizons. Because of palaeowater tables we may ferricrete developed at redox front in some situations and may have experienced processes outlined by Cameron and others. We can take advantage of those processes.
Mineral Systems and R&D

The Why Question

Why is the ore body there?

1. Geodynamics
2. Architecture
3. Fluid reservoirs
4. Flow drivers & pathways
5. Deposition
6. Preservation

The Where Question

Where is the next ore body?
Targeting Distal Footprints

Fisher et al; 2013
We don’t have much to go on ...
The process can be slow

Drill → Sample

Target

Measure

Interp
What is the anatomy of a mineral system and how do we read its story?
The Mineral System?

- Lithology
- Metamorphism
- Metasomatism
- Structure
Map of TOFR in the Kalgoorlie District

Scott Halley Minmap

Undercover, ASEG Workshop - Melbourne, August 2013
This is a map of the antimony distribution based on analyses of end of hole RAB drill samples. Antimony substitutes into the lattice of pyrite, and it has a larger primary dispersion halo than any other pathfinder in Archean gold systems. Because it goes into a widely distributed mineral like pyrite, it has a remarkably regular distribution pattern. Note the scale of the anomalism. Sampling on a pattern of 2km by 2km would not have discovered the gold ore bodies, BUT it would have demonstrated that this was a mineralised segment of a greenstone belt. Broad-scale anomaly definition like this is an excellent way to discriminate between greenstone belts.
Shallow cover techniques
Techniques in the profile

< 50 meters – Gas, hydrogeochem, biogeochem (trees/shrubs)

> 50-100 meters - Hydrogeochemistry

Immobile geochem/mineralogy
Resistate mineral chemistry

Whole rock geochem/mineralogy
Mineral chemistry
Geochemistry extends into 3D
Geochemistry

Petrophysics

Texture

Mineralogy
Modelling the coupled approach
Model & simulating geological history
The listric fault model (see Cleverley et al., 2006) is a model of fluids being expelled from a cooling granite pluton. These fluids travel up the fault, depositing gold at the region of the orange oval. There are also convection cells set up in the greenstones and also the felsic volcanics.

Calcite

Chlorite

0.189 Ma
A mineral system also evolves in time

0.189 Ma

ep destruction
Gravity response from this model

Greenstone

Gneiss basement (~ felsic)

Granite

Density (t/m³)

3.1
3.05
3
3
2.95
2.9
2.85
2.8
2.75
2.7
2.65

Distance along profile (km)
Gravity response with extra ‘cover’

1.0km above top of deposit & 100m regolith

0.5km above top of deposit & 100m regolith

Top of deposit at base of 100m regolith

0.5km below top of deposit & 100m regolith

1.0km below top of deposit & 100m regolith

Deposit buried

Deposit crops out

Deposit is eroded
Technology is driving a new way of thinking ....
DISCOVERIES ARE FALLING

OUR PLAN IS TO INVENT SOME SORT OF WIDGET TO HELP TARGETING

THE VISIONARY LEADERSHIP WORK IS DONE. HOW LONG WILL YOUR PART TAKE?
Regional Prospecting ... 1850
Regional Prospecting ... 2012

Stream Sediment

Standard sampling kit:
- 2 sieves (2mm and 150μm)
- 1 fibre glass pan, 1 wooden pan
- sample bags
- 1 funnel
- 1 trenching tool
- rubber gauntlets.

Sediment is dug from beneath the oxidised layer in the centre of the stream channel and sequentially sieved through coarse (2mm) and fine (150μm) mesh. The fine fraction is collected in a fibre glass pan and left to settle for 20 minutes.

After settlement excess water is carefully drained off. The sediment is homogenised and transferred to a Kraft sample bag.

The samples are air dried until plastic in consistency, before being dispatched to Keyworth for freeze drying and sample preparation.

The excess <2mm +150μm fraction is washed, shaken and panned to provide a heavy mineral concentrate. This is carefully examined in the field for minerals of economic interest and contaminants. Samples are retained in the NGD, Keyworth.
The Story of AEM

Source: (Witherly, 2000)

Thompson, Bathurst, Kidd Creek
Evolving technology

Discoveries by Deposit Style

Source: Witherly, 2000
AEM evolution to platform technology

...and now
The REx Platform
Unlocking Innovation

Growing Australia’s share of the global mineral services & manufacturing sector

New generation pre-competitive data

Transition of science to innovation

Govt & Survey

Exploration & Mining Sector

Service Sector

R&D
X-Ray Detector Revolution

- High count rates
- High energy resolution (e.g. 140 eV)
- Peltier cooling

Curiosity technology
CheMin applied to mineral exploration
Biggest challenges in processing..
Deep Exploration Technology CRC

CT Drilling in hardrock

Sensing While Drilling

Decision Support

Lab-At-Rig
Real time integrated data while drilling
The Dynamic 3D Geology Model
A window on the future?
Linking geophysics and geochemistry
False negatives – transported cover
Characterisation of Cover

TEMPEST GA-LEI

SPECTREM GA-LEI

INTERPRETED GEOLOGY

Yilgarn

Bryah Basin

Geology adapted from English et al 2012
Characterisation of Cover

TEMPEST GA-LEI

SPECTREM GA-LEI

INTERPRETED GEOLOGY

Unmapped sediment filled palaeovalley

Boundary defined by ground gravity

Yilgarn

Bryah Basin

Geology adapted from English et al 2012

Undercover, ASEG Workshop - Melbourne, August 2013
Integration of data in 3D
3D spatial understanding and quantification

Gold isosurfaces: 0.05, 0.1, 0.5, 1.0 ppm

FAV Probability isosurfaces (0.5, 0.6, 0.7)
Large geochemical/mineralogical datasets will require new approaches to support decision making

S/Ti from pXRF during drilling

- Down hole S/Ti value
- Sulphide veinlets
- Broad sulphide zones
- Wavelet transform of sulphur

Large scale features
Medium scale features
Small scale features

Large scale domains
Medium scale domains
1. Lab quality, real-time geochemistry and mineralogy while drilling
   • Geochemistry and Mineralogy like a wire line log

2. Coupled sensor systems and processing will drive the future
   • Light elements
   • Low DL components

3. Data platform analytics
This talk includes many ideas from others ....

Thank You
Model building to support exploration undercover

John McGaughey
Acknowledgements

- Glenn Pears  (Mira Geoscience)
- Peter Fullagar  (Fullagar Geophysics)

(for doing 100% of the work)
Advantages of explicitly modelling cover

• Rapid model validation/testing through forward modelling
• A variety of inversion styles:
  • physical property inversion or updating geological boundaries
• Imposition of geological constraints
  • e.g. drill hole pierce points or litho-based property constraints
• Control over inversion is now possible
  • restrict changes to selected geological boundaries or selected domains
• A driver for integrated interpretation
  • minimise ambiguity associated with non-uniqueness
  • inverted cover model is geological
VPmg / VPem1D inversion styles overview

- Geological model parameterisation lends itself to a variety of inversion styles
VPmg constrains the model geometry according to drill hole intercepts and drill hole paths.

During inversion, the model is fixed at the drill hole ‘pierce points’

An upper bound is imposed on the interface(s) below the EOH
Bouilia Gravity Inversion, QLD

- Sedimentary cover thickness strongly influences area selection for exploration in Proterozoic and Archean terranes.
- Construct basement unconformity consistent with gravity data.
- Natural application for geometry inversion…
  …but fraught ambiguity.

- **Demonstrate via two inversions;**
  - Simply assume Proterozoic basement denser than the overlying Paleozoic cover. Basement contact is flat initially at an estimated depth (~700m).
  - Incorporate all available *a priori* information (eg drilling, aeromagnetic interpretations).
Boulia Gravity Inversion, QLD

Free Air Gravity Data

Mt Isa
Queensland

Mira Geoscience
...modelling the earth

Advanced Geophysical Interpretation Centre

350 000 400 000 450 000 500 000

7 500 000 7 550 000

1.7 16.2 26.1 33.0 39.1 44.5 62.9

mgal

Courtesy QDME
Simple interpretation (inversion)

- Geometry inversion assuming homogeneous cover overlying homogeneous basement, starting model elevation = flat.
Incorporate a priori information

Common Earth Model

Drill hole Data

Coloured points denote magnetic depth solutions

Gravity Data

Basement intersections (2) and water bores (upper bound constraint)

Courtesy QDME

Incorporate a priori information

Advanced Geophysical Interpretation Centre

Mira Geoscience
...modelling the earth
Incorporate a priori information

• Integrated approach implementing drill hole constraints

Basement intersecting drill holes

Light blue holes represent water bores (upper constraints)

VA = 20x

Courtesy QDME
Boulia remarks

- Conventional result in this case is notably different from the integrated approach.
- No more than two basement intersecting drill holes successfully guided interpretation away from the conventional style.
- (gravity high = basement high)
Malhadina Gravity Inversion - Portugal

- gravity data
- 30 mgal range
- primary control is overburden thickness
- secondary control is basement density
- basement density highs reveal new targets
Malhadina Gravity Inversion - Portugal

topo with outcrop lines (Zx10)
Malhadina Gravity Inversion - Portugal

initial top Paleozoic surface
Malhadina Gravity Inversion - Portugal

post-inversion top Paleozoic surface
SPECTREM case study

- N-S flight lines
- 250m line spacing
- Bz (ppm) used for modelling
- Time from 26 micro.s to 9987 micro.s
- Towed bird (slingram)
- 50% duty cycle, processed to 100%.

- Paleochannel modelling application.

Data courtesy of Anglo American
Paleochannel modelling result.

- The result is a 3D conductivity model that explicitly defines the base of paleochannel.

    Extracted basement surface from inverted model

- Direct result of operating on a geological model

- Depth to basement maps are readily produced from the outputs.
TEMPEST survey example – Bull Creek

• Two phases of modelling were undertaken for the Bull Creek data set.

• First pass inversion adopted the same strategy as the SPECTREM paleochannel case study, using two layer model comprising cover overlying basement.

• After geometry inversion, conductivity inversion further reduced the misfit by introducing cover and basement conductivity variations.

• In a second pass, the depth to basement was constrained locally by drill hole pierce points.
TEMPEST survey example – Bull Creek

- The starting model was represented by a two layer model.
- Starting model cover thickness was 50m.
- Cover conductivity was 800mS/m (inferred from VPem1D homogeneous conductivity inversion) overlying a resistive (10mS/m) basement.
- The model was submitted to depth to basement (geometry) inversion followed by heterogeneous conductivity inversion.
Detailed analysis of unconstrained geometry inversion

- Assess consistency to drill hole pierce points.
Drill hole constrained inversion

- Re-submit to conductivity inversion, with base of cover adjusted locally to honour drill hole constraints.
- Consistency with drill holes preserved – but the portion of the model constrained by drilling appears anomalous.
- Drill hole constrained inversion suggests that the previously assumed starting conductivity for cover was too high → impact on inverted depth to basement away from drilling.
Drill hole constrained inversion - Conclusions

- Updated model consistent with drilling - more geologically plausible
- Drill hole depth-to-basement constraints provided additional control on the starting model conductivity.
- Drill hole constrained inversion suggests multiple layers within thicker cover.
Conclusions

- There are many advantages when inversion algorithms operate on a geological model:
  - Rapid model validation (forward modelling)
  - More flexible (more inversion options)
  - More control (operate on selected geological domains)
  - Explicitly incorporate geological constraints
  - A driver for integrated interpretation - the inverted model is geological.

- Explicit modelling of cover is a natural application
- Pierce point constraints can have implications for physical properties as well as geometry
Acknowledgements

• Boulia data courtesy QDME
• Malhadina data courtesy Lundin
• Bull Creek TEMPEST data courtesy Exco Resources
• SPECTREM survey data courtesy Anglo American
• Mt Dore Geotem data courtesy Geological Survey of Queensland
Carrapateena: Discovery and Early Exploration

Lisa Vella, Technical Director

23rd ASEG Conference and Exhibition

Exploration Undercover Workshop

15th August, 2013
Outline of Presentation

• Location and Discovery
• Geological Setting
• Physical Properties
• Geophysical Surveys
  • Aeromagnetics
  • Gravity
  • IP/Resistivity/MT
  • Down hole IP/resistivity
  • EM
• Conclusions
• Acknowledgements
Location

Carrapateena iron-oxide copper-gold deposit lies 160km north of Port Augusta and 100km south-east of Olympic Dam, South Australia.
The project area is located on the Pernatty Station pastoral lease, within the Andamooka Ranges. Topography is dominated by gentle to moderately sloped hills, extensively covered by quartz sandstone. Vegetation comprises mainly salt bush, blue bush and shrubby eucalypts.
Carrapateena – Early History

• In the late 1970s and early 1980s, Carpentaria Exploration Co. Pty. Ltd. and its joint venture partners drilled several holes on gravity and/or aeromagnetic highs at a prospect named Salt Creek (now Khamsin), 100km southeast of Olympic Dam and immediately west of Carrapateena.

• Drill hole SASC-4 intersected hematite – sericite altered Donnington suite from 520 m to the end of the hole (1250m).
Since the discovery in 1975, by WMC Resources Ltd., of the giant Olympic Dam iron-oxide copper-uranium-gold-silver deposit, the Gawler Craton has been subject to a great deal of exploration activity. In the latter part of the 1970s and early 1980s, Carpentaria Exploration Co. Pty. Ltd. and its joint venture partners drilled several holes on gravity and/or aeromagnetic highs at a prospect named Salt Creek, 100 km southeast of Olympic Dam and immediately west of Carrapateena. Drillhole SASC-4 was completed to 1250 m, intersecting hematite – sericite altered Donnington suite from 520 m to the end of the hole, thus providing encouragement to later explorers in this area.
Carrapateena – Rudy Gomez (RMGS)

• RMG Services Pty. Ltd., is a South Australian, unlisted company incorporated in 1974. It’s principal, Rodolfo (Rudy) M. Gomez, previously studied Mechanical Engineering and Extractive Metallurgy.

• RMGS first applied for an Exploration License over Carrapateena to provide salt for a proposed petrochemical plant at Port Bonython. Mr Gomez’s interest in the Gawler Craton for IOCG deposits was fuelled by information searches in the PIRSA library.

• In 1996, RMGS applied for EL2879 (formerly EL2170), based on the belief that the Carrapateena Arm and the Torrens Hinge Zone make this area prospective for IOCG deposits.
RMG Services Pty. Ltd., is an unlisted company incorporated in South Australia in 1974. It’s principal, Rodolfo M. Gomez, previously studied Mechanical Engineering and Extractive Metallurgy and has more than two decades of overseas experience in designing, engineering, construction, commissioning and operation of major mining operations.

RMGS first applied for an Exploration License in the southern part of Lake Torrens (SE of Carrapateena), to provide salt for a proposed petrochemical plant at Port Bonython. Mr Gomez’s interest in the Gawler Craton for iron-oxide copper-gold deposits was fuelled by information searches in the PIRSA (Primary Industries and Resources South Australia) library. In 1996, RMGS applied for EL2879 (formerly EL2170), based on the belief that the Carrapateena Arm and the Torrens Hinge Zone make this area prospective for IOCG deposits (Gomez, 2005).
Early Magnetic and Gravity Data

- Gravity bullseye at margin of moderately strong magnetic domain
- 2.0-2.5 mgal
Regional aeromagnetic and gravity data, acquired by PIRSA, indicated an Olympic Dam – style potential field anomaly - Carrapateena. **Additional gravity** acquisition was carried out by a joint venture of **RMGS and General Gold Resources Ltd.**, confirming the presence of a discrete gravity response.
2003 MIMDAS – Line 738100E

400m spaced, N-S lines, 5km along, using a pole – dipole array (200m dipole spacing). Transmitter frequency 25/512Hz. Current 14A. Chargeability time slice 2.5 – 4 seconds.
In 2003 – 2004, a joint venture between MIM Exploration Pty. Ltd., Terramin Australia Ltd. and RMGS, undertook further gravity surveying. MIM also completed six 5 km long (north-south) lines of induced polarisation (IP) and magnetotelluric (MT) surveying, using its then proprietary MIMDAS system. MIM and Terramin later withdrew from the joint venture and RMGS was on its own again.

While the IP data were ambiguous, modelling of resistivity data over the peak of the gravity anomaly indicated the existence of at least 150m of conductive (0.05 – 0.1S/m) overburden, overlying a several hundred metre thick layer of relatively resistive (>150ohm.m) material, with the underlying basement exhibiting variable, but significantly lower, resistivities. In particular, a deep conductive zone was interpreted to be coincident with or slightly north of the gravity response. The Carrapateena discovery hole (CAR002) was targeted on these anomalies.
PACE – Part-funded Drilling

CAR01
(no significant mineralization, extreme Cu-depleted mafic, terminated at ~560m)

CAR02
(68m @ 3.0%Cu, 0.4g/t Au from 476m, mineralized to bottom – 654m)
Carrapateena is located in the **G2 corridor** and within the Olympic Dam District. The project has benefited from **structural studies** undertaken by **Dr Rodney Boucher**, based on methods utilised by the **late Dr Tim O’Driscoll. Chris Anderson and Associates**, consultants to RMGS, played an integral role, **modelling and interpreting data** acquired by MIM and PIRSA, and **planning final drill hole locations**.

In February 2005, RMGS initially proposed four holes to be jointly funded with PIRSA, through their **PACE** program. This was later reduced to **two drill holes**, **one which would be targeted on the gravity anomaly** and a second hole designed to test the **MIMDAS conductivity anomaly**. These holes were drilled in **May-June 2005** and a new and exciting discovery in the Gawler Craton was announced soon after.
Discovery!

CAR002 - 178.2m @ 1.83% Cu, and 0.64g/t Au, from 476m, including 75m @ 2.89% Cu & 0.4g/t Au.

Source: Greg Adams, Adelaide Now
Beyond Discovery

• In September 2005, Teck Australia Pty. Ltd. farmed into Carrapateena.
• Extensive exploration by Teck resulted in the drilling of CAR050, which intersected **905 m @ 2.1% Cu and 1 g/t Au**.
• Drilling of regional prospects by Teck identified hematitic breccias at Khamsin, and copper mineralised, chlorite, sericite and hematite altered granites and breccias at Fremantle Doctor.
• In April 2011, Oz Minerals purchased Carrapateena and subsequently released an inferred resource of **292Mt @ 1.29% Cu, 0.48 g/t Au, 207 ppm U₃O₈ and 5.4g/t Ag**. Further drilling at Khamsin and Fremantle Doctor has also identified significant copper mineralisation.
Geological Setting

Carrapateena is located on the eastern margin of the Gawler Craton, at the intersection of interpreted major NNE – and NW – trending structures.
• The Carrapateena deposit is located within what is termed the ‘Olympic Fe-Oxide Copper-Gold Province’ in the eastern margin of the Gawler Craton. The Gawler Craton is a region of Archaean to Mesoproterozoic crystalline basement, underlying most of South Australia, which has not undergone substantial deformation in the past 1450 million years.

• The MesoProterozoic Eastern margin – bounded by Torrens Hinge Zone and covered by younger Proterozoic Stuart Shelf sediments and local Palaeozoic cover.

• Carrapateena is located at the intersection of interpreted major NNE and NW trending structures, analogous to structures thought to have played a role in focussing the mineralisation at Olympic Dam.
• Carrapateena lies under 470m of moderately conductive Stuart Shelf sediments, presenting significant technical challenges to exploration.
• The cover sequence consists of Wilpena Group sediments overlying Umberatana Group sediments.
• The Wilpena Group comprises the outcropping Arcoona Quartzite, Corraberra Sandstone and the Woomera Shale.
• The Umberatana Group sediments comprise variably gritty siltstones to sandstones, with minor interbeds of dolomite.
• The cover sequence unconformably overlies the basement, with the unconformity being marked by the basal conglomerate.
• Cu-Au-U-REE mineralisation hosted by the Carrapateena Breccia Complex and occurs in a hem-chl-ser mineralised sequence, of partly conglomeratic sediments, with clasts and fragments of granite, gneiss and vein quartz. These sediments are likely derived from hydrothermal activity re-sedimenting a brecciated host.
• The host rock is a variably foliated and/or sheared gneissic quartz granite and quartz diorite, which has been age dated at 1857 +/- 6 Ma, assigning it to the Donnington Suite.
• Basement rocks locally intruded by felsic and mafic dykes.
Drill Core Samples

- Alteration minerals – hematite, chlorite, sericite, locally abundant quartz & carbonate (siderite and/or ankerite).
- Secondary minerals – barite, monazite, anatase, magnetite, apatite, fluorite and zircon.
- 3 types of hematite.
- Copper sulphides – chalcopyrite and bornite, mainly disseminations, blebs and veinlets. Rare chalcocite.
- Pyrite is locally abundant.
•Three types of hematite are observed – fine – grained earthy red hematite; massive steely grey hematite, and coarse platy grey specular hematite. In my talk on Wednesday afternoon, I’ll discuss how the electrical properties of hematite can vary depending on type.

•(Note: hem = hematite, ser = sericite, chl = chlorite, cpy = chalcopyrite).
Physical Properties

<table>
<thead>
<tr>
<th></th>
<th>Density (g/cc)</th>
<th>Magnetic Susceptibility (SI x 10^-5)</th>
<th>Galvanic Resistivity (ohm.m)</th>
<th>Chargeability (ms)</th>
<th>EM Conductivity (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cover</td>
<td>2.29–2.74</td>
<td>1-75</td>
<td>36–2,484</td>
<td>1-8</td>
<td>-</td>
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<tr>
<td>Basement</td>
<td>2.4–2.72</td>
<td>30-55</td>
<td>9–98</td>
<td>2-3</td>
<td>-</td>
</tr>
<tr>
<td>Basement (altered and/or mineralised)</td>
<td>2.7–4.37</td>
<td>45–11,251</td>
<td>1-176</td>
<td>1-188</td>
<td>0–345 (chalcopyrite vein)</td>
</tr>
</tbody>
</table>

Petrophysical characteristics of basement rocks are dominated by the presence of Fe-oxide. Separation of responses from the Fe-oxides, Fe-sulphides and Cu-sulphides is difficult.
• 72 samples.
• Cover Sequences – low densities, magnetic susceptibilities, chargeabilities and EM conductivities. High apparent porosities. Variable P-wave velocities. With the exception of the Arcoona Quartzite, which is highly resistive, rocks are weakly to moderately conductive, and show significant electrical anisotropy.
• Basement – Densities increase with increasing hematite and/or magnetite and/or sulphide content. Magnetic susceptibilities correlate with % magnetite. EM conductivities generally low, with rare exceptions. Lower galvanic resistivities and higher chargeabilities correspond to increasing sulphides +/- hematite +/- magnetite.
Aeromagnetic Survey

- Survey Date: Dec 2005
- Contractor: Fugro Airborne Surveys
- Data Collected: Mag - Spec
- Line Spacing: 200m
- Line Direction: E-W
- Tie Line Spacing: 2km
- Tie Line Direction: N-S
- Mean Flying Height: 50m
• Carrapateena lies on the SW margin of a broad magnetic anomaly of moderate amplitude and is associated with a weak, discrete, ellipsoidal magnetic response, being elongated in a north-south direction and having an approximate amplitude of 20nT.
Gravity Surveys

- Three detailed gravity surveys:

<table>
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<th>Date</th>
<th>Company</th>
<th>Surveyor</th>
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<tr>
<td>1996</td>
<td>General Gold</td>
<td>Dynamic Satellite Surveys</td>
<td>500m x 500m</td>
</tr>
<tr>
<td>2003</td>
<td>MIM</td>
<td>MIM</td>
<td>400m x 400m</td>
</tr>
<tr>
<td>2006</td>
<td>Teck</td>
<td>Haines</td>
<td>200m x 200m</td>
</tr>
</tbody>
</table>

Hematite breccia (grey), chalcopyrite (yellow) and bornite (blue).
• Carrapateena is characterised by a weak (approximately 2.5mGal) bullseye gravity high, near-coincident with the observed magnetic response.
Forward Modelling – East-West Profile over Carrapateena

(Hanneson, 2006)
• Explain phase diagram. Refer to Adelaide Conference 2003.
• Detailed forward modelling, by Jim Hannessson (Adelaide Mining Geophysics), undertaken during the early stages of exploration. Model suggests observed gravity and magnetic responses could be explained by a non-magnetic, vertical cylindrical body, with a diameter of 1km and average density of 3.27 g/cc, overlying a less dense and weakly magnetic body, having an average magnetite content of no more than a few percent.
• The observed data can also be modelled using economically uninteresting mafic bodies – implications for exploration.
• When the Carrapateena model bodies are made shallower (simulating 350m of cover, like at Olympic Dam), the peak gravity response, increases from about 2.5 to 3.5 mGal, and the magnetic response increases from about 20nT to perhaps 30nT.
Inversion Modelling

- 3D gravity and magnetic inversion model, using high-pass filtered (10km) data.
- The gravity model was constrained for cover.
- Iso-surfaces of density contrast are pink – grey and % magnetite are blue – green.
• Modelling done by Craig Beasley (Wave Geophysics).
• The gravity model was constrained by incorporating a reference model, comprising an overburden layer (450m thick, with a density contrast of -0.1g/cc), overlying a half-space. If the model was not constrained in this way, the dense bodies would come up to surface, which clearly wasn’t geologically realistic.
• Drill holes, to depths >1500m, confirm that hematite dominates in the shallower part of the deposit, with increasing magnetite being observed at depth.
2006 High – Powered IP/Resistivity

Configuration: Dipole – dipole
Transmitter dipole: 200m, 300m and 400m
Receiver dipole: 200m
Station interval: 100m
Number of receiver dipoles: 8+ ("n" levels)
Line Direction: East/West
Base frequency: 0.125 and 0.0625 Hz
Duty Cycle: 50%
On/off time: 2sec and 4sec on-off
Maximum transmit current: 68A
Receiver: Search Exploration Full Time Series (SSIP16)
Chargeability Integration: 590msec to 1200msec
Transmitter: Search Exploration 50kVA
• In 2006, Search Exploration carried out a 2D high-powered IP/resistivity survey, using proprietary technology. Data were collected on seven east-west lines, 300m to 400m apart, with readings being taken at 100m intervals. Line length varied from 3.9 to 5.1km, with a total of 40.7 line km of data collected. Maximum transmit current was 68A.

• Overall, data quality was quite good, however the data almost invariably showed an increase in chargeability with n-level. This was due to the data containing a significant amount of EM coupling at large n spacings. Some data were also negatively impacted by tellurics. These were minimised through sophisticated processing, shared collaboratively between John Paine (Scientific Computing and Applications) and David McInnes (Montana Geophysics).
Inversion modelling (2D Zonge) shows a good correlation between the observed conductivity and gravity anomalies (hematite +/- sulphides).
Chargeability data were ambiguous at times. Interpretation was complicated by the presence of specular hematite, often not noted in geological logs.

Hem breccia +/- sulphides
• Line locations shown on residual gravity.
• Specular hematite can exhibit an appreciable chargeability.
• On some drill sections there was a good correspondence between chargeability and drill results. On others, chargeability anomalies appeared to be shallower than expected (i.e. within the cover). **May depend on whether or not the hematite +/- sulphide mineralisation is in contact with the unconformity, or significantly deeper (signal gets caught up in the cover).**
2006 MIMDAS Survey Layout (3D Pole-dipole)

Dipole length: 200 m
Tx freq.: 25/256, 25/512 Hz
Tx current: 3 – 8.5 A
Tx: Zonge GGT10 10 kVA
Duty cycle: 100%
Chargeability time slice: 21.5 – 2.5 s & 3.5 – 5.0 s
Sampling rate: 100 & 200 samples/second
Magnetometers: 2 pairs of BF-4
• 2006, GRS’s proprietary MIMDAS system. “Ghost Line” 3D setup, comprising 3 overlapping grids, thereby also providing 7 collinear 2D lines of pole-dipole IP/resistivity/MT data. Each line was 4km long, being spaced 400m apart, with a receiver dipole length of 200m. Tx locations extended east and west of the array by 500m.
• Magnetometers - one used on line and the second for remote referencing
The MT data are characterised by clean impedance estimates for frequencies to below 0.1Hz.
IP and resistivity data are generally of good quality.

However, dipole-pole data are dominated by negative EM coupling below n=10.
• The resistivity and IP data acquired were generally of good quality, although this was limited by the magnitude of IP signals, relative to the magnitude of residual EM coupling, at a location with significant low-frequency tellurics. Pole – dipole data contained less EM coupling than dipole – pole data, therefore, the latter was excluded from input into the inversion models.
This can be explained by the general increase in conductivity to the east of the grid which is possibly attributable to the presence of Lake Torrens and the presence of saline groundwater.
2D High-Powered IP/Resistivity Compared with MIMDAS – Line 6543400N

1. A good correlation exists between the MIMDAS resistivity profile and conductivity iso-surfaces (yellow) from the Search high-powered IP survey.

2. The MIMDAS resistivity profile also correlates well with iso-surfaces of density contrast (pink/grey) from the gravity inversion model.
• Like the 2D high-powered IP/resistivity survey and the 2003 MIMDAS survey, a good correlation was observed between the conductive and gravity responses at Carrapateena. However, subtle chargeability anomalies have been negatively impacted by substantial EM coupling. Therefore, it was concluded that the resistivity and MT results would be a more reliable guide for targeting than the chargeability.
Down Hole IP/Resistivity Surveys

• 2006 – 2008 IP/resistivity surveys were undertaken by Search Exploration:-
  • \textit{In-situ} measurements in 21 drill holes, using a collinear Wenner array, with a 3m electrode spacing;
  • Radial measurements in 6 drill holes, using three separate transmitting arrays, and
  • Cross – hole dipole – dipole surveys, using a 100m transmitter in one hole and a 50m receiver in the other.
Radial IP/resistivity measurements were also made in six drill holes in which a single transmitter electrode was placed near the bottom the hole and two other transmitting electrodes were placed about 1.5km from the drill hole and at the drill hole collar. This provided three separate transmitting arrays. Potential electrodes were then set up on eight radial lines around the transmitting drill hole. For each line there were five potential electrodes, 100m apart.
In-Situ IP/Resistivity – CAR002

- Hematite Breccia +/- Sulphides
- Mafic dyke + hematite +/- sulph.
- Granite

Graph showing Depth (m) and Average IP (mV) vs. Res_Calc.
The in-situ IP/resistivity measurements were extremely useful in furthering the understanding of the electrical properties of the Carrapateena rocks. However, the radial DHRESIP does not appear to have worked in the way it was intended, presumably being a victim of 470m of moderately conductive cover and significant electrical anisotropy. Results from the cross-hole surveys were inconclusive and it may be worthwhile re-processing and re-modelling these data.
EM Surveys – Line 6543250N

System: Crone Pulse EM system
Time Base: 150 ms
Ramp Time: 1.50 ms
# Channels: 42

Survey Type: Moving loop (in-loop), with abutting loops
Transmitter Loop Size: 200 m x 200 m
Current: 30 Amps
Receiver Coil Area: 4100 m²

Hem breccia +/- sulphides

![Graph showing survey results](image-url)
2007, Outer Rim Exploration Services conducted 3-component down hole EM surveys in four drill holes, and read one surface moving loop profile. The data were collected using a 42 channel Crone Pulse EM system, and receiver coil. A 600m x 600m transmitter loop, with a transmit current of 27A, was used for the down hole surveys, while the surface profile was read using a 200m x 200m in-loop configuration, with a transmit current of 30A.

Given the disseminated nature of the sulphide mineralisation observed to date, it was not surprising that there were no convincing responses that could be attributed to bedrock conductors away from the drill holes. Similarly, the surface profile did not yield a credible anomaly over the Carrapateena deposit.
Conclusions

• Carrapateena is associated with a weak, discrete, ellipsoidal magnetic response and near-coincident, weak, bullseye gravity high.
• Also characterised by a distinct conductivity anomaly.
• Chargeability data are somewhat ambiguous.
• EM surveys did not provide any responses attributable to bedrock conductors and are not recommended for Olympic Dam – style Fe-oxide Cu-Au deposits.
• Geophysical responses are dominated by the presence of Fe-oxides, especially hematite, with sulphides playing a lesser part.
Acknowledgements

- Rudy Gomez
- Teck geoscientists and many consultants.
- Oz Minerals
  - THANK YOU for listening!
• Rudy Gomex (and colleagues), for the discovery of Carrapateena.
• Subsequent exploration by dedicated Teck geoscientists (especially Mike Cawood) & many talented consultants.
• Permission from Oz Minerals Ltd. to present and publish this information is greatly appreciated.
• Photos taken on the SW edge of the leases.
References

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Exploration Undercover Workshop
Carrapateena Project

Charles Funk

August 2013 – ASEG-PESA Conference

WWW.OZMINERALS.COM
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Certain statistical and other information included in this presentation is sourced from publicly available third party sources and has not been independently verified.
CARRAPATEENA - Location

- OZ Minerals purchased the Carrapateena copper-gold project in 2011 from Teck Australia Pty Ltd and Rudy Gomez for US$250 million.

- The site is located 160km north of Port Augusta at the western edge of Lake Torrens on Pernatty Station in central South Australia.
CARRAPATEENA - Teck Cominco - RMG JV

- Discovery hole CAR02 drilled in mid-2005 by RMG Services (Rudy Gomez) intersected 178m @ 1.83%Cu, 0.64 g/t Au (red collar)
- JV with Teck Cominco (now Teck Resources) for ~80,000m - majority of drilling was vertical
- No compliant (JORC or NI43-101) resource released - Main mineralised zone not intersected until drill hole CAR032 (yellow collar)
- An initial Inferred Resource of 203Mt at 1.31% copper, 0.56g/t gold, in the southern area of the Carrapateena deposit released by OZ Minerals in mid-2011
CARRAPATEENA – 2013 Update Mineral Resource

- Exploration drilling began in late 2011. To the 31 October 2012 resource cut-off date ~46,500 metres drilled by OZ Minerals.

- All angled holes to better define margins of mineralisation and higher grade zones.

- Confidence in continuity of mineralisation.

- Deposit exploration drilling ceased in early 2013 for ~56,500 metres drilled by OZ Minerals; depth extensions confirmed.

OZ Minerals drill traces in red – Teck in black
CARRAPATEENA – 2013 Update Mineral Resource

- 43% increase in total Indicated and Inferred Resources at 0.7% Cu cut-off.
- Based on data obtained from 93 drill holes, including wedges, totalling 57,257m intersecting the main body of the copper mineralisation.
- Cut off date for drilling data was 31st October 2012 – with drilling continuing through to February 2013.

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<th>Classification</th>
<th>COG1 % Cu</th>
<th>Volume (Mm$^3$)</th>
<th>Tonnage (Mt)</th>
<th>Density (t/m$^3$)</th>
<th>Cu %</th>
<th>Au g/t</th>
<th>CuEq2 %</th>
<th>U ppm</th>
<th>Ag g/t</th>
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<td>0.48</td>
<td>1.58</td>
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1 COG refers to cut-off grade
2 CuEq refers to copper equivalent and is calculated as Cu + 0.6 * Au. See the Explanatory Notes for further details of the derivation of this formula

A copy of the 2012 Carrapateena Mineral Resources Statement and accompanying Explanatory Notes can be found on the OZ Minerals website at www.ozminerals.com/operations/resources--reserves.html.
CARRAPATEENA – Indicated and Inferred Resources

2011 INFERRED RESOURCES
203Mt @ 1.31 % Cu, 0.56 g/t Au

2012 INDICATED & INFERRED RESOURCES
292Mt @ 1.29% Cu, 0.48 g/t Au

• The 2012 Indicated and Inferred Resources of 292Mt represent a 43% increase over the 2011 resource at a 0.7% Cu cut-off.

• Much of the 2011 Exploration Target area has been converted to Mineral Resources in 2012.

• Infill exploration drilling program has better defined the higher grade bornite zones - now one bornite zone.

• Deeper infill exploration drilling has led to an extension of the Resource at depth.

* These wireframes show the interpreted limits of the Chalcopyrite envelope and Bornite zones. Area approximates to a 0.3% Cu cut-off grade. Resource classification is shown in 'stylised' view at Section 737800mE with +/-50m window.
CARRAPATEENA – The exploration challenge

Extremely facetious, but a real kernel of truth

What the geologist have to guide IOCG exploration

What the geophysicists provide to guide IOCG exploration
CARRAPATEENA – Exploration opportunity

Khamsin
1.53 mgal residual anomaly

Carrapateena
1.48 mgal residual anomaly

5km residual BA 2.67 Gravity
− E-W section through the gravity inversion models at Khamsin with the KH002 plotted.

− KH002 drills the outer edges of the density anomaly and intersects 50m of Hematite altered breccia within granite.
Could KH002 be the same as CAR044?

- E-W section through the gravity inversion models at Carrapateena with breccia lithologies and Cu and Au grades plotted (Cu – green on right of drill trace, Au in yellow on left of drill trace).
CARRAPATEENA – Khamsin discovery

Khamsin

DD12KMS003
440.6m @ 0.43% Cu, 0.08 Au g/t from 1,005.4m
including 26.7m @ 1.48% Cu, 0.13 Au g/t from 1,005.4m

DD13KMS004W3
632m @ 0.36% Cu, 0.07 Au g/t from 573m
including 36m @ 1.04% Cu, 0.31 Au g/t from 1,030m,
442m @ 0.49% Cu, 0.09 Au g/t from 1,380m
including 48.5m @ 1.01% Cu, 0.07 Au g/t from 1,385.6m

Carrapateena

Residual Gravity Anomaly

OZ MINERALS • PAGE 14
CARRAPATEENA – Khamsin discovery

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<th>From (metres)</th>
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<th>Copper (%)</th>
<th>Gold (g/t)</th>
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<td>**851</td>
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<td>**1188</td>
<td>101</td>
<td>1.31</td>
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*Intervals calculated using a 0.7% Cu cut-off grade, are down hole length-weighted and include unlimited internal dilution.

**Intervals calculated using a 0.1% Cu cut-off grade, are down hole length-weighted with an unlimited internal dilution.
CARRAPATEENA – Khamsin discovery

- Increased hematite alteration, brecciation and copper grade.
- Increased widths of higher grade mineralisation now being observed.
- Higher grade chalcocite and bornite intersected.
- Drilling has commenced from the northern side of the mineralised body.
CARRAPATEENA – Khamsin discovery

Removed at request of author
Subject: IP-resistivity results over Khamsin
CARRAPATEENA – Khamsin discovery

Removed at request of author
Subject: IP-resistivity results over Carrapateena & Khamsin
### Carrapateena – Fremantle Doctor

#### DD13FDR005

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**Fremantle Doctor**

- DD12FDR004: 103m @ 0.68% Cu, 0.25 Au g/t from 726m
- DD12FDR003: 490m @ 0.2% Cu, 0.19 Au g/t from 630m

**Residual Gravity Anomaly**

- DD12FDR003
- DD13FDR005

Carrapateena

- OZ Minerals 2012 Drill Holes
- Teck Cominco 2011 Drill Holes
Removed at request of author
Subject: Location map of seismic survey
CARRAPATEENA – Seismic Interpretation

Stratigraphy and seismic response at Carrapateena with marker horizons labelled.
Migrated TWT VE1.5
Two way travel (TWT) interpretations (left) with seismic images and (right) without any seismic images.

All TWT Interpretations VE1.5
CARRAPATEENA – Palaeotopography corrections

Carrapateena – Cover depth
Carrapateena – Residual gravity
Carrapateena – Basement corrected residual gravity

Prominent Hill – Cover depth
Prominent Hill – 1VD gravity
Prominent Hill – Basement corrected 1VD gravity
CARRAPATEENA – Palaeotopography corrections

Removed at request of author
Subject: Paleotopography corrections using seismic
CARRAPATEENA – Breccia body detection?

Removed at request of author
Subject: Seismic section over deposit
Removed at request of author
Subject: Seismic panels over deposit
Thank you to OZ Minerals

- Particularly the exploration team and our supporting contractors and consultants.
WHAT ROLE FOR GOVERNMENT IN PRE-COMPETITIVE R&D

Ted Tyne
Executive Director, Mineral Resources

Workshop on Exploration Undercover
ASEG-PESA 2013 Melbourne

www.dmitre.sa.gov.au
What role for government in pre-competitive R&D

• Adding value to our wealth of pre-competitive datasets through targeted R&D and research partnerships that will attract explorers to invest in exploration

• Targeted pre-competitive R&D and research partnerships on exploration undercover, deep exploration and copper and uranium mineral systems that will highlight discovery opportunities
Australia’s Geological Surveys have an enviable record of outstanding science delivery and pro-active geological programs covering almost 150 years of Australia’s history.

In the past two decades there has been a significant refocussing of Geological Survey programs from regional mapping coverages and collection of mineral deposit information towards programs that will support exploration success – High Fraser Institute rankings for “Geological Databases” for Australia.

The term “pre-competitive data” highlights the importance of the public good value of this information – referred to as non-exclusive, non-rival public good data by government funding authorities.
on discovery …
the Cadia Orebody was discovered through analysis of the comprehensive Mineral Deposits information sheets published by the Geological Survey of NSW

on deep exploration technologies …
Greater effort is required in integrating geology-geochemistry-geophysics and geophysics is best used as an ore-system vectoring tool
Discoveries & Expenditures : Australia

In spite of higher expenditures, Australia’s discovery rate has declined in recent years, especially for larger deposits.

Discoveries and expenditures exclude Bulk Minerals (such as coal, iron ore and bauxite)

- Moderate: >100Koz Au, >10Kt Ni, >100Kt Cu equiv, >5 kt U₃O₈
- Major: >1moz Au, >100Kt Ni, >1mt Cu equiv, >25 kt U₃O₈
- Giant: >6moz Au, >1 mt Ni, >5mt Cu equiv, >125 kt U₃O₈

Sources: ABS and MinEx Consulting © August 2012

after Richard Schodde, MinEx Consulting 2012
Government Geoscience – the public policy debate …

In the last 10+ years Australian, Canadian and other western governments have continued to question the value of Geological Surveys to the resources sector and the community

AND …

governments have continued to question who should pay for this information … or rather …

why shouldn’t industry pay for all of this free data ???
The geoscience knowledge provided by federal, provincial and territorial governments as a public good is widely acknowledged to be one of Canada’s competitive advantages in attracting mineral exploration and to have contributed to this country’s standing as a leading mineral producer.

As governments move into deficit in the wake of the recent recession, survey budgets will likely come under renewed pressure.

This paper reviews the public policy rationale for government geoscience and its impact on mineral exploration, and concludes that a more robust public effort will be needed as part of a strategy to deal with deceasing rates and increasing costs of mineral discovery.
Geoscience Australia and the State/NT Geological Surveys contend that …

Greenfields exploration is a high cost, high risk activity with a low probability of a commercial discovery.

The provision of pre-competitive geoscience assists companies make informed decisions on selecting licences in greenfield areas and reducing the cost and risk of exploration.

However, Australia’s Geological Surveys need to do more than deliver a stream of world class pre-competitive data … focus on underwriting exploration success and that means discovery under cover …
GOVERNMENT

- Land Access

PRIVATE SECTOR

- Availability of Finance

Human & Intellectual Capital
- Education and training
- R&D – new exploration & processing technologies

Availability of State-of-the-art Pre Competitive Geoscience and Mineral Systems Data and Targeted R&D

Greenfields

Quality of Exploration

Quantity of Exploration

Discovery

(From Derek Carter)
Geoscience Australia and the state/NT Geological Surveys strategy focused on greenfields discovery

DELIVERY OF STATE-OF-THE-ART
PRE COMPETITIVE GEOSCIENCE AND
MINERAL SYSTEMS DATA AND TARGETED R&D

Focus on underexplored and undercover regions

* Please see National Mineral Exploration Strategy, produced by Exploration Investment and Geoscience Working Group (EIGWG) of the Standing Council on Energy and Resources (SCER) as well as Australian Academy of Science UNCOVER documents for further context
What role for government in Pre-Competitive R&D

South Australia’s perspective …
EXPLORATION OPPORTUNITIES AND GEOLOGY OF SA

Pathways to Discovery
- New statewide and regional datasets
- New geophysics and spectral data
- Multi-element reanalysis of historic calcrite samples

Pathways to Prospectivity
- Multidisciplinary mineral systems analysis
- Multidisciplinary approach with mineral systems focus

Discovery to Development
- Six-month target approvals for mining lease assessment
- Online tenement applications, tracking, management and reporting

Next Generation Policy
- World’s best practice in resources industry regulation and management
- Next generation suite of industry policies and guidelines

Innovation through Integration
- Unique and innovative products and data delivered through SARP 2020
- 3D modelling of mineral systems and prospective tenures

PACE Partnerships
- PACE Targeting – geophysical surveying
- PACE Discovery Drilling – exploration drilling
- PACE Geochronology – mineral systems dating

PACE exploration

PACE mining

PACE energy

PACE global

SA Geothermal
- Partnership with South Australian Centre for Geothermal Energy Research
- Precompetitive data, state prospectivity model and reservoir modelling
- Research into enhanced (engineered) geothermal systems (EGS) and hot sedimentary aquifer (RSA) systems

Unconventional Gas Resources
- Investigation of South Australia’s unconventional gas potential
- Research into factors affecting productivity in unconventional reservoirs

CO2CRC
- Support for the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC), Australian School of Petroleum, University of Adelaide
- Research into carbon capture and storage methods and technologies

Water for Mining
- Partnerships with key agencies and industry to address water issues
- Mapping the state’s groundwater systems

Communities
- Community engagement strategy and toolkits for industry
- Continuing support for regional and remote communities

Data Pathways
- Launch and expansion of SARP 2020
- National Virtual Core Library online
- Digitising of historic company reporting

Building Awareness
- Linking investors with explorers
- Fostering greater awareness of the resources sector
- South Australian Minerals and Petroleum Expert Group (SAMPSEG) ambassadors

South Australian Resources Analysis
- Triple bottom line Minerals ScoreCard
- South Australian minerals industry annual review
Example 1 – What role for SA in Pre-Competitive R&D

Land Access + Exploration Targeting Challenges

Assessment of Mineral Prospectivity of the Northern Flinders Ranges Using GIS Analysis

W.M. Cowley, L.F. Katona and G. Gouthas
Geological Survey Branch, Mineral Resources Group
Report Book number 2009/19
Geoscience Mapping & Prospectivity Analysis

The Adelaide Geosynclinal, Stuart Shelf and Northern Flinders Ranges

Northern Flinders Ranges Project Study Area

Geological map showing the project study area, including the Adelaide Geosyncline, Stuart Shelf, and Northern Flinders Ranges. The map highlights selected mines and deposits, generalized outcrops, and localities and populations.
Geoscience Mapping & Prospectivity Analysis

Northern Flinders Ranges
1:100,000 Surface Geology

Surface Geology 1:100 000 scale
- Cenozoic
- Mesozoic
- Palaeozoic breccias
- Palaeozoic granitoids
- Delamerian and post-Delamerian granitoids
- Lake Frome Group
- Arcoona Creek, Wilrexala Limestones; Billy Creek Formation
- Hawker Group, Uratanna Formation
- Wilpeena Group
- Yerelina Subgroup
- Umbertana Group (interglacial)
- Yudharnmutana Subgroup
- Bulte Group
- diapirs
- Calanana Group
- Wollotana Volcanics
- Meso-Neoproterozoic mafic intrusives
- Mooleswatana Suite
- Petermorra Volcanics
- Mount Neill Granite
- Pepegoona Porphyry
- Palaeo-Mesoproterozoic granitoids
- Palaeo-Mesoproterozoic felsic volcanics
- Palaeo-Mesoproterozoic metasediments
- Radium Creek Metamorphics
- quartz
- undifferentiated breccia
- fault and shear zones
Geoscience Mapping & Prospectivity Analysis

Northern Flinders Ranges
Buffered Linear Structure

- Town
- Settlements
- Structure 500m Buffer
- DEPOSIT
- DIGGINGS
- MINE
- OCCURRENCE
- PROSPECT
- QUARRY

Northern Flinders Study Area

1:1,000,000
GDA 94, LCC
Geoscience Mapping & Prospectivity Analysis

Northern Flinders Ranges
Combined Copper Prospectivity

Copper Prospectivity
- 0
- 3
- 6
- 9 - 15
- 18 - 24
- 27 - 36

Copper Geochemistry
PPM
- 1001 - 5000
- 5001 - 20000
- 20001 - 460000

Copper Occurrences
- <all other values>
- Diggings
- Mine
- Occurrence
- Prospect
- Town
- Settlements
- Northern Flinders Study Area

Scale:
1:1,000,000
GDA 94, LCC
Geoscience Mapping & Prospectivity Analysis
Geoscience Mapping & Prospectivity Analysis
Geoscience Mapping & Prospectivity Analysis

Northern Flinders Ranges
Combined Base Metals Prospectivity

Base Metals Prospectivity
- 0
- 3
- 6
- 9 - 15
- 18 - 24
- Lead > 3000 ppm
- Tin > 10 ppm
- Silver > 8 ppm
- Zinc > 800 ppm

Base Metals Occurrences
- DIGGINGS
- MINE
- OCCURRENCE
- PROSPECT
- Town
- Settlements

Northern Flinders Study Area
Geoscience Mapping & Prospectivity Analysis

Northern Flinders Ranges Combined Exploration Values

Combined Exploration Values
- 0
- 3
- 6
- 9
- DISPOSIT
- DIOGGINGS
- MINE
- OCCURRENCE
- PROSPECT
- QUARRY

Cultural
- Town
- Settlements
- Northern Flinders Study Area
Example 2 – What role for SA in Pre-Competitive R&D

SA Data Integration …

latest work in progress –
refining depth to crystalline basement
Old – no attributes, only depth. Coarse grid (2km x 2km)
New – accurately located point data attributed with depth of horizon, elevation of horizon, geology.
Depth to Crystalline Basement Project Objectives

Old – no attributes, only depth. Coarse grid (2km x 2km)

New – accurately located point data attributed with depth of horizon, elevation of horizon, geology.
Depth to Crystalline Basement Project Objectives

Old – no attributes, only depth. Coarse grid (2km x 2km)
New – accurately located point data attributed with depth of horizon, elevation of horizon, geology.
Depth to Crystalline Basement Project

Depth to crystalline basement datasets

The depth to crystalline basement project will assemble GIS datasets that portray or infer depth to crystalline basement in South Australia, on a province-by-province basis. These datasets will be made available for public download.

A depth to basement surface will simultaneously be produced and updated as the project progressively models each province. A reliability map will also be produced and made available. The project’s focus for 2011-2012 is the Gawler Province.

Defining depth to crystalline basement

Crystalline basement for the purposes of this dataset is generally taken to be the shallowest rocks affected by a pervasive orogenic event in any given area. For the Gawler Province, this includes Mesoproterozoic and older rocks affected by the Mesoproterozoic Karakar Orogeny and older events. On current interpretations this definition includes the Hildesdoo Basin (Blue Range Beds) but excludes the Cundeelee Basin (Pandalama Formation). The eastern and southeastern margins of the area are placed along the eastern edge of the Torrens Range Zois and Stuart and Spencer Shales and along the Kangaroo Island Shear Zone. These included areas are essentially unaffected by the Delamerian Orogeny.

Datasets that provide depth to crystalline basement information or estimates

- Drillhole Stratigraphy (high confidence)
  - The primary and most geologically data source for depth to crystalline basement is drillhole stratigraphy. Drillholes whose stratigraphy matches the crystalline basement criteria were extracted from SA Geosaurus as a point dataset, and stratigraphic attributes (sourced from SA Geology) were appended to each data point.
  - Rule: Depth to crystalline basement surfaces interpolated from combinations of input datasets should honour the drillhole basement intercepts.
- Outcropping basement surface geology (high confidence)
  - Surface geology extracted from the South Australian 1:50k geology GIS layer represents crystalline basement at surface.
  - Rule: Depth to crystalline basement surfaces should honour the perimeter of outcropping basement units and honour the topographic surface within outcropping basement units.
- Drillholes that stop short of crystalline basement but intersect a surface interpolated from crystalline basement intercepts (medium confidence)
  - These and of hole depths are used to form an interpolated crystalline basement surface downward, where the plot interpolated surface intersects non basement intersecting drillhole.
  - Rule: Depth to crystalline basement surfaces should always be deeper than non-basement intersecting end-of-hole measurements.
- Seismic interpretation (medium confidence)
  - Crystalline basement piles along seismic lines are depth-converted and used to delineate crystalline basement in areas where drillhole information is sparse or non-existent.
- Geophysical depth estimates (variable confidence)
  - Geophysical models based on airborne geophysical surveys are used to estimate depth to crystalline basement in areas where drillhole information is sparse. Known depths (drillholes) will be used to validate the geophysical estimates to increase confidence in the results.
Example 3 – What role for SA in Pre-Competitive R&D

Uranium Geoscience - International Partnering

South Australia is building strategic partnerships and targeted R&D to grow capacity and deliver new uranium mineral systems insights which will lead to new discoveries …
Global Context - Uranium discoveries: Since 2000

In the last decade, 17 deposits >10 kt U₃O₈ have been found in the world. 3 of those were in South Australia.

Source: MinEx Consulting ©
July 2012
“Uranium is the next great China story. What China did for iron ore in the last decade, it will do for uranium in the coming decades”.

A Trench & D Packey 2012
Australia’s Next Top Mining Shares – Major Street Press
China – South Australia – Saskatchewan Uranium Geoscience Partnership established October 2012
Saskatchewan Ministry of Energy and Resources

Early March 2009 Memorandum of Understanding signed between DMITRE (PIRSA) and the Saskatchewan Ministry of Energy and Resources, CANADA

Saskatchewan is the leading jurisdiction in North America for uranium exploration and mining production.

Athabasca Basin

- World’s largest high grade U mines
- Produces ~23% world U

MoU aims to:

- Promote geoscientific exchange
- Facilitate geoscience knowledge sharing
- Generate new U models for SA
- Develop regulation and best practice policy
Athabasca Basin – 3D modelling work
CARIEWERLOO BASIN UNCONFORMITY-RELATED URANIUM PROJECT

Wilson T., Fairclough, M., Gouthas G., van der Wielen S., Mauger A. and Gordon G.

A Memorandum of Understanding between the Geological Survey of South Australia and the Saskatchewan Ministry of Resources and Energy, Canada was signed in 2009.

Analogies between the Athabasca Basin, Canada and the Cariewerloo Basin, South Australia.
CARIEWERLOO BASIN PROJECT DATA RELEASE 2012

HyLogger
95 drillholes
SWIR and TIR
PY-1 (DH 20712) SWIR
Vanguard-1 (DH 18092) TIR

Stratigraphic Logging
HyLogger datasets

Geochemical Datasets
FPXRF
Assay
Example 4 – What role for SA in Pre-Competitive R&D

Land Access + Exploration Undercover Challenges

South Australia is building strategic partnerships and targeted research to open up the Woomera Prohibited Area to modern exploration and potential for new discoveries …
PACE Program in WPA (2013-2015)

1. WPA Gravity survey (PACE 2020 extension)
2. WPA Alteration Footprints (PACE FRONTIERS)
3. WPA / eastern Gawler Craton regional drilling (PACE FRONTIERS)

- Gravity survey designed by GSSA
- Approximately 34,000 gravity stations
- Majority of survey is a 1km x 1km grid (2km x 2km grid in Southern region of the Continual Use Zone)
- Partnership with GA in the tender process and managing the survey
Western Gawler / Eucla Basin (TMI backdrop)
WPA Regional Mineral Systems Drilling ($2 M 2014-15)

From DET CRC…

PACE Type Contract to drill 130,000m on 10km x 10km grid through cover for basement and/or unconformity sample at $50/m: $6.5M
(excluding where basement > 1km depth)

$2 M invested @ $200/m drilling = 10,000m drilling
If average hole ~ 500m then ~20 holes
(plus industry co-investment….)
WPA Alteration Footprints (2013-2015)

Mapping alteration in Eastern Gawler Craton (DET CRC P3.4)
- Characterisation of sunset clause release drilling samples and data in 2013-14 (e.g. Western Mining Stuart Shelf drilling from 1970s)
- Working with regional prospecting drilling in 2014-15

- Increase the size of the target
- Predict where you are within the mineral system
- Emmie Bluff case study – 3D model (geology, alteration, inversions, data)
What role for government in pre-competitive R&D?

A priority for Australia is to address the falling rate of discovery through innovative and integrated undercover exploration technologies that build on our wealth of existing pre-competitive data -

Australian Geological Surveys are working closely together to build value-adding on our pre-competitive databases as well as strategic R&D partnerships and targeted interdisciplinary research that will bring forward new discoveries under-cover.

A key driver for South Australia is to directly influence or support new discoveries through strategic international and R&D partnerships.
Disclaimer

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How to Exploit Recent and Current Undercover Initiatives

Richard Hillis
ASEG Workshop on Exploration Undercover
Melbourne, Thursday 15 August 2013
Technologies will enable ‘Prospecting Drilling’
Coiled Tubing Drilling for Minex

- CTD achieves 2x ~1,000m Alberta gas wells per day in soft, predictable sedimentary rocks
- 2-3 hours move in and rig up time
- penetration rates: up to 100m/hr
Coiled Tubing Drilling for Minex

- CTD achieves 2x ~1,000m Alberta gas wells per day in soft, predictable sedimentary rocks
- 2-3 hours move in and rig up time
- penetration rates: up to 100m/hr

- CTD offers improved cost, safety, and environmental impact in mineral exploration
- key challenges for mineral exploration include: coil durability and low weight-on-bit drilling
- initial target: greenfields rig to 500m, weight less than 10 tonnes and $50/m
Coiled Tubing Drilling for Minex
Down-Hole Rock Characterisation
Minex LWD:
Autonomous Sonde and Shuttle
Carbon Fibre Rod with Embedded Sensor
Carbon Fibre Drill Rod
Carbon Fibre Drill Rod
Minex Lab-at-Rig
Minex Lab-at-Rig
Deep Exploration: Current Practice

- IOCGs, Gawler Craton, SA
- drill through deep cover based on grav & mag anomalies alone
- many false +ves
- many anomalies tested by one hole
- sparse data collected with little knowledge to inform follow-up drilling
Deep Exploration: Prospecting Drilling

- build out from initial targets using 5km coiled tubing drilling grid and resampling prior holes for consistent geochemical data
- downhole & lab-at-rig tools define petrophysics and geochemical halos real-time
- anomalies re-modelled and followed up during same campaign
- targets based on broad bandwidth of geophysical and geochemical data reduces false +ves and allows recognition of new deposit types
- start to map entire mineralising system with regional scale vector potential
Prospecting Drilling Animation
Brukunga DRTF is located in a disused mine close to Adelaide.

- critical to testing DET CRC’s new technology and also for training.
- researchers have access to state-of-art drill rig, drilling crew and fully logged and assayed test hole.

Technologies will enable ‘Prospecting Drilling’
Uncover

- characterising Australia’s cover
- investigating Australia’s lithospheric architecture
- 4D geodynamic and metallogenic evolution of Australia
- distal footprints of ore deposits
Mapping Igneous Activity Associated with Mantle Plumes and Rifts to Target Mineral Deposits

ASEG-PESA 23rd International Conference
August 11-14-Melbourne Australia

Workshop on Exploration
Undercover
August 15, 2013

Peter Gunn
Bohuon Resources
AIRBORNE GRAavity VERTICAL DERIVATIVE

0.5 tcf gas

1 mg contours

10 tcf gas
70 k boe/day
US$33.5 billion
MAPPING IGNEOUS ACTIVITY ASSOCIATED WITH MANTLE PLUMES AND RIFTS TO TARGET MINERAL DEPOSITS

SOME, POSSIBLY DIFFERENT, IDEAS FOR NEW EXPLORATION APPROACHES

Presented by –

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P. Gunn’s model of a mantle plume (generally consistent with most current models e.g. Pirajno (2000) to the right)
Seismic P wave velocity approx. 8 km/sec

Approx 7 km/sec.

Voila, intracratonic sedimentary basin!

Subsidence due to cooling, shrinkage, becoming denser weight of intrusions, sediments etc.

Following slides will attempt to show that these things are probably responsible for important mineral deposits

From Gunn (2000)
PLAN VIEWS OF MAGNETIC DATA

Reversely magnetised gabbro 50 km in diameter

Flood basalts and/or sills

Intrusive plugs and volcanoes

MODEL

Plume track along WA-SA border

Other plume positions

Dykes

Flood basalts

S.A

From Gunn (2000)
Depth to basement of Patchawarra Trough, Cooper Basin, South Australia

Figures from Meixner, Gunn et al. (2000)
Removed at request of author
Subject: Suspect mantle plume in Gulf of Carpentaria
Magnetic intensity of South Australia

Cooper Basin HS

Olympic Dam HS? Cu-Au-U-REE

Flinders Is. HS? Diamonds

Magnetic intensity of Olympic Dam area

Model
So what are the sources of the magnetic anomalies?
Possibly mixed mafic/ultramafic/anorthositic complexes something like the layered Cr and PGE rich Stillwater Complex and/or the Cu-Ni rich Duluth Complex in the USA.
Another possibility, something like the Bushveld Intruson (PGE, Cr, Ni, Ti).
DEPOSIT TYPE
Hard rock Ti in anorthosites
c.f. Lac Tio, Quebec
Major dyke swarms can be used to identify mantle plume locations. In this example there appears to be a correlation between the centre of the dyke swarm and the locations of diamond bearing kimberlites.
Magnetic response of the Mt Weld carbonatite from Duncn and Willet (1990)

Unhappily not a carbonatite but a zoned carbonated peridotite.

DEPOSIT TYPE:
Carbonatites containing Cu, REE, U, phosphate and Ti.
MINERAL DEPOSITS THAT APPEAR TO BE ASSOCIATED WITH MANTLE PLUMES:

1. Cu-FeO-Au-U-REE (Olympic dam)
2. Hard rock Ti in anorthosites c.f. Lac Tio, Quebec
3. Diamonds in kimberlite pipes.
4. Cu in breccia pipes (c.f the Messina deposits, South Africa, Redbank, Qld.)
5. Ni-Cr-PGE in layered intrusions
6. Ni in anorthosites, c.f. Voisey’s Bay
7. Ni in feeders to flood basalts c.f. Norilsk
8. Carbonatites (Cu, REE, U, phosphate)
9. Alaskan-type peridotite intrusions containing PGE e.g. Fifield, NSW
10. Etc.

Note: most of these deposit types can be directly targeted using aeromagnetic data
Formation of a triple junction above a mantle plume dome - Burke and Dewey (1973)
Classic mid-crustal sill image

Axial dyke beneath the Batten Trough Rift

Mid-crustal sills beneath the Macarthur Basin?

Magnetic intensity reduced to pole and continued up 1000m
Schematic evolution of a rift
From Gunn (1997)
Plan view
Rift system
From Gunn (1997)

Figure 2. Plan view of the stages of crustal extension. Different degrees of extension are accommodated by transfer faults. This diagram assumes that there is no significant strike-slip component occurs in the extension.

Figure 3. Magnetic and gravity expressions of the pre-rift and syn-rift stages. Sections correspond to sections shown in Figure 2.
Ethiopian Rift elevation

Seismic tomography after Keranen et al. (2004)
From Baldwin et al. (2003)
MAGNETIC INTENSITY PROFILE

From Goncharov et al. (2004)

BONAPARTE GULF RIFT

Gravity from Gunn (1984)

Sorby Hills Pb-Zn

RTP magnetics

Gunn (1988) section
Broken Hill Bouguer gravity 10 gu contours. Known mineral occurrences shown. BH Ag-Pb-Zn type mineral occurrences in purple.
Cuttaburra Cu-Ag-pyrrhotite discovery
Under 75 metres of cover
New mineral province
50 km from nearest mineral drillhole
Never before held under an exploration licence.
Discovery based on rift model and Cobar analogues
THANK YOU