Australian Academy of Science

Theo Murphy
High Flyers
Think Tank **2010**
proceedings

Searching the Deep Earth:

**The Future of Australian
Resource Discovery and
Utilisation**

**The Shine Dome, Canberra
19–20 August 2010**

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Searching the Deep Earth:

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THE ROYAL
SOCIETY

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Sustaining Australia's wealth for the next century

Australia is an old continent and much of its remaining mineral wealth is masked by a thick cover of weathered rock, sediment and soil that poses formidable exploration challenges. Australia relies on its mining industry for economic prosperity but currently lacks fundamental data and scientific and technological tools needed to discover new, economically valuable ore deposits deeply buried beneath the cover.

In the 19th Century, individual prospectors discovered gold and base metal deposits at the surface through skill, perseverance and luck. Following their early successes, in the 20th Century our geological surveys systematically mapped Australia's surface. The nation's landforms, surface geological formations and structures were revealed on a continental scale, providing a scientific basis for commercial exploration on a much larger scale than before. The formations and structures discovered through this effort host the near-surface rich deposits that underpin our economy today.

These surface riches are running out. Exploration success in Australia is in decline as the challenge of seeing beneath the cover defeats the explorers. Sustaining our wealth in the 21st Century requires that we now produce the next generation of maps – maps that define the physical and chemical properties of the subsurface of Australia. To do this we need to find ways to sample and analyse the ancient covered land surfaces and to image the structures that trap deep fluids that transport economically important metals, allowing deposition of those metals.

The *2010 Theo Murphy High Flyers Think* participants propose that future exploration success can be realised through an innovative, well-defined and nationally coordinated strategy. They recommend bringing together the relevant expertise into a coherent, collaborative research network, working within a well-designed strategic framework or 'road map', to address the fundamental needs of the exploration industry. To prioritise search areas across the nation it is essential to know where the cover is thick and where it is thin. We need to deploy geophysical and geochemical tools in a coordinated manner to image and understand the deep crust and upper mantle, because these regions provide the context within which economic mineralisation occurs. We need to understand the large-scale forces and processes – geodynamics – that act on and within the crust and upper mantle, and so exert control on mineralisation. We must understand the background signature of geochemistry and mineralogy where economic deposits do not occur so that we can then recognise the distal footprint of commercially viable deposits at distance from their actual location. Finally, we must ensure that the knowledge gained is properly delivered and that there is an ongoing supply of well-trained and inspired geoscientists ready to take up the exploration challenge. To achieve these goals, several strategic initiatives are proposed.

The *2010 Theo Murphy High Flyers Think Tank* participants propose an integrated set of initiatives to address the challenge of 'seeing through' the materials that cover Australia's ore deposits.

We recommend a national road map for deep earth exploration that integrates components of the Federal innovation effort in a coherent deep earth mapping program.

The proposed road map would be underpinned by the following six initiatives:

1. A national map of the depth and character of the cover of Australia that will prioritise new areas for exploration and new directions for research.
2. A national map of the deep crust and adjacent upper mantle that will employ innovative methods to acquire new geophysical and geochemical data. This map will be supported by a competitive crustal drilling program to constrain the interpretations resulting from these new data.
3. A national 'distal footprints' program to detect the far-field signatures of giant ore systems in ancient land surfaces now buried by cover.
4. A national four-dimensional (3D plus time) metallogenic map that relates Australia's major mineral deposits to the geodynamic contexts in which they formed.
5. A national research network to bring the exploration community together and ensure we understand and exploit the available synergies.
6. A national education and technology transfer program to foster rapid uptake and application of the results and ensure exploration success.

These initiatives will open up new frontiers for mineral exploration and enable the private sector to undertake Australia's next phase of exploration competitively. The data and knowledge created through these initiatives will also assist in further defining our water, energy and land resources.

Seven principal national outcomes are anticipated:

- identification of new subsurface exploration frontiers
- discovery of a new generation of world-class mines
- realisation of the deep geothermal potential of Australia
- identification of deep groundwater resources and water quality
- improvements in earthquake prediction on the continent
- establishment of Australia as a world leader in deep earth science
- development of unique Australian mining and exploration sector expertise that will be deployable world wide.

By taking a national approach to integrating our world-class scientific expertise, we can help the local mining industry reveal what is hidden beneath us, achieve a better return on their investment, provide new wealth to the nation and continue to prosper in this century.

Detailed recommendations and initiatives

National road map for deep earth exploration

Australia has a vibrant and diverse geoscience research community that is currently studying many of the issues important to improving our ability to explore under cover for major new mineral resources. The community is made up of university geoscience departments, CSIRO, Geoscience Australia, seven state and territory geoscience agencies, the Deep Exploration Technologies CRC, the ARC Centre of Excellence in Ore Deposit Research (CODES, University of Tasmania), the Centre for Exploration Targeting (University of Western Australia), the Virtual Geological Observatory (VIRGO) in Sydney, the Sustainable Minerals Institute (University of Queensland) and the recently funded Centre for Core to Crust Fluid Systems ARC Centre of Excellence.

There is currently no national strategy that links these organisations and industry partners into a single coherent and efficient framework that would permit integration of the initiatives advanced here. We propose development of a road map that would facilitate broad consultation with all stakeholders, identify long- and short-term research objectives, identify critical paths in research strategy, allow consideration of outlier technologies or approaches that might otherwise be ignored, and provide a baseline reference for those thinking strategically about this area. The road map would be the overarching framework to guide research investment in the sector for up to 30 years, reflecting broad support amongst stakeholders.

Six initatives for searching deep earth

The following elaborates on the *2010 Theo Murphy High Flyers Think Tank* participants' six proposed initiatives that would underpin the national road map for exploration under cover:

1. National cover map
2. National map of the deep crust and upper mantle
3. National distal footprints program
4. National 4D metallogenic map
5. National exploration research network
6. Education and technology transfer program

1. National cover map

Following the discovery of gold in New South Wales by Edward Hargraves in 1851, a wave of prospectors swept over Australia. These hardy people found thousands of outcropping deposits, defining the birth of our mining industry. Next, in the 20th Century, state, territory and Australian Government geoscience agencies systematically mapped the surface geology of Australia and made these maps available to explorers, leading to a second wave of major discoveries in the near surface. Following World War II, new geochemical and geophysical exploration tools made it possible for the first time for industry to find covered deposits. Even with these tools, half of all discoveries made in the past 60 years were buried under less than 15 metres of cover and only 10% were found under more than 200 metres of cover (see Figure 1).
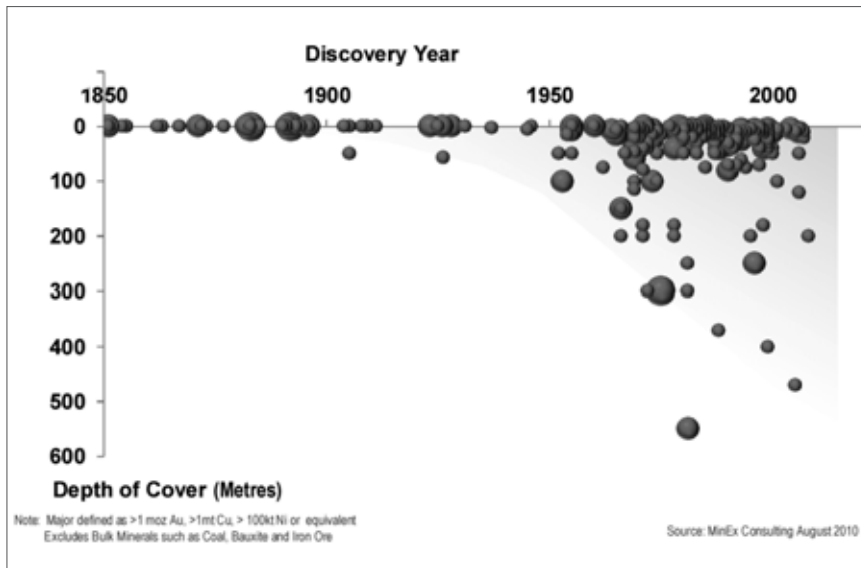
FIGURE 1 – Major mineral discoveries since 1850 with depth

Figure 2, a very crude cover map, shows that most deep discoveries are clustered where deposits were already known from surface outcrop and historic production. In other words, companies use the detailed geological knowledge from existing mines to find similar deposits in the local area. Although this 'brownfields' strategy demonstrates that deeply buried deposits can be economic, the exploration approach is not sustainable in the longer term. The future of our mining industry in the 21st Century will depend on deeper, 'greenfields' exploration to locate the next generation of deposits that are not associated with existing operations. Australia is underexplored, despite the inherent prospectivity of the covered areas.

Knowledge of the depth of cover is critical to the minerals industry for two reasons. First, the depth of cover is a clear indication of how difficult it will be to explore successfully in an area because the effectiveness of different exploration tools decreases and the cost of drilling increases with depth. Second, cover thickness dictates the minimum size and grade of a potential target needed for economic viability. Deeper deposits are more expensive to mine, but sufficiently high-grade deposits under even 500–1000 metres of cover can be viable.

We propose a high resolution 'national cover map' that will show the thickness and nature of the cover sequences across the continent. This depth to basement map would reveal where cover is relatively thin and enable identification of high-priority areas for exploration. As new tools for cheaper and more effective exploration under cover become available, new areas for exploration will become apparent.

FIGURE 2 – Distribution of major mineral discoveries (geographic and with depth)

Cover depth can vary significantly on a local scale. For example, in the Gawler Craton of South Australia the depth to basement can vary from 100 to 1000 metres over just a few kilometres.

Knowing how much of the continent is covered by a thin (< 30 m) versus thicker layer of cover could be used to prioritise R&D programs and would have a big impact on future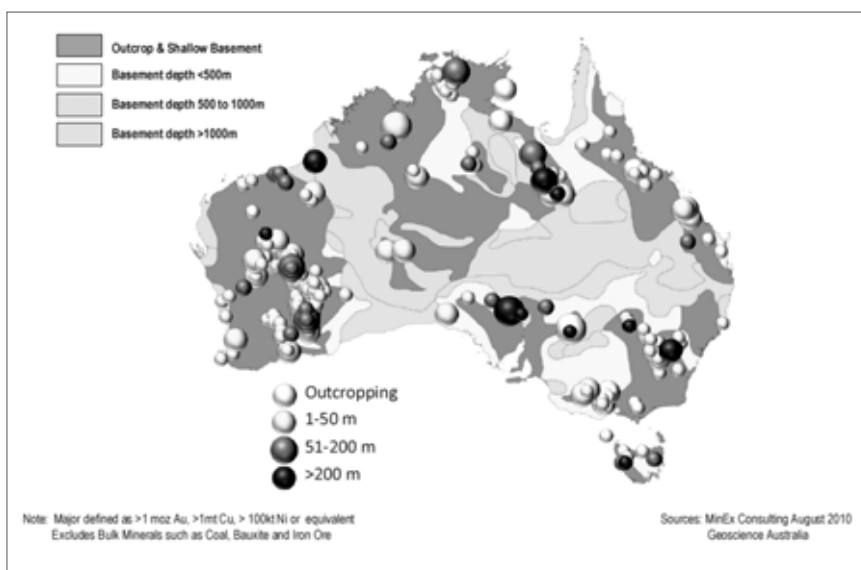 discovery. Where cover is relatively thin, biologically mediated physical and chemical processes can produce detectable surface geochemical signals of buried mineralisation. Research has indicated that, in favourable situations, termite mounds, *Acacia* leaf litter and *Spinifex* may signal buried mineralisation. This is important because surface geochemical sampling is far cheaper and disturbs less ground than drilling. For these reasons, recent research has been directed towards these thinly covered terranes. However, if the national cover map suggests that only a small proportion of prospective covered areas are shallow and the overwhelming majority realistically requires drilling-based exploration, this would reliably inform the strategic focus of our national research effort.

Knowledge of the thickness, nature and internal variations of the covering sequences will enable more effective exploration with stand-alone geophysical technologies, because the masking effects of cover can be understood and modelled. The older the cover, the more likely it is that geochemical signals will have migrated from the underlying basement rocks up into the surface layers and therefore give exploration companies a greater chance of detecting a signal of buried mineralisation. The interfaces between different parts of the covering sequences are likely to have localised both mechanical and geochemical signals from buried orebodies and therefore will be important sites for subsurface sampling. A better understanding of the distribution and nature of aquifers within the cover is critical to enable effective hydrogeochemical exploration for buried deposits. Fortunately, outback Australia has an extensive network of water bores that, when geochemically sampled across wide areas, can become an effective regional sampling tool to find buried giant ore deposits. An additional benefit will be a much better definition of groundwater resource potential.

Much of the data required to produce a national cover map is already available. This includes information from exploration and water-bore drilling that has penetrated cover sequences as well as relevant regional geophysical datasets, most notably electromagnetic and aeromagnetic data. These data are now held by various government geoscience agencies. A national effort to compile the various data sets and interpret the likely depth of cover at a local scale will help produce a single unified cover map of the country, in the same way that we now have unified geological, geophysical and radiometric maps.

The national cover map is one of the first enabling outputs from this initiative that could rapidly have a marked impact on the Australian mineral exploration industry and quickly deliver national economic benefit.

2. National map of the deep crust and upper mantle

Our international competitive advantage in minerals is based on huge, high-quality resources discovered long ago. Future exploration success requires opening the discovery space to greater depths.

Geophysical and geochemical methods are the cost-effective way to explore wider areas where cover is more substantial. Consequently a nationally coordinated approach to deployment of new geophysical tools (such as magnetotellurics and passive seismic), the collection of novel geochemical data (including stable and radiogenic isotope fingerprinting of rocks and minerals to help understand the evolution of the crust) integrated with a comprehensive drilling program is the optimal way to improve targeting success. The work plan is straightforward but, when collected on a large scale, will be of unprecedented scope. These new tools and sensors should be deployed to collect data on a comprehensive, continental scale. Next, using petascale computing, storage and network resources, these new data will be integrated with existing geophysical and geological information to create three-dimensional images of the deep subsurface. Finally, strategic drilling and logging will control and iteratively refine these subsurface images using physical properties from subsurface samples, constraining the interpretation of the geophysical observations and providing a basis for quantification of uncertainty.

Our proposed initiative is analogous to the highly successful and globally coordinated Integrated Ocean Drilling Program and its precursors, whose goal was a comprehensive understanding of the structure and evolution of the world's largely unknown ocean basins. By working on a continental scale and using multidisciplinary tools, subsurface geological imaging will drive exploration targeting and increase our knowledge of the mineral systems that produced Australia's hidden world-class ore bodies.

3. National distal footprints program

As exploration moves increasingly into covered areas, drilling costs increase significantly. Explorers will demand increasingly sophisticated targeting tools to constrain their drilling programs and will demand maximum benefit from drilling even when mineralisation is not intersected. It is therefore vital to understand the distal signature of major ore deposits well beyond the current approach of mapping local alteration and mineralisation styles. We must infer the likely proximity of giant ore deposits by interpreting subtle variations contrasted against a regional background.

To this end, we propose a 'national distal footprints program' that will provide a basis for detection of the subtle indicators of major ore systems preserved at and beneath the ancient land surface.

The program will be linked with existing geoscientific datasets, the proposed national cover map, the proposed 'Australian crustal drilling program', and the proposed 'national 4D metallogenic map' to establish the regional background in prospective terranes. Next, researchers will partner with the minerals industry, Geoscience Australia, and the state and territory geoscience agencies to perform integrated multidisciplinary case studies, studying drill transects that reach beyond traditional mineral system and ore deposit halos, well into the regional background. This research program will characterise:

- The eroded products of ore systems preserved in cover sediments and ancient thermal signatures;
- The regional geological, physical, chemical and mineralogical footprints of known deposits, relative to the background signature; and
- Maps of mineral system fluid recharge, source and transport pathways, looking for subtle indicators relative to the background.[1]

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1 Examples might include copper, sulfur and hydrogen anomalies around gold and porphyry (deposits associated with an igneous rock having large crystals in a fine-grained matrix) systems; Platinum-group element (PGE) depletion patterns around nickel-sulfide deposits; and organic signatures around sediment hosted lead-zinc systems.

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4. National 4D metallogenic map

It is increasingly clear that the geodynamic context in which ore deposits form is critical, particularly for very large deposits. Major ore deposits were formed only in a few very narrow time intervals, when large deposits formed at approximately the same time over wide areas. For example, the giant gold deposits of Western Victoria and the giant copper-gold deposits of eastern NSW both formed about 440 million years ago, even though they are separated by more than 500 km. These ore-forming periods represent unusual geological conditions that persisted only for geologically short time periods.

We already have some insights into these intervals; for example, they appear to be correlated with periods of major plate tectonic reorganisation.

Our challenge is to apply emerging insights to the practical task of mineral exploration. Significant progress has been made recently by developing 4D (that is, 3D plus time) dynamic models of the evolution of the Australian crust.

Simulation modelling provides a critical vehicle for synthesis of a wide range of observations and observation types within a sound theoretical framework and then allows us to ask sensible questions. It allows us to understand the consequences of the different structural (physical, chemical and thermal) configurations of the Australian lithosphere during the ore-forming periods. It can be used to predict the gravity, magnetic and electrical characteristics of potential ore systems so that explorers can readily compare numerical modelling results with commonly used exploration datasets. Consequently, ongoing developments in Australian computational information management and modelling advances will lead to enhanced exploration methodologies. The technologies developed while achieving this will have application universally across all systems, not just for the mining industry, and so will have a strong beneficial impact on the rest of Australia's industry and society.

In principle, this type of modelling could prioritise untested terranes and assist to predict the location of undiscovered mineral deposits, but the method has not yet advanced to the point where this can be achieved. Four advances are required:

- increased spatial resolution of and confidence in these dynamic models
- improvement in our knowledge of the basic building blocks of the Australian continent (knowledge that would be delivered by the 'national map of Australia's deep crust and upper mantle' proposed here)
- much closer integration between high-resolution radiometric ages dating ore body formation and 4D geodynamic models

- much closer integration between the geodynamic modelling community, the economic geology community and the exploration industry.

To achieve the above, we propose a 'national 4D metallogenic map for Australia' that will link Australia's major mineral deposits with the geodynamic context in which they formed. Development of the map is a cross-disciplinary initiative that will for the first time fully engage the geodynamic modelling community with the economic geology community on the regional scale most critical to predictive targeting. The project could deliver for the first time a clear spatial and temporal definition of the rare critical geodynamic conditions that created most of Australia's mineral wealth and hence will assist companies in targeting new giant deposits.

5. National exploration research network

The achievement of the 'national road map for deep earth exploration' would require a framework to integrate the aforementioned initiatives and bring together the world-class scientific expertise that exists in Australia for exploration geoscience research. The network would cross geographical and institutional boundaries and engender a national approach to exploration research. Formal activities will include:

- an annual meeting, that would be held in different Australian regional centres
- a nationally coordinated program of workshops and training courses for early- to mid-career researchers and industry explorationists
- cross-institution (including industry) study visits or secondments for researchers to collaborate across disciplines around the country
- regular public forums for dissemination of results to industry and the public.

At the annual meeting, the community will offer the opportunity to present research results to an informed audience all working towards exploration success. A public forum and media event at each annual workshop will develop better public understanding of the outcomes as well as closer engagement with the scientists and the science. The researchers will also be encouraged to use modern media (podcasts, vodcasts and social networking websites) to inform students about this exciting area of science. Particular emphasis will be given to early-career researchers, exploration geologists and postgraduate students.

The network will provide mentoring, workshops and opportunities for study visits to institutions across the country. It will be a contact base and resource for government policy makers, industry and researchers and become a forum for identification of opportunities for new research directions.

The ultimate objective of the research network is to ensure that the work done by local researchers is focused on identifying ways to explore under the cover in Australia.

6. Education and technology transfer program

A highly visible national geoscience effort should inspire young scientists and engineers with physics, chemistry and mathematics backgrounds to take up geoscience. These basic science skills are critical, to research and exploration and in the interpretation of large datasets produced by modern exploration programs. Through these initiatives, the next generation of researchers will develop greater capability for accurate and rapid decision-making, pivotal to support industry counterparts and to encouraging more rapid technology uptake and faster innovation in exploration.

The education and technology transfer program proposed here addresses three issues:

- *Practical inspiration*: summer schools, targeted bursaries, fee waivers for the promising international postgraduate students and a program of school visits to publicise and enhance the profile of geoscience.
- *School curriculum development*: Earth Sciences WA (ESWA) and the Teacher Earth Science Education Program (TESEP) support teaching of earth science in schools by developing teaching and learning resources including field trips for students. These initiatives, when executed on a national scale, will enhance recruitment and retention of talented young Australians.
- *National embedded researcher program:* post-doctoral researchers will be embedded in industry to work as part of an exploration team and promote rapid uptake of research products in the business of exploration. The resulting interactions will also ensure that researchers develop a better appreciation of the commercial aspects of their ongoing work. In a complementary fashion, industry exploration staff will be embedded in research institutions of the exploration research network to learn about and more rapidly deploy new research findings.

Introduction

Purpose of Think Tanks

The purpose of the Theo Murphy High Flyers Think Tank series is to bring together early- and mid-career researchers from a broad range of relevant disciplines to engage in thinking about novel applications of existing science (including social science) and technology to issues of national significance, and to identify gaps in knowledge that should be addressed. These events are a unique opportunity for career development and network creation amongst the nation's next generation of research leaders and their institutions.

Think Tanks are one of the premier events of the Academy's calendar and this year is the eighth that the Academy has held since 2002.

Previous Think Tanks

Previous Think Tanks have culminated in reports to government that have been timely, well received and instrumental in influencing policy development. Past Think Tank topics (found at www.science.org.au/events/thinktanks.html) have been:

2002 – Australia's national research priorities

2003 – Safeguarding the nation

2004 – Emerging diseases – ready and waiting?

2005 – Biotechnology and the future of Australian agriculture

2006 – Innovative technical solutions for water management in Australia

2007 – Extreme natural hazards in Australia

2008 – Preventative health: Science and technology in the prevention and early detection of disease

2009 – Agricultural productivity and climate change

2010 Think Tank: *Searching the Deep Earth: The Future of Australian Resource Discovery and Utilisation*

Effective minerals exploration has been central to previous and current mining booms. Australia's future economic prosperity will, to a large degree, depend upon future resource discoveries. Those mineral deposits that were easy to discover have been found and it is becoming increasingly difficult to find large new ore deposits that are economically viable. To continue previous successes in mining requires identifying and resolving the key issues impeding effective minerals exploration in Australia. This will involve exploration of potential cross-discipline opportunities to integrate and extend existing data; foreshadowing the technologies necessary for the next generation of minerals exploration; and putting in place a policy framework that will encourage effective science and successful exploration.

The 2010 Think Tank, *Searching the Deep Earth: The Future of Australian Resource Discovery and Utilisation*, is a valuable opportunity for some of Australia's leading early- and mid-career researchers to identify and propose new approaches to Australian minerals exploration. Participants will focus on identifying new approaches, technologies, data management systems, and policy innovations to facilitate science in delivering a better understanding of the deep Earth and ultimately helping to maintain mining productivity into the future.

The process

The Think Tank theme is introduced with a keynote address and five brief presentations. These presentations are aimed at stimulating lateral thought in the discussions that form the remainder of the Think Tank, rather than providing comprehensive coverage of the theme or any of the four specialist topics.

The afternoon session of the first day of the Think Tank is dedicated to discussions in small breakout groups. Each participant has been assigned to one of four breakout groups and each group will be chaired by the relevant topic speaker(s). Each group comprises a mix of skills and experience in order to stimulate lateral thinking and to challenge the participants to extend themselves and think dynamically. Each Chair has pre-selected a participant to act as the group's rapporteur. The role of the rapporteur is to collate the group's discussions and distil the discourse into a 15 minute presentation. The breakout groups are asked to examine and address their group's discussion questions (below) but are also encouraged to move beyond these questions to other topics identified during the discourse.

On the second day of the Think Tank, after a final review by the breakout groups, each of the four rapporteurs will present the findings of their breakout group. There will be an opportunity for questions and discussion after each presentation, during the general discussion, and in response to the final summing up.

Breakout groups

Group A	Name
Computational, information management and modelling advances	Dr Graham Baines
	Dr Peter Graham Betts
Chair	Tania Dhu
Professor Dietmar Müller	Dr Weronika Gorczyk
	Dr Jane Hodgkinson
Rapporteur	Associate Professor Eun-Jung Holden
Dr Thomas Landgrebe	Dr Margarete Jadamec
	Dr Thomas Landgrebe
	Dr Craig J O'Neill
	Dr Tim Rawling
	Dr Nicholas Rawlinson
	David Robinson
	Dr Gideon Rosenbaum
	Dr Nick Williams
Group B	Name
Giant ore deposits	Dr Tim Baker
	Christopher Chambers
Co-chairs	Dr James Cleverley
Richard Schodde and Dr Jon Hronsky	Dr Robert Dart
	Assistant Professor Marco Fiorentini
Rapporteur	Associate Professor Klaus Gessner
Dr Rob Hough	Dr Ian Graham
	Dr Anthony Harris
	Dr Rob Hough
	Dr Lawrence Leader

Group B (Continued) **Giant ore deposits**	Professor John McLeod Miller
	Thomas Poulet
	Dr Frank Reith
	Dr Simon Richards

Group C **Innovation and new technology** **Chair** Dr Tom Whiting **Rapporteur** Dr Katy Evans	**Name**
	Dr Benjamin Ackerman
	Dr David Beck
	Dr Elena Belousova
	Laurie Callaghan
	Dr Raj Das
	Dr Katy Evans
	Dr Ryan Fraser
	Dr Wojtek James Goscinski
	Dr Steven Micklethwaite
	Dr Anya Reading
	Dr Carl Spandler
	Dr Mark Symmons
	Dr Stephan Thiel
	Dr Mark Tingay

Group D **Exploration policy – the way forward** **Chair** Peta Ashworth **Rapporteur** Dr Chris Yeats	**Name**
	Dr Graham Begg
	Dr Stephen Beresford
	Dr Zhaoshan Chang
	Dean Collett
	Miles Davies
	Professor David Giles
	Aleksandra Kalinowski
	Dr Maxim Lebedev
	Professor T Campbell McCuaig
	Dr Kieren Moffat
	Professor Steven Reddy
	Dr Alanna Simpson
	Dr Hrvoje Tkalcic
	Dr Chris Yeats

Discussion questions

Group A – Computational, information management and modelling advances (specifically including geology, geophysical inversion, geochemistry and geochronology)

- With respect to minerals exploration, what is currently being well-achieved using information management, computational and modelling methodologies?
- What are the significant issues Australia's computational capability faces in becoming an effective tool for understanding crustal processes and identifying mineralisation niches? (Hardware, software, people?)
- Is there a need for a computational strategy to manage the increasing quantities of geological data? If yes, what shape should this strategy take?
- Ideally what systems (including software and hardware) need to be developed to advance this field in relation to minerals exploration?
- How can Australia's current and future computational capabilities be better integrated with the other topics of this Think Tank (Giant ore deposits; Innovation and new technology; and Exploration policy – the way forward)?

Group B – Giant ore deposits

- What successes have there been with regard to understanding the genesis of and exploration for giant ore deposits since the discovery of Olympic Dam, and what specifically supported these discoveries?
- What are the specific causes in Australia of poor progress in the discovery of giant ore deposits?
- How could a strategy be developed that better targeted available resources for future giant ore deposit discoveries?
- What additional resources are necessary to advance Australian minerals exploration, particularly for giant ore deposits?
- How can Australia's current and future mineral exploration capabilities be better integrated with the other topics of this Think Tank (Computational, information management and modelling advances; Innovation and new technology; and Exploration policy – the way forward)?

Group C – Innovation and new technology

- Where in Australia have innovation and/or new technologies been well-utilised to improve Australia's mineral exploration capability?
- What has impeded the innovation and development of new technologies that would improve and enable Australian minerals exploration?
- What key innovations or new technologies will be necessary to advance Australian minerals exploration in the near and distant futures?
- How can investments be strategically made to achieve these new innovations/technologies?
- How can Australia's current and future innovation and new technologies for minerals exploration be better integrated with the other topics of this Think Tank (Computational, information management and modelling advances; Giant ore deposits; and Exploration policy – the way forward)?

Group D – Exploration policy – the way forward (particularly the need for scientists to communicate effectively with politicians and the community at large regarding both the impact and value of searching the deep Earth)

- What is the current state of exploration policy in Australia, including engagement with key stakeholders?
- What policy impediments are there to minerals exploration in Australia?
- What type of strategy is necessary to integrate the views of the various key stakeholders (community, government, industry, academia/research)? How could such a strategy be implemented?
- What policy tools could be invoked to improve Australia's research capability in understanding the crust and in improving our exploration success? In particular, what policy levers could be used to drive more effective integration of the other topics of this Think Tank (Computational, information management and modelling advances; Giant ore deposits; and Innovation and new technology)?

Outputs

The proceedings will be taped, transcribed and made available on the Academy's website. This includes all presentations (verbal and PowerPoint slides), breakout group reports from the second day of the Think Tank, general discussions, and the final summing up. The event proceedings, available in electronic and print formats, will also provide contextual information, identify knowledge gaps and summarise the major outcomes from the Think Tank. These proceedings will offer options for a 'way forward' and subsequently can be used to underpin policy development and research prioritisation.

Organising committee

Chair

Dr Phil McFadden FAA

mcfadden@grapevine.com.au

Phil McFadden was a Chief Research Scientist from 1990 at Geoscience Australia and then Chief Scientist there from 1999 until his retirement in late 2008. He holds BSc honours degrees in physics and mathematics and a DPhil in geophysics. He is a past Chair of the Academy of Science's National Committee for Earth Sciences and in that role developed a national strategic plan for Australian geoscience. He has sat on many high-level government science committees, including the National Resource Infrastructure Taskforce and the National Collaborative Research Infrastructure Strategy committee. He has served as Treasurer of the Academy of Science and in that role served on both the Council and the Executive of the Academy. He was awarded the Gold Medal of the Geological Society of South Africa. He is a Fellow of the American Geophysical Union and a Fellow of the Academy of Science.

Committee members

Peta Ashworth

Science into Society Group Leader, CSIRO Earth Sciences and Resource Engineering
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Biographical details available on page 24.

Professor Michael McWilliams

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Mike McWilliams is Chief of CSIRO Earth Science and Resource Engineering (CESRE). Energy research in CESRE is focused on maximising the efficiency of petroleum exploration and production, new geothermal energy technologies and geological storage of CO_2. Minerals research in CESRE is enabling prediction and discovery of ore deposits with greater accuracy whilst improving safety, productivity and sustainability in mining.

Before joining CSIRO, Mike was Director of the John de Laeter Centre of Mass Spectrometry, a joint research venture between CSIRO, the University of Western Australia, Curtin University and the Geological Survey of Western Australia. He is Professor Emeritus at Stanford University in California, where he was a scientist and teacher from 1978 to 2006. He is author or co-author of more than 160 papers and has been a consultant to 38 companies, government organisations and universities engaged in minerals and energy exploration and production, electronics and aerospace technologies and science publishing.
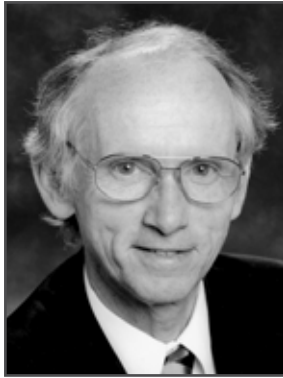
Professor Robin Stanton FTSE

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Robin Stanton is Pro Vice-Chancellor (eStrategies) at ANU. Prior to that appointment, he was the inaugural Dean of the ANU Faculty of Engineering and Information Technology, head of the ANU Department of Computer Science and held various industry and academic appointments. He also served as Director of the Cooperative Research Centre – Advanced Computational Systems and the Centre for Information Science research.

Robin's background is in engineering, computer science, information systems and IT governance; developed largely through research, education and management roles in higher education. His academic interests have focused on artificial intelligence, high performance systems, information systems, knowledge management and IT governance. As PVC, he has carried portfolio responsibilities for information infrastructures, enterprise systems, libraries, e-research, e-learning and digital futures planning. Robin holds a PhD in computer science from the University of NSW and is a Fellow of the Australian Academy of Technological Sciences and Engineering.

Dr Neil Williams PSM FTSE

Immediate past CEO, Geoscience Australia
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Biographical details available on page 19.

Mr Roy Woodall AO FAA FTSE

Consultant, Earthsearch Consulting Pty Ltd
Kerrieromeo@aol.com

Roy Woodall is a graduate of the University of Western Australia and Berkeley University, California. He joined Western Mining Corporation (WMC) in 1953 and spent his entire career with that company directing their mineral and petroleum exploration for nearly 40 years.

Through exploration success WMC became one of Australia's great mining companies. Discoveries were made in Western Australia; important gold deposits and a new previously unknown nickel province which is now a major world producer from nickel sulphide ores. In 1976 the company discovered the giant Olympic Dam copper, gold, uranium deposit in South Australia which transformed the area into one of the world's great mineral provinces. Oil fields were also discovered offshore Western Australia.

The WMC geological staff made important contributions to the understanding of ore deposits through careful scientific documentation. Roy is a Fellow of the Australian Academy of Science, the Australian Academy of Technological Sciences and Engineering and the Australasian Institute of Mining and Metallurgy. Honours and awards include Officer of the Order of Australia and the Academy of Science's Mueller and Haddon Forrester King medals.

Speakers

Dr Neil Williams PSM FTSE

Immediate past CEO, Geoscience Australia
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Neil was the Chief Executive Officer of the Australian Government's national geoscientific research and spatial information agency, Geoscience Australia, and two of its predecessor agencies for 17 years until his retirement in January 2010. He trained as an economic geologist and received his BSc (Hons) degree from the Australian National University and his PhD from Yale University. Upon completion of his PhD he returned to the ANU and worked there for five years as an academic specialising in the genesis of sediment-hosted base-metal deposits. In 1981 he joined the then Mt Isa Mines group of companies as a mineral explorer and remained with them for 10 years before joining one of Geoscience Australia's predecessors, the Bureau of Mineral Resources, in 1991. He was appointed CEO of the Australian Geological Survey Organisation in 1995 and oversaw the transformation of that agency into the present-day Geoscience Australia.

Neil received the Public Service Medal in the 2006 Australia Day National Honours List for outstanding public service in the provision of geoscientific advice to government, geoscience services, industry and the public. He is a Fellow of the Australian Academy of Technological Sciences and Engineering and was awarded the Society of Economic Geologists Lindgren Award in 1981 for his research on the McArthur River lead-zinc deposit in the Northern Territory. He was the President of the Society in 2008. He also led Oceania's successful bid for the 34th International Geological Congress to be held in Brisbane in August 2012, and is President of the 34th Congress.

The challenge of discovering deeply buried ore deposits

The world's hunger for mineral commodities is unlikely to lessen in the foreseeable future, given the twin drivers of global population growth and economic expansion.

During the 20th century, and particularly after World War 2, supplies of minerals were sustained by an unprecedented period of successful mineral exploration that was dominated by the discovery of a wide range of outcropping and near-to-surface ore deposits.

Factors contributing to this success included:

- the opening up of prospective terranes for exploration;
- comprehensive geological maps of these terranes;
- a revolution in surface geochemical exploration techniques;
- the development of a wide range of geophysical exploration tools – both ground-based and airborne; and
- advances in our understanding of the genesis of ore deposits and the geological environments in which particular ore types form.

However, discovery rates began to slow towards the end of the 20th century. This is attributed to the declining number of outcropping and near-surface, and hence easy-to-find, ore deposits that remain to be discovered.

The challenge now facing explorers is how to find more deeply buried ore deposits, both in regions of known mineralisation and in regions where terranes of unknown prospectivity are obscured by overlying barren rocks.

To meet the challenge many new activities will be needed. Some of these are:

- methods for producing accurate 3D and 4D geological maps to facilitate deep exploration in the same way that surface geology maps aided exploration in the 20th century (this will involve the integrated inversion-modelling of different geophysical datasets – an activity that will involve many mathematical and ITC challenges);

- the redefining of ore types in geophysical terms, rather than in geological, mineralogical, and geochemical terms as is the norm today; and
- the development of a new generation of genetic ore-deposit models that focus on *where* particular ore types form in time and space, rather than on *how* particular ore types form, as is the norm today.

Participants in this Think Tank have the opportunity of probing these challenges further, as well as coming up with other innovative ideas for improving our ability to successfully discover the world's future sources of minerals.

Professor Dietmar Müller

Professor of Geophysics and Australian Laureate Fellow, School of Geosciences, University of Sydney
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Dietmar received his undergraduate degree from the Christian-Albrechts University of Kiel in Germany, followed by a PhD in Earth Science from the Scripps Institution of Oceanography in San Diego/California in 1993. After joining the University of Sydney as a lecturer in geophysics in 1993, he established the University of Sydney Institute of Marine Science and built the EarthByte e-research group. The EarthByters are known for pursuing open innovation, involving the collaborative development of open-source software and global digital datasets, made available under a creative commons license. One of the fundamental aims of the EarthByte group is geodata synthesis through space and time, assimilating the wealth of disparate geological and geophysical data into a 4D Earth model.

In 2000 Dietmar was awarded the Fresh Science Prize by the British Council and ScienceNOW, followed by the Carey Medal in 2004 for his contributions to the understanding of global tectonics. In 2006 he was elected Fellow of the American Geophysical Union and in 2009 he was awarded an Australian Laureate Fellowship. From January to July 2010 he was a visiting professor at the Ludwig-Maximilians-Universität München, Germany, funded by a Deutsche Forschungsgemeinschaft (German Research Foundation) Mercator Fellowship.

Knowledge discovery via a virtual geological observatory

Earth science has a history of being data-rich and information-poor, an imbalance that is growing year by year, due especially to a flood of remotely sensed data. A major problem now faced by geoscientists is how to amalgamate data and to connect them to analysis- and process-modelling tools. This is particularly relevant to the study of mineral and petroleum resources, which typically form over time periods of hundreds of millions of years. In order to make digital Earth datasets suitable for resource exploration, one needs to be able to restore the geographic positions of all data back through geological time, and link data to models of the processes by which resources are formed. The Virtual Geological Observatory (VIRGO) project is designed to fill this fundamental technological gap. VIRGO is set up to develop a formal knowledge-discovery platform that connects testable ideas, concepts and models regarding plate tectonic and geodynamic processes with reconstructable digital geodata. A GIS-like framework with temporal awareness forms the core of the information model, interoperating with various GIS formats. It is able to reconstruct point, line, polygon and raster (gridded) data in accordance with past plate configurations, and model other time-dependent attributes in a coherent fashion. An important capability provided by VIRGO is the provision of quantitative spatio-temporal data analysis and data mining. Data co-registration considers spatial relationships over time and transforms disparate datasets into a homogenous data structure, which can then serve as an input to subsequent analysis- and data-mining tools, partitioned into supervised and unsupervised paradigms. Visual analysis tools in the form of interactive plots, charts and statistics will be an integral part of the process, helping to convey information from machine-learning tools such as cluster analyses, data projections and classifications.

Richard Schodde

Managing Director, MinEx Consulting
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Richard has 30 years experience in a wide variety of project analysis and strategic planning roles within the international resources industry – including 15 years at Western Mining Corporation (in their Business Development Group and as Strategic Planning Manager for the Exploration Division) and, more recently, four years at BHP Billiton (as minerals economist in their Global Exploration Team). Two years ago he founded MinEx Consulting to provide strategic and economic advice to industry and government. From his work Richard has developed a deep understanding of the drivers behind mineral exploration and assessing the various trade-offs between the geological, technical, economic and business risks of a given project. This underpins his work in helping companies identify how to make money out of exploration.

Richard has a first class honours degree in materials engineering and an MBA. Along the way he has learnt some geology. He serves on several industry committees, including the AusIMM and the Melbourne Mining Club. In 2009 he was appointed an Adjunct Professor at the School of Earth Sciences at the University of Western Australia and is a member of the AusIMM, SEG, SME and PDAC. He has published several papers on exploration discovery rates and industry performance and is internationally recognised by his peers as a world leader in mineral economics.

Giant ore deposits: Why they are important!

For obvious reasons, all explorers would like to find giant orebodies. However, what we really need to find is world-class mines (WCMs) – as not all giant accumulations of mineralisation are economic.

There are many benefits in finding WCMs. The geologist is keen to receive the kudos, the developer is keen to make money and have a 'company-making mine' that transforms their business. From society's perspective, WCMs create employment and enable major investments in infrastructure and downstream processing. Such mines often redefine the cost base of the industry, leading to cheaper materials and a better standard of living for everyone. Finally, they generate most of the industry's profits and taxes.

The challenge is that, for many commodities, it is progressively becoming more difficult to find WCMs. By definition they are extremely rare, but on the flip-side they tend to have large and obvious signatures. The problem for Australia is that all of the outcropping deposits have been found, and one now needs to look under deep cover and/or go to new search spaces. This requires:

- being innovative and creative in knowing where best to explore;
- being effective in testing the target; and
- developing new mining and processing technologies to best extract the ore.

Related issues are:

- Given the riskiness of exploration, what is the best way to manage your project portfolio?
- How do you measure the exploration effectiveness prior to discovery?
- What are the best tools, models and techniques for finding a WCM under deep cover?
- How to know whether a deposit has the makings of being world-class?
- Are WCMs made or found? Innovations in mining and processing can change what is economic ore.

Dr Jon Hronsky

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Jon is currently a principal of Western Mining Services (WMS), a consultancy group with offices in Perth and Denver that provides services to the global mineral exploration industry. WMS specialises in the strategic management of mineral exploration and the exploration targeting process. Jon is also Chair of the Board for the Centre for Exploration Targeting, an industry-focused research group based at the University of Western Australia and Curtin University in Perth. In addition, he is a director of Encounter Resources, a Western Australian-focused uranium- and base-metals junior explorer. Prior to his current role, Jon was Manager of Strategy and Project Generation for BHP Billiton's global mineral exploration group, and before that Global Geoscience Leader for Western Mining Corporation Resources.

Jon graduated from the Kalgoorlie School of Mines with a degree in mining geology in 1983 and then joined WMC Resources. He completed his PhD at the University of Western Australia in 1992. Subsequently his career focus has been on developing an understanding of the key business dynamics that drive mineral exploration and the interface between innovative geoscience and pragmatic exploration business outcomes, particularly as related to exploration targeting. His exploration targeting work led to the discovery in 2000 of the West Musgrave NiS province in WA. Jon was awarded the Gibb Maitland Medal in 2005, the highest award of the WA Division of the Geological Society of Australia. He was the 2009 Society of Economic Geology Distinguished Lecturer.

Giant ore deposits: How do we get better at targeting them?

Twentieth century economic geology failed to determine why some ore deposits were giants. However, recent advances now point the way towards a new paradigm for understanding ore formation and therefore a future in which predictive models for giant deposits may be developed.

The first key realisation is that ore deposits are the focal points of much larger systems of mass and energy flux. These 'mineral systems' are very large scale, commonly involving the entire lithosphere and subcontinental-size areas. The other key advance is recognising that ore-forming systems are primarily physical systems. The critical element is a highly anomalous spatial concentration of mass flux (via the agency of advective fluid flow). Historical research was biased towards chemical aspects of ore formation, largely because these have been easier to study, and the more important (from a targeting perspective) physical processes were relatively neglected.

The above two fundamental concepts provide a powerful framework for unifying our understanding of ore-forming process. There are several important aspects that derive from these:

- lithosphere-scale architecture is a fundamental control on the location of giant ore systems;
- the importance of regional-scale pre-fertilisation of the upper mantle in many systems;
- ore systems, especially giant ore systems, require a high degree of self-organisation and therefore a major gradient barrier to ore fluid flow;
- only a small number of geodynamic scenarios have ore-forming capability; and
- the size of any deposit will depend on a combination of available advective fluid/energy flux and the degree of organisation of that flux.

Finally, we can now propose an explanatory hypothesis for the 'lineament concept', one of the earliest empirical concepts relating to the targeting of giant ore deposits: that they represent an emergent property of the complex interaction of the various elements of the long-lived orogens that host most major ore deposits.

Dr Tom Whiting

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Tom has 32 years experience in global exploration project generation and management. He is currently a consultant, working in the minerals exploration and R&D fields. He is also currently the independent Chair of the newly formed Deep Exploration Technologies CRC.

Tom held numerous senior exploration management roles within BHP Billiton, including vice president of Minerals Exploration from 2000-2004. In this role, he was responsible for BHP Billiton's global minerals exploration program whilst based in Melbourne. He has a successful exploration discovery record. Prior to joining BHP Billiton, he worked for CRA Exploration Pty Ltd and Geoterrex Pty Ltd, an international geophysical contractor, in Australia and Canada. He started his career with Delhi Oil, based in Adelaide.

Tom has a history of involvement in industry-led research developments. This includes Falcon, the world's first airborne gravity gradiometer, and helping develop and instigate the Deep Exploration Technologies CRC. His current interests revolve around helping various organisations solve the problem of lifting exploration investment and improving current declining discovery rates in Australia.

Current issues for the future of innovation and new technologies in minerals exploration

Although its national benefits have been overwhelmingly positive, one issue resulting from the recent minerals boom has been an acceleration in the decline of resource quality due to the interplay of rapidly increasing commodity production rates and the longer term decline of discovery rates of world-class mines.

One solution to this challenge is new innovative technologies and exploration methods aimed at expanding the effective search space within which these world-class mines may be found. In Australia that is both within the deeper sections of existing terranes of known high prospectivity and within poorly understood terranes generally covered by unconsolidated cover.

New technologies would seek to improve targeting through exploration tools that enable improved detection and discrimination of ore deposits and improved testing technologies (eg, drilling). Innovative methodologies may include the way information is bundled or visualised to create knowledge leading to discovery.

Australia's minerals industry R&D capability is amongst the best in the world. There are several important initiatives under way that are a carefully researched response to the national issue outlined above. These include CSIRO's Minerals Down Under Flagship, the National Collaborative Research Infrastructure Strategy/AuScope initiative and the new Deep Exploration Technologies CRC. Many university groups are also in this research space (eg, Centre for Exploration Targeting, University of Western Australia; ARC Centre of Excellence in Ore Deposits (CODES)) and there is much relevant research outside the minerals industry (eg, petroleum, defense and medical industries).

So will this ensure success in the future?

One could pose the question of how we draw these various research initiatives together to maximise our chances of success. Some key issues for consideration include the following:

- Ensuring a flow of information and results across the various organisations involved in minerals research initiatives in a systematic and strategic way.
- Research capacity appears tight as most researchers are fully engaged on existing programs. This makes it difficult to free up capability to identify new transformational innovations and technologies outside of what has currently been identified.
- Success will require early and aggressive adoption of innovations by industry. For this to occur, the link between mining houses/explorers, their industry service providers and R&D providers needs to be transparent and efficient.

Peta Ashworth

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Peta Ashworth brings over 20 years of experience working in a range of senior management and research roles. She is currently group leader of the Science into Society Group within CSIRO's Division of Earth Sciences and Resource Engineering, leading a team of social researchers examining stakeholder perceptions to areas of national significance to Australia. Peta's main research interest is how to deliver information to best effect. She has gained an international reputation as a leading researcher in understanding stakeholder perceptions to climate change and low emission energy technologies, in particular carbon capture and storage. This research is critical because although much of the effort to address climate change will be led by industry and government, energy users at the community level will also play a critical role both in technology acceptance and behaviour change. Peta believes it is important to educate and empower them to engage with this issue and work towards environmental sustainability. She co-authored The CSIRO Home Energy Saving Handbook – How to save energy, save money and reduce your carbon footprint, which was released late 2009, and is currently chair of the International Energy Agency Greenhouse Gas Social Research Network.

Society and exploration: Considerations for now and in the future

The worlds of industry, society and governance are intertwined. Changes in one will affect the others and influence the rate of change and the acceptance of the industry, technology or process. A key issue for whether an industry is accepted by society is how the industry, and the risks associated with it, is perceived. If society perceives the risks to be too great it can delay or cease a project.

The Australian minerals and exploration domain face similar challenges of this interconnectedness. Declining ore grades, increasingly difficult operational conditions, accelerating constraints around water and energy use and changing policy contexts are impacting on the way business is done. Each of the challenges has societal implications that also impact on those involved in exploration.

When projects are delayed, as a result of public opposition, in most cases government will be brought in to decide whether to overrule or allow the local opposition to stand. Reasons most often cited for opposition include concerns around environmental impacts, subsidence, impacts on local housing prices, effects on local agriculture and local water supplies. Many of these concerns can arise through a lack of knowledge about the processes involved, a lack of adequate regulatory frameworks, or competing priorities between stakeholder groups.

This paper will explore the role that social sciences can play to enhance societal acceptance of minerals and exploration. It will draw on a number of case studies to highlight potential issues and present some considerations of what may constitute a positive way forward, and identify ways to think about these in relation to minerals and exploration in the next 20 to 30 years.'

Chairs

Dr Phil McFadden FAA

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Phil was a Chief Research Scientist from 1990 at Geoscience Australia and then Chief Scientist there from 1999 until his retirement in late 2008. He holds BSc honours degrees in physics and mathematics and a DPhil in geophysics. He is a past Chair of the Academy of Science's National Committee for Earth Sciences and in that role developed a national strategic plan for Australian geoscience. He has sat on many high-level government science committees, including the National Resource Infrastructure Taskforce and the National Collaborative Research Infrastructure Strategy committee. He has served as Treasurer of the Academy of Science and in that role served on both the Council and the Executive of the Academy. He was awarded the Gold Medal of the Geological Society of South Africa. He is a Fellow of the American Geophysical Union and a Fellow of the Academy of Science.

Dr Sue Meek FAICD FTSE

Chief Executive, Australian Academy of Science

Sue has 25 years experience working in a variety of capacities at the interface of industry, academia and government. Her particular interests are in promoting awareness and understanding of science and technology, and the formulation of policies and programs to stimulate the conduct and application of research and development. Sue held the position as Australia's inaugural Gene Technology Regulator from December 2001. This statutory appointment was established to administer the national regulatory system for the development and use of genetically modified organisms. Immediately prior to that, she was Executive Director, Science and Technology in the Western Australian Department of Commerce and Trade. In this role she was responsible for the development and implementation of state policies on science and technology and public sector intellectual property management and the administration of grant programs to support innovation and the development of research infrastructure.

Sue has a PhD in marine biology; a Masters in oceanography; and an honours degree in microbiology. She is a Fellow of the Australian Institute of Company Directors and of the Australian Academy of Technological Sciences and Engineering. She is a member of the Centre for Environmental Risk Assessment Advisory Council and was one of 14 inaugural recipients of James Cook University's Outstanding Alumni award.

Rapporteurs

Dr Thomas Landgrebe

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Tom is a data-mining specialist, having obtained Bachelors and Masters degrees in electrical engineering at the University of the Witwatersrand in Johannesburg, South Africa, and a doctorate in the area of statistical pattern recognition at Delft Technical University, The Netherlands. He spent around seven years performing R&D at De Beers, focusing on image-processing and pattern-recognition related technology. Hyperspectral-based mineral sorting and image-based diamond population analyses for diamond exploration were two significant projects where he played a primary role, including project management. Tom joined the EarthByte group in 2010. His research interests span several areas of computational intelligence, ranging from the design of practical machine-learning systems, the formal incorporation of expert knowledge into learning machines, and image, video, GIS and hyperspectral data processing. Recently his research focus has shifted towards developing a coherent spatio-temporal data-mining framework for paleo-GIS data analysis.

Tom's research is directly related to the Think Tank theme, especially regarding new technology and data management. He is developing a data-mining infrastructure integrated into the GPlates tectonic plate simulation software to identify complex relationships between diverse geographical data sources. The technology will be in a unique position to coherently analyse data both spatially and temporally, thus exposing important dynamics related to deep Earth time. Studies with large potential impact for Australian exploration will be made possible, such as the relationships between plate tectonics and ore deposit formation, and explicitly showing associations between pre-competitive data and late-stage exploration outcomes.

Dr Rob Hough

Research Stream Leader in the Discovery Theme of the Minerals Down Under
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Rob is a geologist and senior research scientist in CSIRO whose major research is in the properties of natural gold and how it is deposited within the Earth. He is the author of publications in Nature, Geology and Science. He has received research funds in the form of fellowships from the Robert Blair Fellowship and the Royal Society. He received the Western Australian Premier's Award for Early Career Achievement in Science in 2004, the Perth Convention Bureau Scholarship in 2006 and the CSIRO Julius Career Award recognising mid-career excellence in 2009. He has been invited to edit a special issue on nanominerals in ore deposit processes in Ore Geology Reviews in 2011; he was editor of Elements' special issue on gold in 2009; and he won the Geological Society of Australia's AB Edwards Medal in 2008 for the best paper in economic geology. He has been an invited plenary speaker at 15 international conferences and was a convenor at the Goldschmidt Conference in Knoxville, USA, in June.

Rob has worked for eight years at the interface between regolith (surface) and hypogene (deep crust) exploration geochemistry, with specific emphasis on gold exploration and targeting. He is a research leader in gold mineralogy and geochemistry in ore deposits and exploration samples. His work has focused on developing innovative new avenues in research on gold at all scales, from nanoplates to nuggets. Rob partners very closely with university collaborators on research across Australia and internationally and is renowned for his ability to develop a collaboration and to communicate his results widely. He works very closely with the gold exploration and mining industry in Australia and leads

several research projects heavily funded by industry and is a co-investigator on several others. He has already begun to develop a group of young researchers to work on these projects and as such can be seen as a future leader in exploration geochemistry in Australia. His ability to integrate across disciplines (gold in plants, gold with bacteria, metallography of gold, gold colloid chemistry) in order to pursue new research directions for the Australian gold industry is well-recognised as necessary to promote new exploration in Australia and to foster the discovery of new gold deposits.

Dr Katy Evans

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Katy was awarded a PhD on metamorphic fluid flow by Cambridge University in 1999. Subsequent postdoctoral work on mineral dissolution and precipitation in mine spoil was followed by a move to Australia in 2002 to CSIRO Exploration and Mining to work on gold deposits and the thermodynamic characteristics of sulfur-bearing, high ionic strength, mixed solvent fluids. In 2005 she was awarded an Australian Synchrotron Research Fellowship and moved to the Australian National University, where she performed experiments on CO_2-bearing solutions, with applications to the formation of gold deposits from CO_2-rich fluids. She began a Research and Teaching Fellowship at Curtin University in 2007.

Katy's research focuses on fluid-rock interaction, particularly open-system interactions that redistribute redox-sensitive elements such as Fe, S and C. These systems have tremendous relevance to ore formation, as redox reactions in open systems are a key factor in the formation of a range of ore deposit types.

Dr Chris Yeats

Research Program Leader, Mineral System Science
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Chris received his PhD in 1996 and is a mid-career ore systems geologist. He has 20 years experience in base- and precious-metal exploration and research in terranes ranging in age from the Archaean to modern active seafloor hydrothermal systems. His current research focuses on exploration for and the geochemistry, mineralogy and petrology of volcanic-hosted massive sulfide mineralisation in ancient and modern terranes. He has played a leading role in 14 research cruises on a range of vessels; the highlights include a manned submersible dive on the PACMANUS hydrothermal field, the first attempt to drill an active felsic-hosted hydrothermal system during Ocean Drilling Program Leg 193 (where he led the crucial hydrothermal alteration study) and the first commercial exploration drilling for seafloor sulfides on the Kermadec Ridge in December 2005. As a member of the Seafloor Hydrothermal Systems Team, in 2002 he received the CSIRO Chairman's Medal for Research Excellence. He is the Western Australian Divisional Chair of the Geological Society of Australia.

In his role as Research Program Leader for Mineral System Science, Chris leads 90 staff who represent Australia's largest multidisciplinary mineral-exploration focused research group. His position provides him with a broad perspective of emerging trends and technologies in the Earth sciences, while CSIRO's unique role within the National Innovation System requires that he is cognisant of the issues that impact on the minerals industry. Chris has also had significant involvement with the nascent seafloor exploration and mining industry in the South Pacific region and is able to speak on the benefits and barriers to this potentially major new opportunity for the minerals industry in Australia.

Welcome

Professor Suzanne Cory AC PresAA FRS

It really is a very great pleasure for me to welcome you all here today to the Australian Academy of Science and, of course, to welcome you to the 2010 Theo Murphy High Flyers Think Tank.

We initiated these Think Tanks in 2002 and, since then, we have hosted them annually. They are certainly one of the highlights on our yearly calendar. They are always focused on nationally important issues. The topics have been very diverse, ranging from extreme natural hazards to preventative health. One of the most important and key elements of these Think Tanks is that they aim to bring together researchers from a very broad range of disciplines, enabling them to meet each other and be challenged in ways that they are not normally challenged in their own work places and enabling a very high crossdisciplinary approach to the issue under discussion. So we hope that we are going to throw up novel ideas and big thoughts. The Think Tanks also, we believe, provide a really exceptional opportunity for young researchers to build and strengthen networks with their peers. We hope that these networks will grow over the years and will sustain you in your careers. This is just one of the activities that the Academy undertakes to support the development of Australia's next generation of great researchers and thinkers—and, of course, that is one of our most important tasks.

I would like, in particular, to thank and acknowledge the very significant efforts of the Organising Committee members who put together the program for this year's Think Tank, and to the speakers who have joined you here today to help you to develop this very stimulating two day experience. It is my very great pleasure now to invite Dr Phil McFadden to the podium to tell you about the theme of this year's Think Tank—which, as you know, is *Searching the Deep Earth*. It is a very different field from mine—I am a cancer researcher—so I am looking forward to learning a lot too. Welcome again and I hope you have an exceptional two days that you look back on over your entire career and think, 'Yes, that was the time that something special started in the way I think about my discipline.'

Professor Suzanne Cory AC PresAA FRS
President Australian Academy of Science

Opening address

Dr Phil McFadden FAA

I would like to add my own welcome and thanks to all of you as participants for providing your time, your intellect and your enthusiasm to help the Australian Academy of Science make this event a success. You might say: how can I say that at the beginning of the meeting—to thank you for your enthusiasm, your intellect *et cetera*? How do I know? Well, during breakfast I was watching the excitement that was building up and listening to some of the conversations, and I was in a little group in which the conversation was so animated that I have already run out of voice and am sucking a 'Strepsil' in order to continue talking!

I would also like to thank the members of the Organising Committee for their hard work. On the committee are Ms Peta Ashworth, Professor Mike McWilliams, Professor Robin Stanton, Dr Neil Williams, and Mr Roy Woodall, or, in this context, perhaps I should say 'Mr Olympic Dam'. So I would like to say thank you very much to the organising committee and thank you for your seminal contributions to this Think Tank.

Also, as you would be aware, an event like this does not happen by magic; it takes a tremendous amount of behind-the-scenes work to arrange all the logistics. This has been undertaken by the staff of the Academy, under the direction of Dr Sue Meek. In particular, I would like to thank Dr Fiona Leves, Ms Savita Khiani and Dr Sharon Abrahams. I am sure that you have all seen these names on the emails you have been receiving and that you appreciate the work they have been doing on your behalf. Also, the proceedings of this Think Tank will be produced and made use of—and people like Fiona will have a tremendous amount of involvement in that as well.

Searching the deep Earth: The future of Australian research discovery and utilisation—why does this matter to the nation? I got an answer to that when my phone rang at half past five this morning for the first interview. People really are interested; it does make a difference to them. They are interested in our ability to find resources and to carry on with our wealth creation. What are the opportunities for us for new thinking, new understanding and different approaches to the way we do things: proper societal engagement, teaching of new graduates, and policies that go around our investment in intellectual capital? All sorts of things like that are part and parcel of the issues that we have to discuss over the next couple of days.

But why does it matter? As you know, the Australian continent has been endowed with mineral riches; it is probably one of the more economically mineralised regions of the Earth's crust. A lot of large, rich ore bodies in Australia have either had surface expression or been fairly close to the surface and, as a consequence, they have been relatively easily discoverable. This has made a big difference to us in more and deeper ways than most people realise. It has affected our economy, our industries, our distribution of towns and infrastructure, and the ebb and flow of different types of employment. Indeed, it has affected our very psyche as a people; I have no doubt about that. It has even had a significant influence on the makeup of the peoples who have come to this land and made it their home. If you go back to the 1800s and look at the immigration that was consequent upon the mineral riches in this country, you will see that it really has had a very significant impact on who we are.

But times, unfortunately, are changing a bit. We have already discovered most of the easily found mineral deposits and now we face the problem that it is getting harder and harder, and the success rate of mineral exploration in Australia has dropped quite sharply. This is the major topic that we are here to discuss. If we do not reverse this trend and find new, large, rich ore bodies to replace the ones currently being mined, it will have an impact on our society just as profound as the impact that our mineral wealth has had. The problem is that, this time, the impact will be negative instead of positive.

This presents a very significant challenge for us, but it is an exciting one. It is one where we can do absolutely outstanding quality science; we can do outstanding work in getting the policy structures in place; we can do outstanding work in developing new technologies; and we can have real fun doing the science and developing new understanding of concepts while, at the same time, knowing that we are dealing with something that is societally very important—something that will have a real impact on the future of the nation.

One thing that is quite evident is that there is not much point in continuing to just work harder at the things we already have been doing. We need a new paradigm in our approach. We need to think about this in new ways. That is what this Think Tank is about. That is what you are here to talk about and to come up with new ideas on. We need to understand the processes all the way from the top of the mantle through to the top of the crust. We need to understand the energy flows together with the stresses and the consequent strains on the crust. We need to understand the consequences of rapid shifts or switches in those stresses and energy flows. We need to understand them in terms of the generation of giant ore bodies—that is, we now actually need to understand the geodynamics. It is no longer good enough just to understand the surface and do exploration there; we need to understand what is happening at depth. We need to understand in a predictive way the things that control where an ore body is produced. Yet, if you think about it, a lot of our effort to date has been on how the bodies are produced rather than where they are, and we need to change that focus to some extent.

But the times are exciting. We are in a situation where we are right on the verge of an information revolution built upon new capabilities in data management and modelling, visualisation, joint inversions and all those kinds of things—things that I hope you will be discussing in some depth over the next couple of days. This, of course, has the potential to open for us a whole new world of understanding by helping to move us from a science that has historically been data-rich to a science that will become information-rich, and that is part of the transition that we have to go through.

New and amazing technologies are continually being developed, both within and without the Earth science context. There is a significant question here: as has happened in many other sciences, will one of these technologies, quite possibly from outside the Earth sciences, provide us with the breakthrough that we need? Are we—and I would ask the question 'are you'—paying enough attention to what is happening elsewhere, or are you locked within the confines of your own thinking? What we are hoping is that, over the next day or so, we will help you to step outside these confines to come up with new ways of doing things. So the opportunity for you here, as participants, is to unshackle your minds, think outside of your experience and develop new ways of considering the problem so that we can develop truly exciting science. Science should be fun, so let's develop some really exciting science—and then Australia will be able to benefit from what we have done by continuing to enjoy the rich endowment of minerals that we have.

I would remind you that part and parcel of thinking outside the box includes a different perspective in thinking about the things that you already know. I quote from Dr M King Hubbert. He is well known for his estimation of energy resources and the prediction of their patterns of discovery and depletion. He made the comment: 'Our ignorance is not so vast as our failure to use what we know'. I am sure that locked away in your minds there is a tremendous amount of information that, if looked at from the right way, will change our understanding of what is happening and change our ability to identify and find new mineral deposits. So, over the next couple of days and throughout your careers, do not forget, please, to make good use of what you already know while continuing to increase your knowledge.

This Think Tank is intended to serve two purposes: it has the purpose, *as I have* been saying, of finding specific solutions; but it also has the purpose of providing you with new opportunities, through networking, to develop your own interests in the research and to direct that research at societally important problems. You will see that, for the discussions, you have been split into four groups. It may well be that you have been put, say, into group A, but you feel that your skills are particularly suited to group C. Or you may be asking, 'Why have I been put into group C instead of group A?' We have done that because we want to stimulate and challenge you. We want to create these groups with a mix of skills so that there will be a fertilisation of crossdisciplinary ideas. We also want you to make contacts here with people whom you normally would not have met so that you can have these contacts for the rest of your career—expand your abilities and networks so that they will be beneficial to you for the rest of your career. That is an important part of what we want to achieve here over the next couple of days. So we have a lot of opportunities and a lot of things to discuss. A lot of new possibilities will come out of it. At this stage I do not know what will come out of it. My experience is that you put young, bright minds together and they do wonderful things, and my expectation is that that is what we will achieve over the next two days.
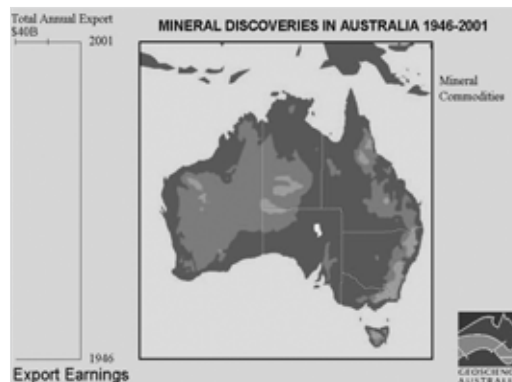
## Discovering the next generation of mineral deposits—what are the right questions?

Dr Neil Williams

I trust that you are all fired up to think about searching deep beneath Australia for our new resources. To help get you started, I am going to challenge you in my presentation to think carefully about what are the right questions that we should be asking.


In 1946, at the end of World War II, the great Australian geologist Sir Harold Raggatt convinced the then Commonwealth government in Canberra to set up a national geological survey. It was called the Bureau of Mineral Resources (BMR) and in time it evolved into Geoscience Australia (GA). The basis for the government's decision to set up the BMR was Sir Harold Raggatt's vision that, with good regional geological and geophysical maps, industry would be able to discover new mineral wealth and Australia would one day be a very wealthy country due in large part to its mineral resources. The animation I am about to show demonstrates just how well Sir Harold Raggatt's vision has been realised. The animation was actually made by Phil McFadden when he was GA's Chief Scientist and it shows mineral discoveries year by year from the year 1946 to 2001. You will see a red flash when there is a discovery and then that red flash will collapse back into a little yellow circle, which will remain. Very importantly, on the left-hand side, in dollars, you will see export earnings from Australia's minerals. You will see that they are very impressive.
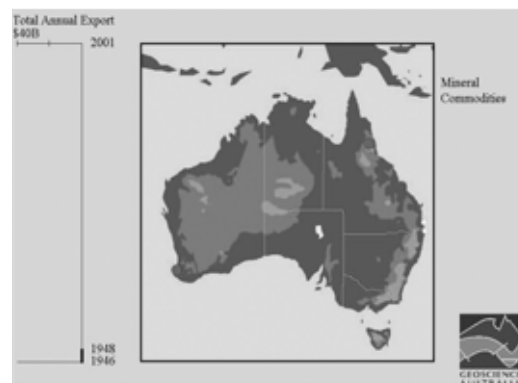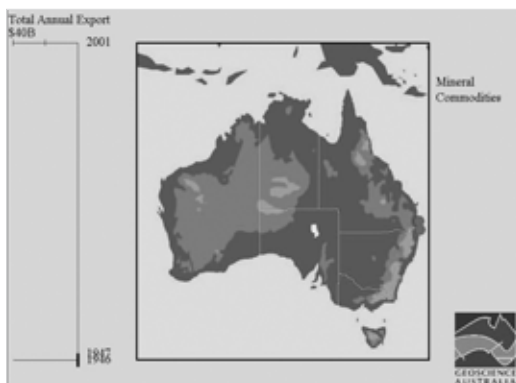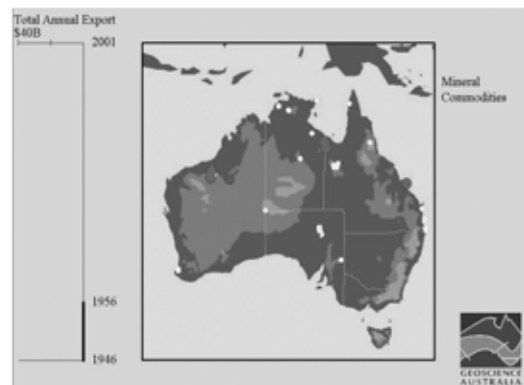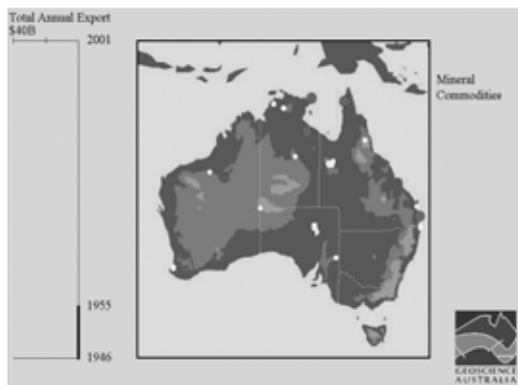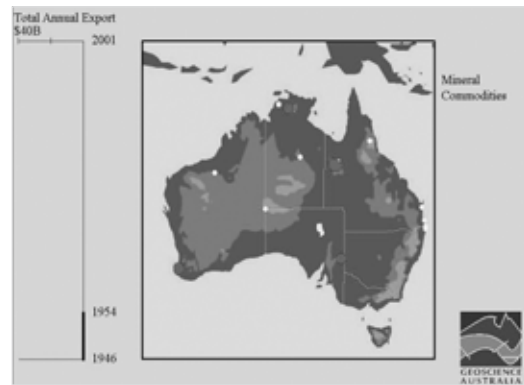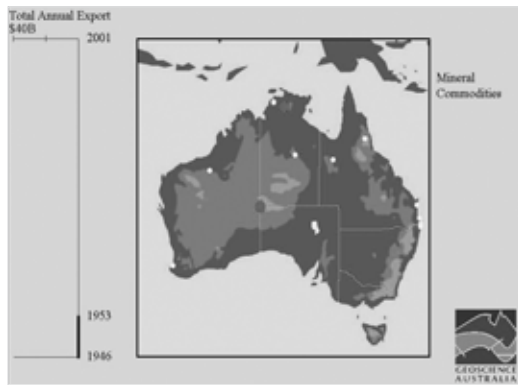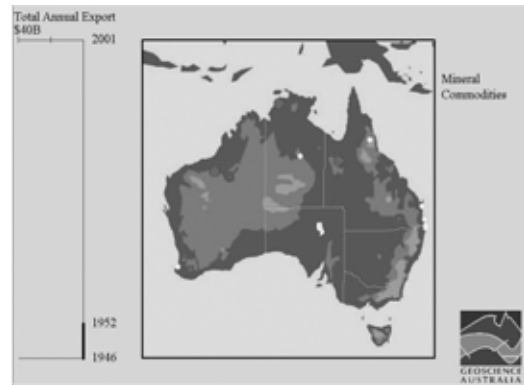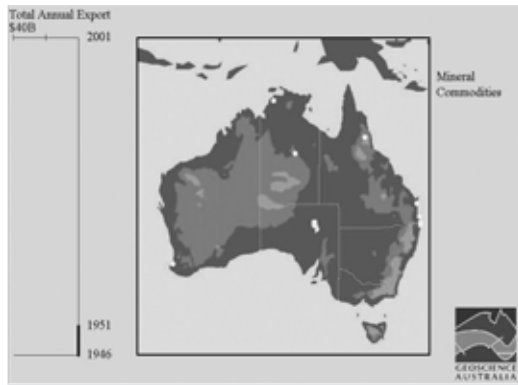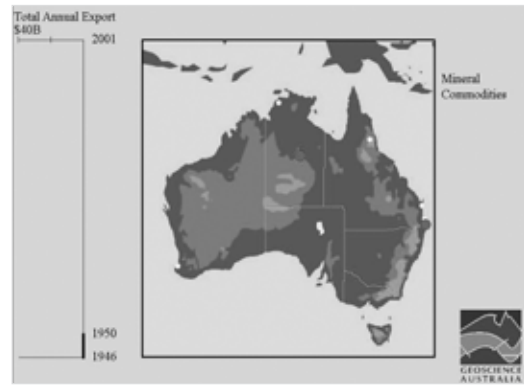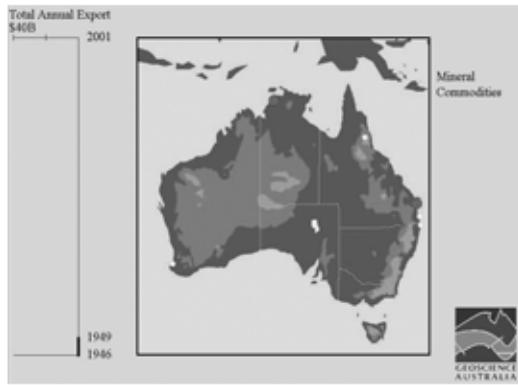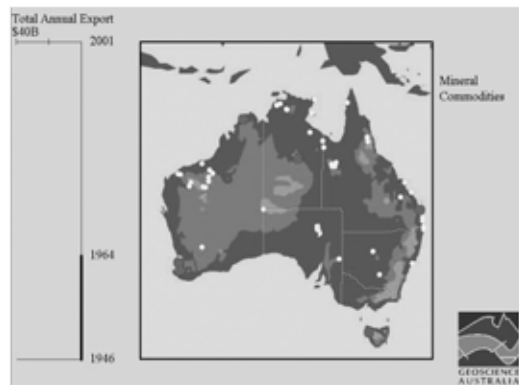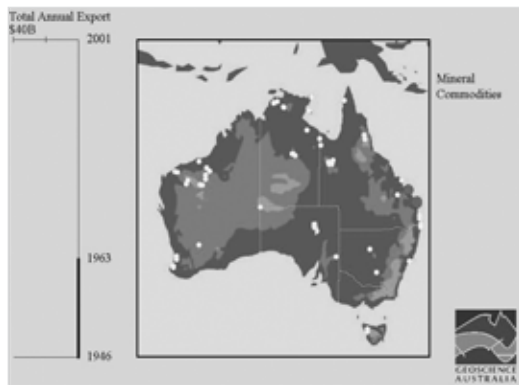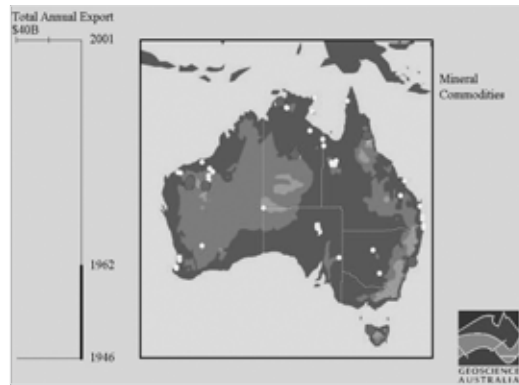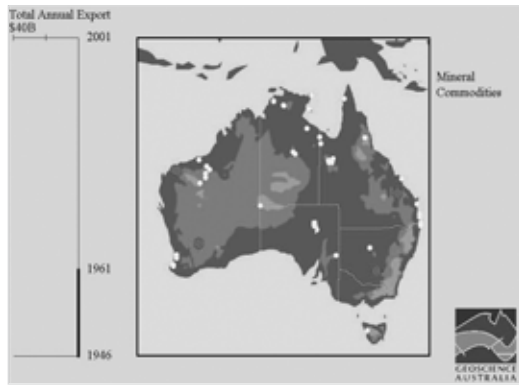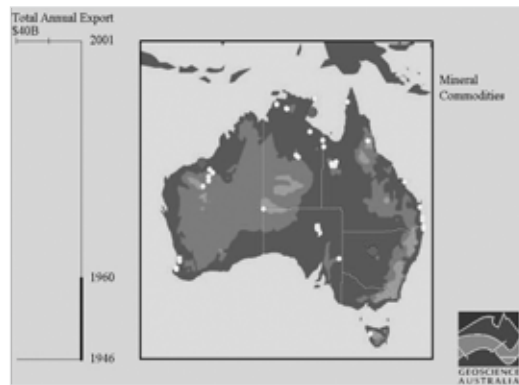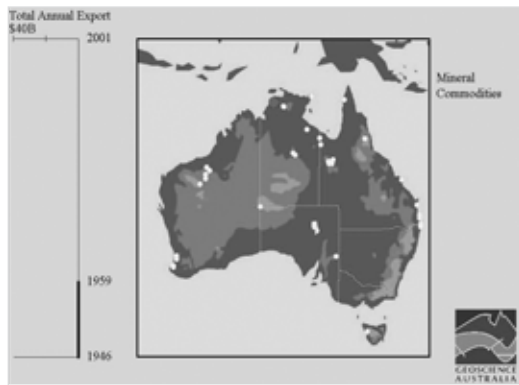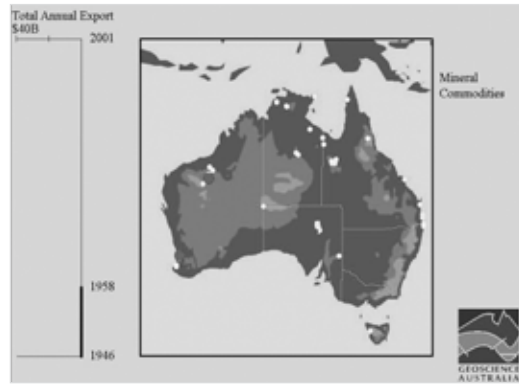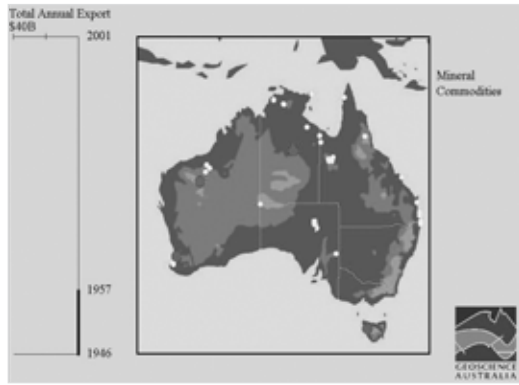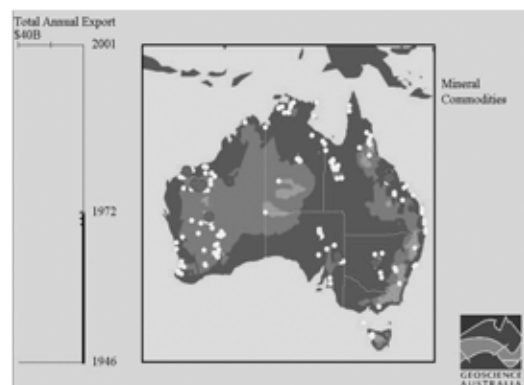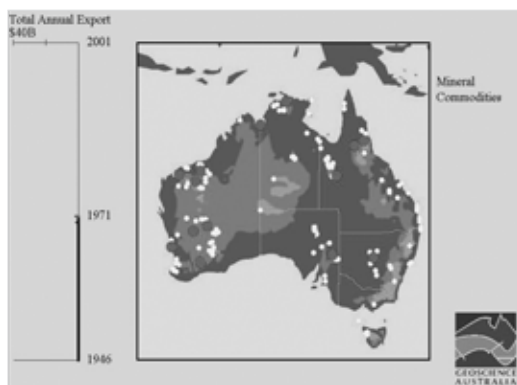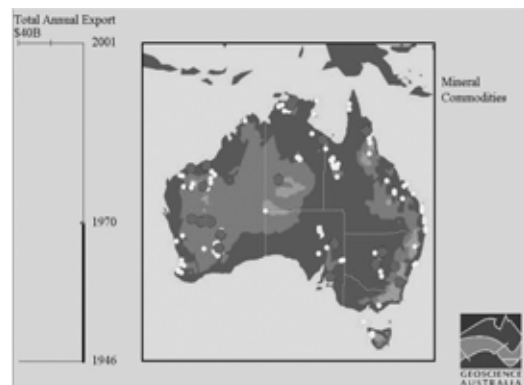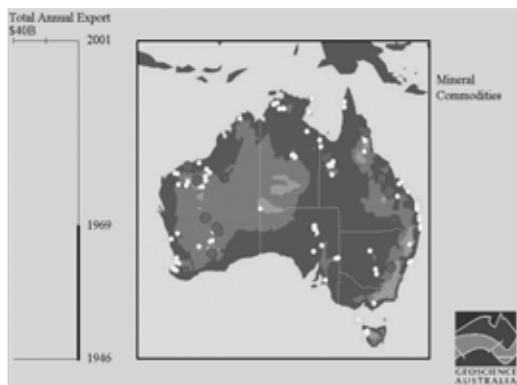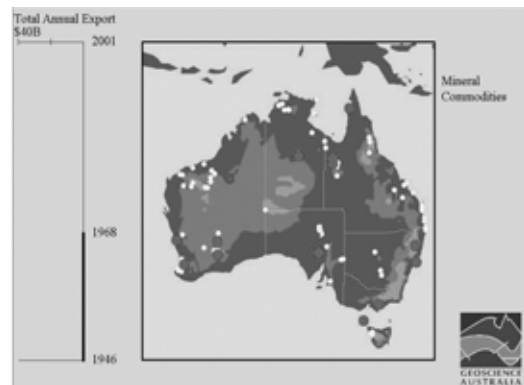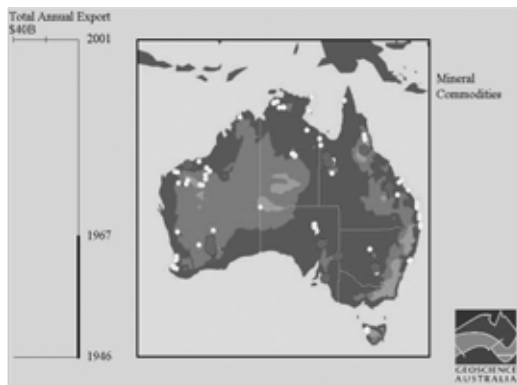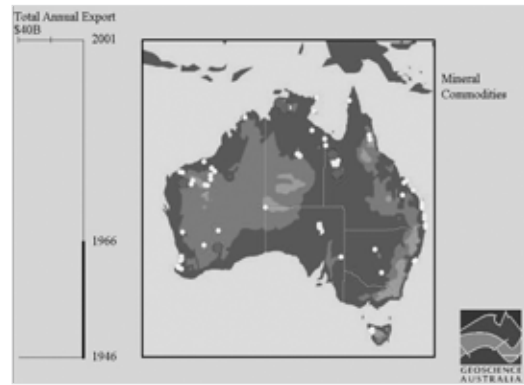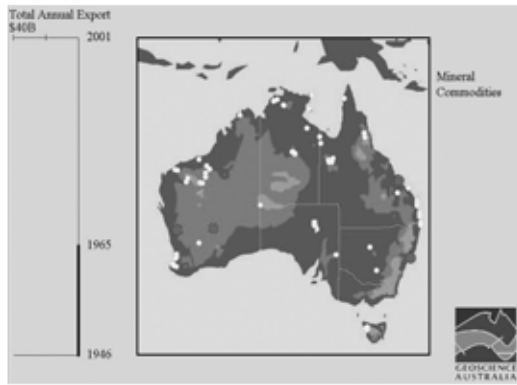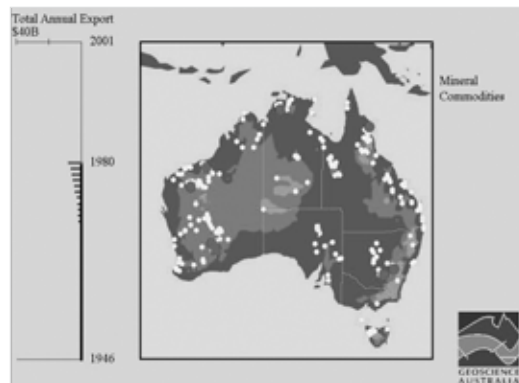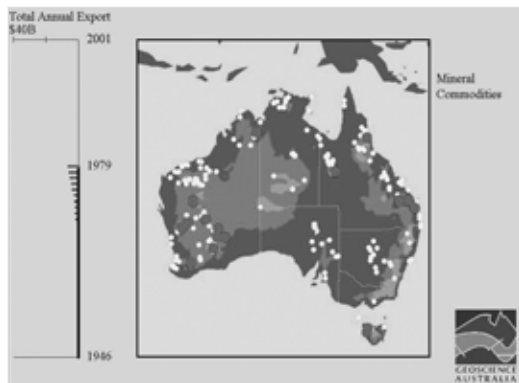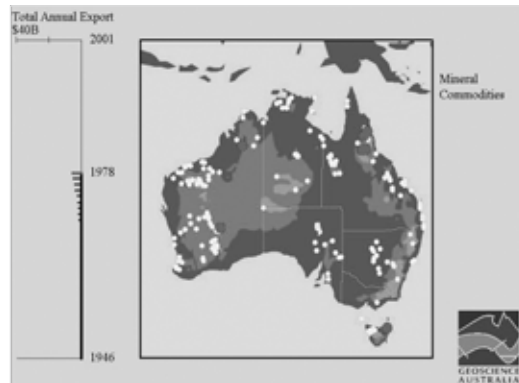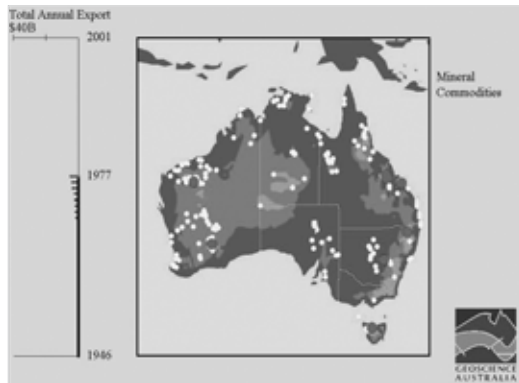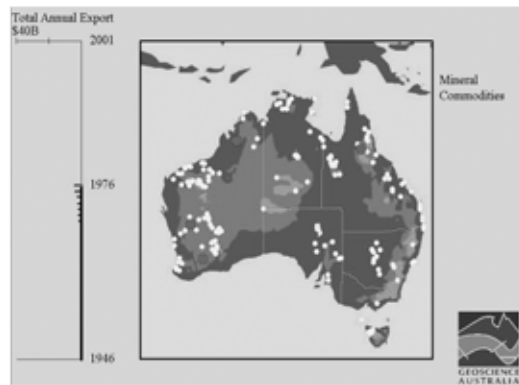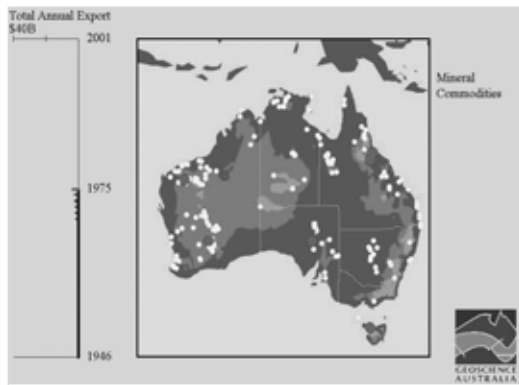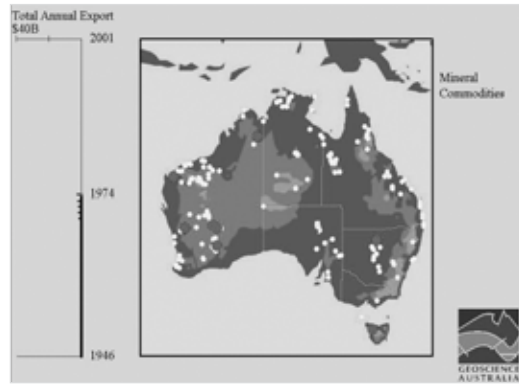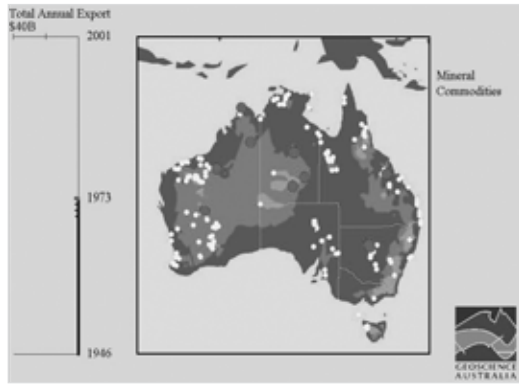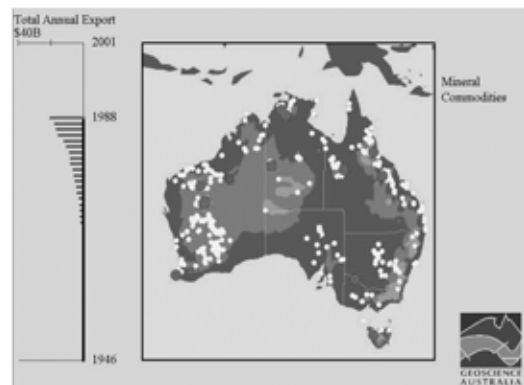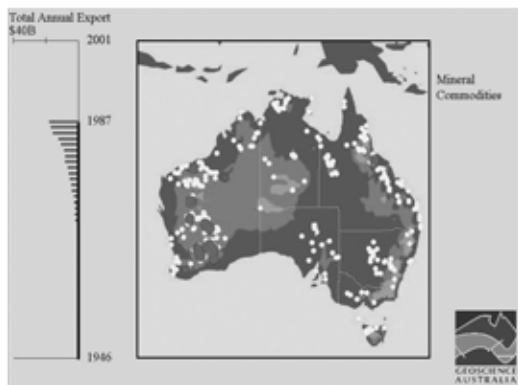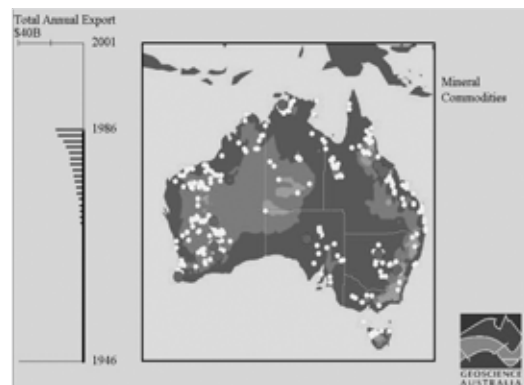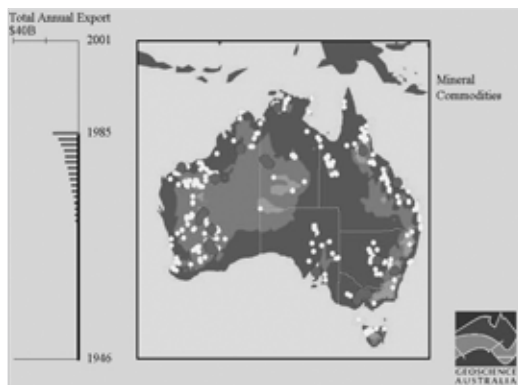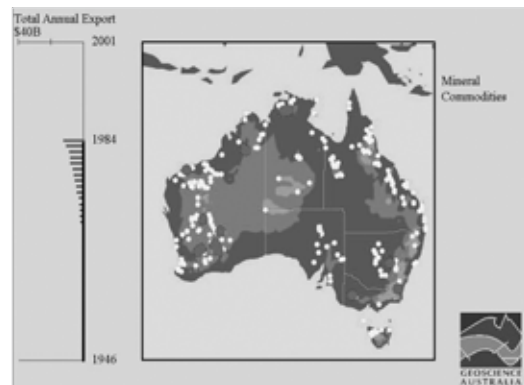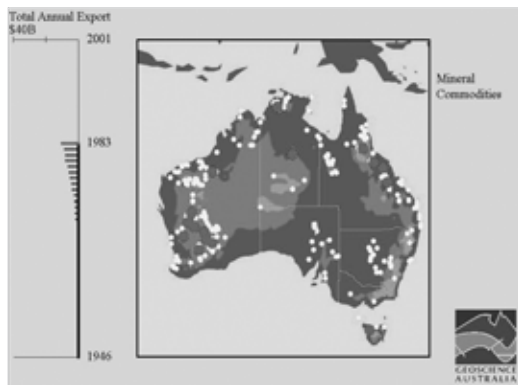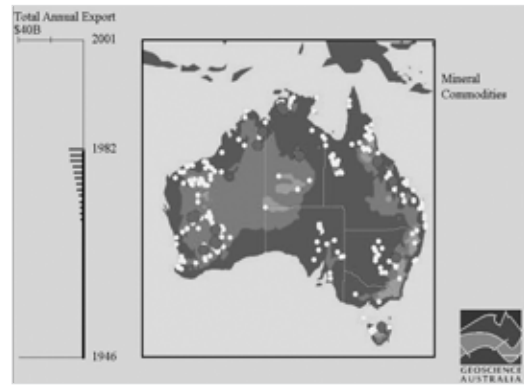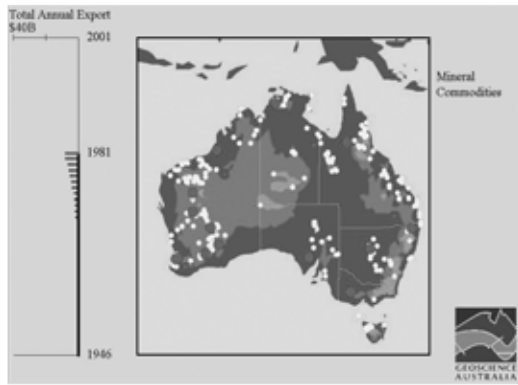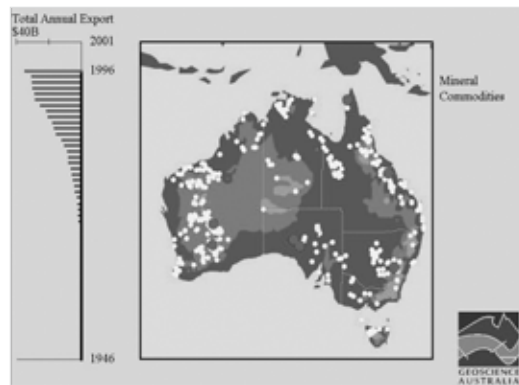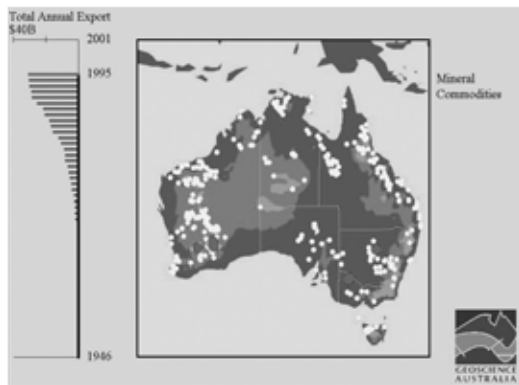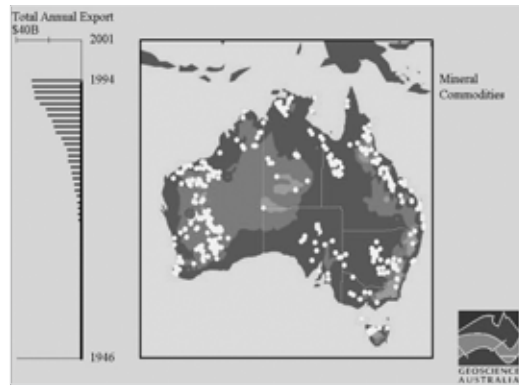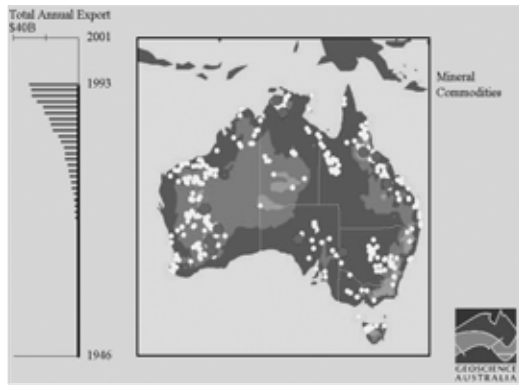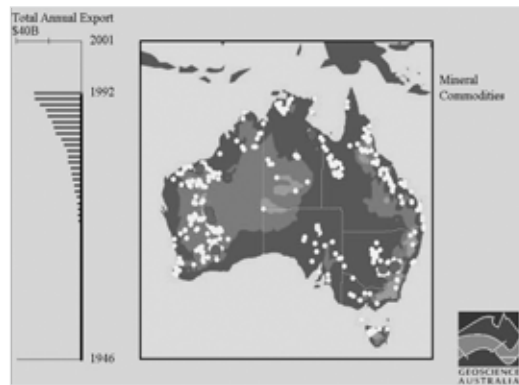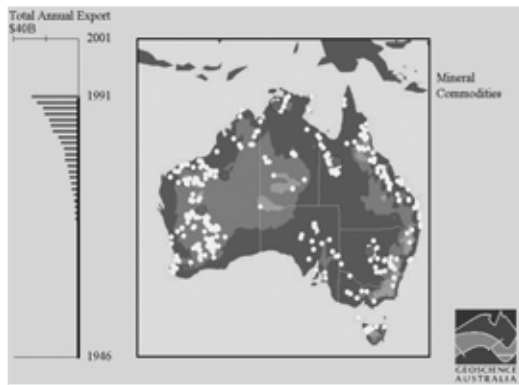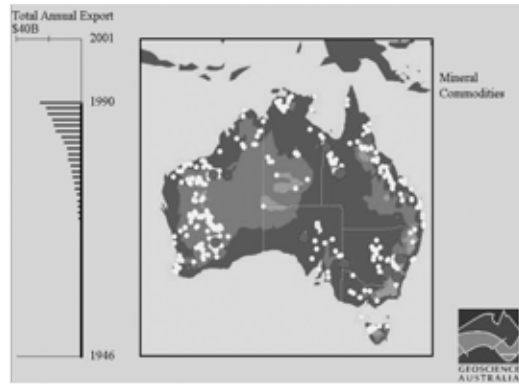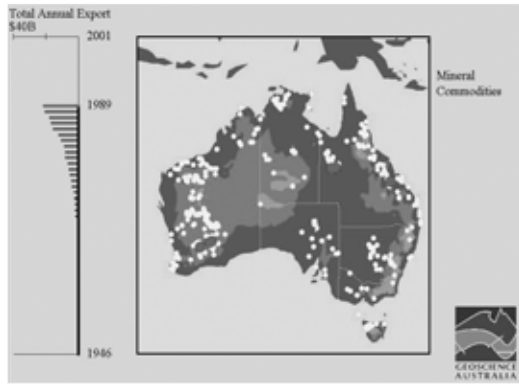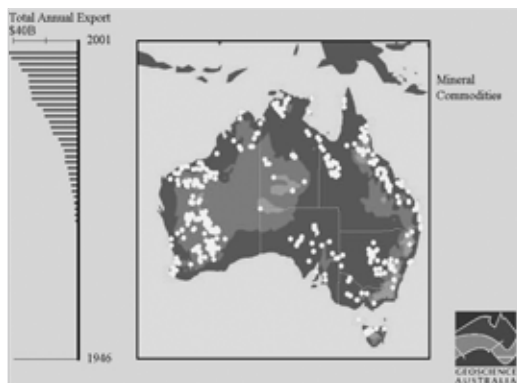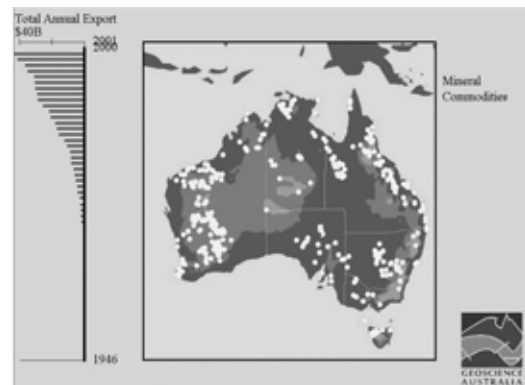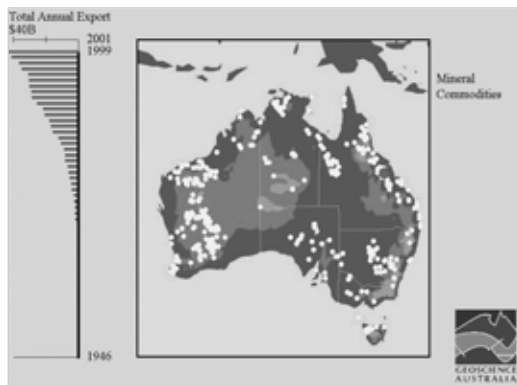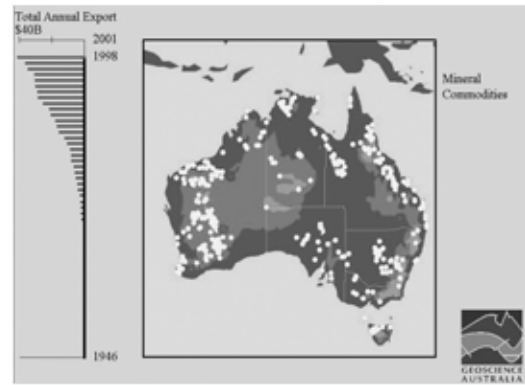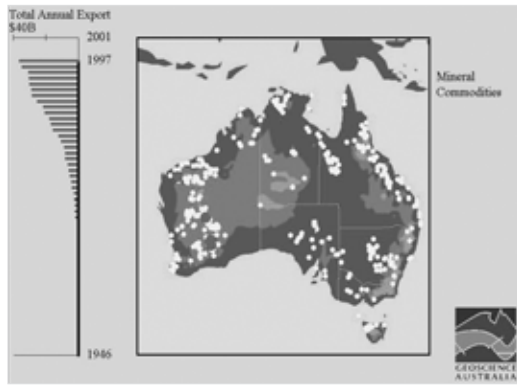
Were Phil to update the animation, you would see two things. Firstly, you would see that mineral exports now stand at about $75 billion per annum; so it is really a very, very significant part of the Australian economy. Secondly, you would note, if you had a good eye or Phil slowed the animation down, that the discovery rate of greenfields deposits is slowing. We have seen tremendous growth in mineral production over the past few years, but this has come from accelerated production at existing mines, from brownfields exploration within and adjacent to known mineralisation and also from innovations that have improved the efficiency and effectiveness of mining and processing. But we do have a problem in the greenfields area. These are the sorts of explorations where you build new mineral provinces, new mines and new towns – activities that sustain the long-term health and wealth of the industry.
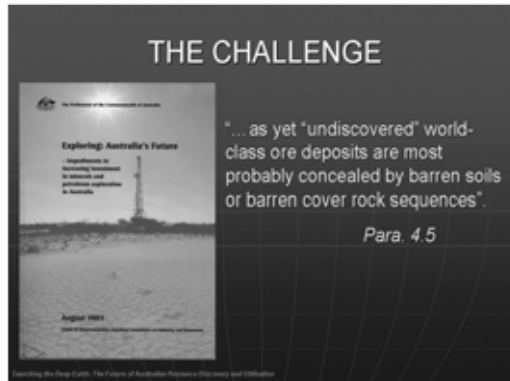
This issue of the slowing down of greenfields success in Australia has been troubling. It certainly concerns the Australian Government as well as the state and territory governments. Over the years there have been several inquiries into what is the problem with greenfields exploration. One of the better known inquiries was the Prosser inquiry, which was undertaken by the House of Representatives in Canberra. Like many other reports it highlights the big problem, which is stated here: '...as yet "undiscovered" world-class ore deposits are most probably concealed by barren soils or barren cover rock sequences'.

This is the challenge, or a good example of the challenge, for all of you—but, to my mind, it is an exciting, intellectually stimulating and economically rewarding challenge to take on. This slide shows the black soil plains of the Barkley Tableland north-west of Mount Isa. The nearest areas of regional outcrop to the spot where I took this photo constitute one of the most richly endowed parts of the Earth's crust for lead-zinc mineralisation. There is every likelihood that, somewhere beneath these vast, featureless black soil plains, giant lead-zinc deposits will be lurking and awaiting discovery. The question is: can we find them? As a former mineral explorer and optimist, my view is that of course we can —'Yes, we can,' as someone else recently said.

But the big challenge really is – how do we go about doing it? We know that what we are doing at present in exploration is beginning to fail and we therefore need to think beyond the current exploration 'paradigm': we need to think beyond the square and to go about deep exploration in a different way from how we do exploration today in what I will from now on refer to as 'surface exploration'.\

CENTRAL SOUTH AUSTRALIA

Let's go from northwest Queensland to another equally flat part of Australia. This slide shows the landscape around Woomera near the famous old rocket range in central South Australia. One of the reasons that I am so optimistic about the future of mineral exploration in Australia is based on what has been achieved in exploration in the Woomera region. Where I grew up, in Albury, NSW, the landscape that you see on this slide was called the 'back of beyond'. It has many other names, few of them flattering. However, for all geoscientists, both here in Australia and all around the world, this place is, or should be, a place of great wonder because lurking 350 metres below the desert's surface, at a sheep station called Roxby Downs, sits one of the world's biggest known ore deposits: the super-giant Olympic Dam deposit.

THE OLYMPIC DAM MINE COMPLEX

Photo courtesy of BHP Billiton
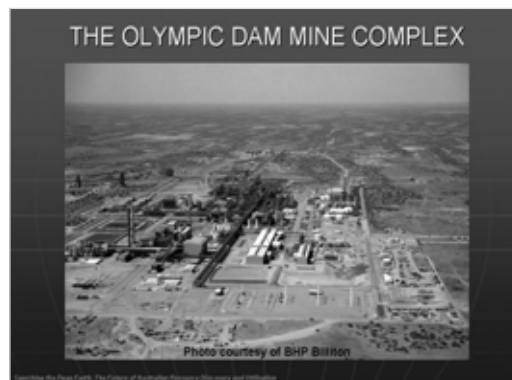
Olympic Dam was discovered in 1975 by the then Western Mining Corporation. The WMC team that found Olympic Dam was led by the great Australian mineral explorer Roy Woodall. We have the privilege of having Roy here with us today. Roy is a legendary figure in the world of mineral exploration. I hope that all of you take the opportunity to talk to Roy—because, if ever there was a person to think beyond the square and to ask the right questions and challenge his staff to do the same, it was Roy.

Olympic Dam is now owned and operated by BHP Billiton and, on the basis of known resources, it is now ranked as the world's fourth largest copper deposit, the world's largest uranium deposit and the world's fifth largest gold deposit— all of that in one deposit. It is truly a giant amongst giants. That is all the more impressive when you remember that we still do not know just how big Olympic Dam is, as it has yet to be drilled out fully. Furthermore, the deposit is of a type of mineralisation that was previously unknown and is now generally referred to as an iron oxide-copper-gold deposit. I do not like that term; I think it deserves its own name: it is an Olympic Dam type deposit because of its huge size and uniqueness.

Olympic Dam occurs in basement rocks beneath 350 metres of relatively flat-lying cover sediments that are a billion years younger than the 1.6-billion-year-old rocks that host the deposit. The discovery of Olympic Dam provides some fantastic insights into how we might go about future deep exploration, so let's have a quick look at how WMC went about finding the deposit. In the little time that I have, I cannot do full justice to the discovery, but I will try to capture the key elements of the discovery.

'Driscoll, E.S.T., 1986. Observations of the lineament-ore relation. Phil. Tras. R. Soc. Lond., A317, 195-218
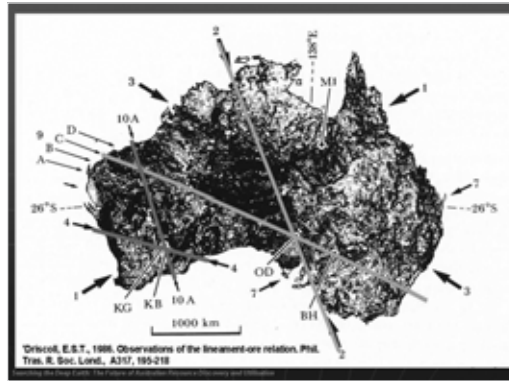
The thinking that led to the discovery was developed by a team with diverse expertise. One member of that team was a structural geologist, Tim O'Driscoll, who had discovered that, if you carefully analysed BMR's national-scale geophysical maps, you could see long linear features crisscrossing the country. This slide shows one of Tim's processed BMR magnetic maps of Australia. His main lineaments are marked on the slide. This work was, and remains to some, controversial but, without Tim O'Driscoll's lineaments, I doubt that Olympic Dam would be a mine today. He noted along the way that many of Australia's big mineral deposits lay on these lineaments and actually, more often than not, lay where they crossed one another.

'Driscoll, E.S.T., 1986. Observations of the lineament-ore relation. Phil. Tras. R. Soc. Lond., A317, 195-218
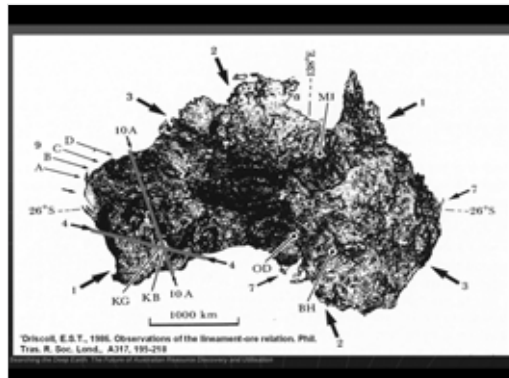
This is Kalgoorlie and here we have Kambalda. The famous giant Kalgoorlie gold system, for example, sits where these two lineaments cross one another.

Another member of the team was Doug Haynes; he had done a PhD at the Australian National University. He research topic centred on what sourced the copper in large copper deposits. Based on his PhD research, he developed a sediment-hosted copper exploration model that led to WMC's copper exploration program to focus on areas of South Australia underlain by particular basic igneous rocks: the copper source rocks that were an important element of the search model and of Doug's PhD thesis. One such area of known copper mineralisation was at Mount Gunson, well south of Olympic Dam. At Mount Gunson, beneath the known mineralisation, in the BMR's regional geophysical data sets there was an area with coincident gravity and magnetic anomalies that was interpreted to be Doug's copper source rocks - basic igneous rocks. Interestingly, Mount Gunson also lay at the intersection of two of Tim O'Driscoll's lineaments.

Another member of the WMC team, geophysicist Hugh Rutter, had identified from BMR's regional magnetic and gravity maps some other areas of coincident magnetic and gravity anomalism well north of Mount Gunson and these were refined as drilling targets, using Tim O'Driscoll's lineaments.
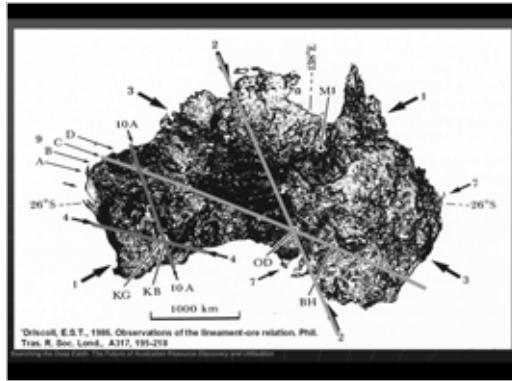
On this slide we see these particular lineaments – and indeed these two cross where Olympic Dam was subsequently discovered.

I have skimmed across a fascinating story and I am sure that a lot more can be told. Interestingly for me, at Olympic Dam, we now know that the mineralised body is strung out in this direction – the same as one of Tim O'Driscoll's lineaments. This suggests a strong structural control on the location of this giant deposit and I think it gives additional support to the ideas that Tim put together back in the 1970s.
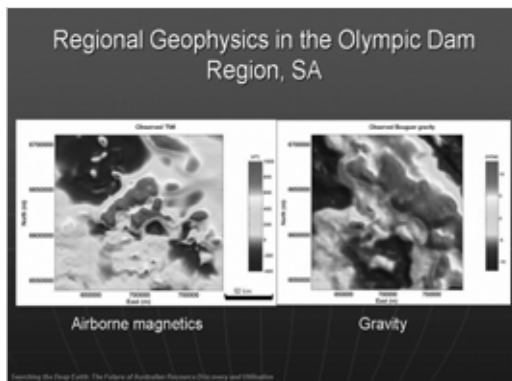
This is a modern-day image of the regional magnetic and gravity data that cover the Olympic Dam region. Magnetics are on the left and gravity is on the right, and the little faint white circles show the position of Olympic Dam.
You might ask after looking at the two images: 'Well, why did WMC drill where they were?' The answer is: 'Remember the lineaments'.

The point I want to make now is that these data were available through the old BMR to anyone who was interested in exploring for minerals in central South Australia. Many companies had the data and many companies had analysed the data, but it took the genius of the Western Mining team to think beyond the square and to turn these data into a veritable treasure map. A lot of research has occurred since the discovery of Olympic Dam, and I am looking forward to Jon Hronsky's talk. He will talk more about some of the more recent thinking that has gone on about what controls where giant ore deposits like Olympic Dam occur.

The three fundamental questions in exploration are 'what?', 'how?' and 'where?'. The Olympic Dam discovery gives us some good clues to the 'what?', 'how?' and 'where? of deep exploration and to a new deep exploration paradigm, and I am going to use some of the lessons from Olympic Dam to give you some thought joggers to help your think-tank thinking.

Regarding the 'what?' question – Richard Schodde, another old Western Mining person, will be speaking later this morning. He is going to talk in a lot of detail about the 'what?' question. So all I want to do now is just give you a few thought provokers. Clearly, the answer to the 'what?' question is 'giant ore deposits'. High grades and large tonnages make for economic attractiveness. There is no point in drilling and looking deep undercover at great expense for anything small as you will never mine it economically. That said, I must stress that giant ore deposits are geology's really rare events. Any ore deposit is an anomaly in the Earth's crust, but the giant deposits— ones like Olympic Dam—are the real rarities and they are anomalous anomalies. Therefore, in the world of deep exploration, we should not be speaking about normal run-of-the-mill deposits of the type that we would often mine near the surface today. Instead we need to think about really rare geological events and think very differently about how we go about understanding these events and their related deposits, and about how to go about finding where they took place.
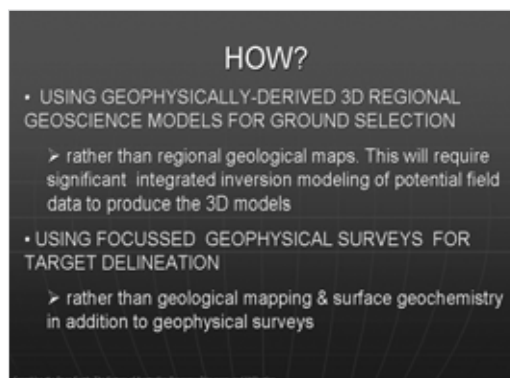
Let's turn quickly to the 'how?' question. I want to make three points – two short ones and one longer one. The first point is that, as the Olympic Dam discovery illustrates, ground selection in the deep exploration paradigm will of necessity have to be based on geophysics. Today we are already seeing 3D regional geological models derived from geophysics beginning to replace the old geology maps that were the mainstay of ground selection in the surface exploration paradigm and Tom Whiting, formerly with BHP Billiton, will be talking in detail about all this in his presentation.

The 'how' question. The second point is that these 3D models require significant integrated inversion modelling of potential field data, a process that involves huge computer and data management challenges. Some of these will be covered in some detail by Dietmar Müller later today in his presentation.

In terms of defining drilling targets, as opposed to ground selection, I think that in the deep exploration paradigm, geophysics again replaces the surface exploration tools of geology maps and the surface geochemistry that have been used so effectively in surface exploration, sometimes in conjunction with detailed ground geophysical surveys. So, again, I see a very geophysical future when it comes to the deep exploration paradigm.
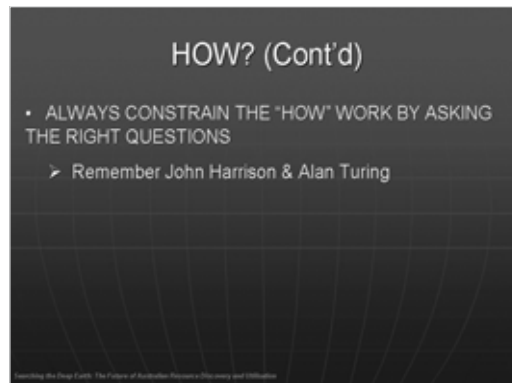
The final point I want to make about the 'how?' question is the importance of asking the right questions. What I would like you to do later in this Think Tank is to remember John Harrison and Alan Turing. Forget these people, and the lessons they have taught us, at your peril.

A few weeks ago while vacationing in Europe, I made a pilgrimage to the Royal Observatory at Greenwich, near London, where you can stand astride zero degree longitude, with one foot in the eastern hemisphere and one foot in the western hemisphere—but that is not why I went there. Inspired by Dava Sobel's must-read book *Longitude*, I went to Greenwich to see the legendary clocks made by John Harrison that ended the longitude nightmare that had haunted sailors over the years. In this slide we see two of the clocks: H3 on the left—'H' stands for 'Harrison'—and H4 on the right. H4 evolved from H1, H2 and H3 and was the prototype for all subsequent marine chronometers used in navigation from that point on. In terms of impact on human history, H4 ranks up there with the wheel and the steam engine. The original clocks, still in working order, can be seen every day at Greenwich. As a young clockmaker, Harrison set out to win the coveted longitude prize that was being offered by the British government and being administered by the infamous Board of Longitude. Before tackling the longitude problem, Harrison had built several land-based clocks that had accuracies that far exceeded the norms of the day. He knew, like everyone else, that, if a navigator anywhere in the world knew the precise time back in Greenwich, it was a simple exercise for that navigator to fix longitude. But in Harrison's case he also knew that if he could make a clock that could do as well at sea as his land-based clocks, the prize was his. The questions for him were: firstly, 'How do I modify my innovative friction-free clock mechanisms to survive in the corrosive, salty atmosphere of the marine environment?'; and, secondly and very importantly, 'What do I put in my sea clocks to replace my fancy timekeeping pendulums that work so well on land but which would be useless on a ship bouncing around in the waves out at sea?'.

Harrison was a genius as a clockmaker but answering his questions took him many, many years of research and experimentation with H1, H2 and H3. By the time he had condensed it all down into this wonderful little H4, he had succeeded in answering his questions and, with H4, he had met all of the requirements for the longitude prize. But, sadly for him, recognition and reward was a long time coming, and the way that Harrison was treated by the Longitude Board was nothing short of scandalous. In fact, it took the intervention of a king to roll those on the Longitude Board.

The problem was that the Longitude Board was stacked with mathematicians, navigators and, particularly, astronomers. To quote Dava Sobel, the Board did not welcome a mechanical answer to what it saw as an astronomical question. As history has shown, it was not an astronomical question. The Board was convinced that you needed good star charts and to know where the moon was relative to any star at any time to solve the problem; it was not interested in a lower-class watchmaker coming along and saying, 'I've solved your problem.' The astronomy questions were the wrong ones; the mechanical questions were the right ones.

So, coming back to exploration, I see the framing of the right questions as being critical to success. For example, are the right questions geophysical ones as I have just argued; maybe they are not. Maybe there are other 'outside the square' questions that we really should be focusing on like, 'What do I do instead of having a little pendulum in my clock?' Over the next two days I encourage you to think very carefully about what are the right questions regarding all aspects of deep exploration.

All of us have a natural tendency in group-think environments like we have in this Think Tank to push our own areas of expertise. I urge you to contribute from your perspective and from the area that you are familiar with, but at the same time to remember that it might not be your area in which the right questions reside. So, ignore the story of longitude at your peril.

ALAN TURING

The Enigma Machine

107,458,687,327,300,000,000,000
possible settings

Let's turn now to another British genius, Alan Turing, who was a mathematician when World War II broke out. The question he ended up addressing as part of the British war effort in World War II was how to crack the coded messages being used by the German military. The mainstay of the Germans' military coding was the machine shown in the slide: the ingenious Enigma machine. Basically, it was a typewriter on steroids that encrypted normal messages according to how the wheels were set. Each day the German message encryptors would set these wheels to an agreed combination. With all of the machines set to the daily code they could talk to one another, but only for that day as the wheel settings were changed daily to minimise the chances of the other side deciphering any message in a timely fashion. Along the way, as happens in wars, the British managed to capture an Enigma machine and, by poring over its workings, they found to their horror that the number of possible wheel settings for any particular message was the number shown on the slide: around 1×10^{23}. That is a lot of different combinations. From that, they knew that timely decoding was very unlikely, just as the Enigma designers had intended.

However, neither the designers of Enigma nor, in fact, the British side of the war, had bargained on the genius of Alan Turing. He asked the right question too. He asked whether it was possible to categorically eliminate particular wheel settings rather than the more obvious question that everyone had been asking up until then: 'Oh dear, how do we speed up the testing of all of the different possible combinations?' Given the way that the Enigma wheels worked, Turing was able to show mathematically that, for any one coded message, because of some clues buried in each message, all but 17,500-odd possible combinations could be eliminated. Just remember that for the next message it would be a different 17,500, but 17,500 is something like 19 orders of magnitude improvement over the problem of the decoding a raw Enigma message. The Enigma designers would have been horrified had they known what Turing had worked out.
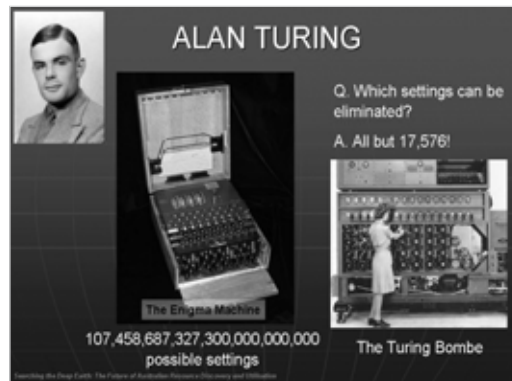
What happened next is the stuff of history and it basically heralded the start of the computer age. The British, led by Turing, developed what they called 'bombes'; early computers that ran on valves that literally tested the 17,500-odd possible Enigma wheel settings for each message that they wanted to decode. It was slow and tedious at the start, but eventually it led to code-breaking protocols and faster 'bombes' that enabled Allied military forces, through much of the war, to eavesdrop on the thinking of their opposite numbers. During your Think Tank deliberations, as well as trying to think about what the right questions are, as John Harrison did, also think of Alan Turing and remember to ask the 'what is not?' question, which is always a very important question to ask. Do not ask 'what is?' all the time; always ask 'what is not as well', a point I will come back to later.

Now to the 'where?' question. Selecting the right regions on which to focus exploration is critical to success and, no matter how good your tools, you will not find economic mineralisation where there is none to be found. Later, Peta Ashworth will be talking about some of the societal issues surrounding exploration and development and one of the big issues that I am sure will come up is access to land. Because of issues like community concerns, indigenous land rights, and environmental protection, it is now getting harder for explorers to get onto properties to explore. It is not impossible, but it takes a lot of time and effort to negotiate conditions of entry, and we do not want to waste any time in areas that are poorly prospective. So, for many different reasons, it is important that we try to focus on good ground.

Very importantly, as we saw from the contribution that Doug Haynes made to the Olympic Dam discovery, good ground selection requires good search models. Doug had a copper search model that found a deposit that was a different sort from what he started out looking for, but clearly a lot of the search model had something going for it because it led WMC to the right areas. Search models are something that economic geologists spend a lot of time working on and are something that I have thought about a lot over the years. The best summary that I have ever found of what a search model is all about comes from Ohle and Bates in a great paper in the 75th anniversary volume of Economic Geology, published in 1981:

'The mental processes whereby geologists try to understand and depict the genesis of ore deposits are called "modelling". Formally or informally used by explorationists, modelling involves an effort to explain the process or processes that gave rise to known ore deposits and their geological relationships, and its users anticipate the effort will point to other likely places to explore.'

From my experience, I believe that this sort of thinking dominates present-day shallow exploration and, to my mind, this is absolutely the square that we have to break out of. Obviously we must have search models, but they must not have the flaws that are inherent in the thought processes that are so well summarised by Ohle and Bates.
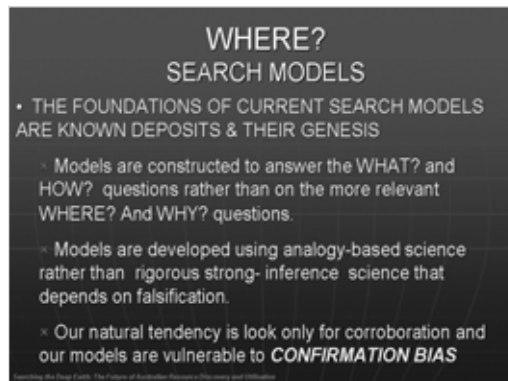
As we have just seen, the foundation of current research models is known deposits and their genesis. If you read the 100th anniversary volume of Economic Geology, which came out 25 years after the paper by Ohle and Bates, you will see paper after paper describing to the 'nth degree' the genesis of some porphyry copper deposits somewhere and the minutiae of their genesis. Invariably the ore deposit models arising from this approach are built around two questions:

1. What is the ore type we are dealing with? (Answer – for example – some type of porphyry copper deposit – and
2. How did it form? Answers to this second question generally cover issues like the origin of the mineralising fluids and the temperature and pressure at which the mineralisation was precipitated.

There is some, but not a lot, of emphasis on the 'very relevant to exploration' questions, 'where?' and 'why?'. Why is Olympic Dam here and not in the next map sheet, or why is Mount Isa where it is and not across the road and down the creek a little bit? 'Why?' and 'where?' questions get very little attention in current economic geology research. Part of the reason for this is that models are developed using analogy-based science rather than rigorous, strong inference science that depends on falsification. We geologists are not good when it comes to the falsification of hypotheses or models. Also, when we have our model, our natural tendency always is to start running around looking for evidence corroborating our model or models. These models are therefore vulnerable to what is known in the science philosophy game as 'confirmation bias'.

At this point I need to say a little more about analogy-based science. Analogy-based science is something that we have to do a lot of in geological research because of the poor preservation and erratic exposure of the geological record. We usually don't have a lot to work on, so we are drawn into reasoning by analogy. The argument involved is along the following lines—if two things are alike in some respects, they must be alike in others. Often, similarities among geological features lead to flashes of insight and to an inductive leap that solves the problem. Needless to say, as I am sure that some of you have found, many similarities can be very misleading and recognition of analogous conditions is not sufficient to establish more than a working hypothesis.

Earlier I stressed that the giant ore deposits that we would like to find in our deep exploration are really rare, and this is very, very dangerous territory for analogy-based science. If you want to pursue this topic further, I commend to you a recent book on rare events by Nassim Taleb entitled *The Black Swan*. Giant ore bodies are one class of geological black swans, and I would like to leave you with this wonderful quote by Taleb regarding rare events and working them out, and this is a particularly relevant quote for what we are talking about over this two-day Think Tank: 'We can get closer to the truth by negative instances, not by verification! It is misleading to build a general rule from observed facts.' Again, ignore this thought at your peril.

Now, enough philosophising. I would now like to close my talk with two exploration stories that illustrate the dangers of remaining within the analogy-based science box when it comes to exploration.

As far as I can determine, the first mineral resource assessment ever made in Australia was by the Dutch explorer Jan Carstensz, who sailed down the west coast of Cape York Peninsula in 1623. How many of you were taught about Jan Carstensz in your geology classes at university or even your Australian history classes at school? Anyone? No. What a hero we are ignoring. The red line on the slide shows roughly where he sailed along the west side of Cape York Peninsula. At the point where I have stopped the line, Carstensz went ashore and explored inland for a few kilometres and along the way he and his party captured an Aboriginal and brought him back to their boat, but history doesn't record what happened to the poor captive.

Based on what he saw—this is the fascinating part of this story—he subsequently wrote the following, which was translated and appeared in a book edited by Tim Flannery, *The Explorers*:

'...there are no mountains or even hills, so it may be safely concluded that the land contains no metals'.

Think about that everyone. He is talking about Australia, a country that is now one of the world's powerhouses of mining.

I would make two points regarding Carstensz's assessment. Firstly, he sailed right past, and went ashore just south of, the huge Weipa bauxite deposit and he probably would have been able to see for much of his trip the big reddish cliffs of the lateritic bauxite that crop out along the western edge of the Cape. Weipa today is one of the main sources of the world's aluminium. However, I think we could forgive Carstensz for not recognising this metalliferous gem, because it was not until some 200 years later—in the early 1800s—that the metal, aluminium, was isolated as a metal and its attractive properties finally determined.

There is an important lesson here: we don't know what we don't know; so we must always keep on doing good research.

Secondly, and I think much more excitingly, his erroneous conclusion is a wonderful example of the problem of using analogy-based science thinking in exploration. The received wisdom of the day was that metals occur in hills and mountains. Obviously, guided by this rule, the medieval explorers looked for metals—guess where?—in hills and mountains, so they always found new mineralisation in hills and mountains. With every discovery, of course, this received wisdom was reinforced.

I'm still looking for, and I am yet to identify, the first real negation of this received wisdom that mountains and hills equal metals, but certainly the Olympic Dam discovery would be a terrific example of how we can get closer to the truth through a negative instance. That said, and before anyone gets too excited, the Olympic Dam area might have once been within an orogenic setting. I will leave others to think that one through and to argue about it.

THE PROTEROZOIC Pb-Zn-Ag
PROVINCE OF NORTH AUSTRALIA

McARTHUR
RIVER -1955

LADY LORETT 1970

MT ISA -1923
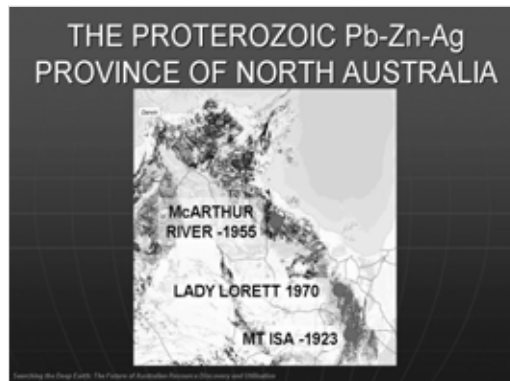
My final story is one I tell against myself regarding my own experiences working for Mount Isa Mines (MIM) in the 1980s. I was hired by MIM in 1980 to help them find another Mount Isa. When I went to Brisbane to undertake this work, MIM's thinking was dominated by the red dots shown on the slide, which show the location of four stratiform lead-zinc deposits: the Mount Isa and Hilton deposits, the McArthur River (Here's Your Chance – HYC) deposit – all giant world-class deposits, and one other, which was important but not for the same reasons.

Mt Isa had been found sticking out of the ground in 1923 by a prospector. McArthur had been found in 1955 through analogy-based science, looking within an area that looked a bit like Mount Isa—one through which a large regional-scale fault passed, along which there were several small lead-zinc showings or smoke. When I joined the company, I had already done my PhD on McArthur River and I knew that the McArthur deposit had been found by saying, 'We need an area with a big fault and we need lead-zinc smoke along or near that fault.' So I did my research and very quickly was intrigued by the Lawn Hill area, not far north of Lady Loretta, where there was a major fault, the Termite Range fault, and lots of lead-zinc smoke from the old Lawn Hill mineral workings. However, my boss sighed, patiently took me to one side, and said, 'Neil, we don't need to go up there; we worked there in the 1960s'—in fact, he had been based in Lawn Hill running that program. He further added—'We don't need to go there because the sediments are too young.' Let us look at this in a little more detail.

CARPENTARIAN STRATIGTRAPHY
OF NORTHERN AUSTRALIA

From Large et al, 2005, 100ᵗ Anniversary
Volume, Economic Geology

This is the stratigraphic position of Mount Isa [indicates on slide], and this is the stratigraphic position of the McArthur River deposit [indicates]. When McArthur was found, the company was quite confident that these two red areas on the slide were roughly stratigraphically equivalent because they had at their disposal the beautiful BMR regional maps of the area that showed that you could pretty well correlate these two sequences over a huge distance. Of course, corroboration came in time with the discovery of Lady Loretta [indicates]. It was a much smaller deposit, but it also occurred in this stratigraphic position [indicates]. With this latter discovery MIM had three good reasons for concluding that this stratigraphic horizon was where lead and zinc mineralisation occurs in the district. Subsequent corroborative research (a geochronology study by Rob Page, an old BMR colleague of mine) was undertaken by dating zircons from thin volcanic ash beds in all the deposits using SHRIMP. In all of these deposits the zircon ages were very similar, so it became the received wisdom of the company: 'This is the stratigraphic level at which you look for new Mt Isa or McArthur deposits.' The sediments at Lawn Hill occur up here at this younger stratigraphic position [indicates] and are therefore unattractive for exploration.

Much later the Company did an analysis that asked both the 'what is?' and the 'what is it not?' questions: The answer to the first question was: 'ore occurrence is restricted to a narrow stratigraphic range'. By contrast the answer to the second question might have been; 'ore occurrence is not restricted to a narrow stratigraphic range'. When we thought about these possible answers we said, 'Oh, hang on, we know from our work at that time in Canada and Germany that similar deposits in both Germany and Canada occurred at many different stratigraphic levels in any particular area.

In our search model, the obvious received wisdom answer was wrong and the other second answer was the correct one.

Not long after that, the then CRA company found the giant Century zinc deposit here in the Lawn Hill area. I was pretty depressed by their find because we had missed making the discovery ourselves – one that we might well have made many years earlier had we asked back then the 'what is not?' question and answered it correctly. However, later I was cheered up when CRA told me that looking along a major fault, in areas with lots of lead-zinc smoke, was indeed one of the main reasons why they also went into that area. Their success owes much to the fact that they didn't restrict their exploration model to the stratigraphic level of the Mt Isa, Lady Loretta and McArthur River deposits.

So, in conclusion, here are a few key points I want to leave you with.

1.   Remember John Harrison and remember Alan Turing. That is what are the right questions to ask and how do we narrow our focus? These are both critical questions for any exploration, be it shallow or deep under cover. Also, remember Taleb's black swans: we get closer to the truth with the negative than we do with verification.

2.   Here is a new question to close on.

Imagine that you are a deeply buried giant ore deposit. What are the things about you that you cannot hide from an explorer looking for you from the Earth's surface, 350 metres above you? Turn your exploration thinking around, put yourself in the position of the deposit and think: 'How can I hide from the guy up there?'

May all your thinking be outside the square, challenging and fun!

Thank you.

Knowledge discovery via a virtual geological observatory

Professor Dietmar Müller

I am going to give you a short overview of our efforts to build a virtual geological observatory. Geoscientists in Australia have been told over many years that we should try to be a little more like astronomers because astronomers are well known for being quite united. Firstly, they put a telescope on a particular hill and they all use it and are quite happy about that, but they have also been further united by building virtual observatories, and virtual observatories have further revolutionised astronomy by giving people anywhere in the world access to a vast area of sky observations and tools.
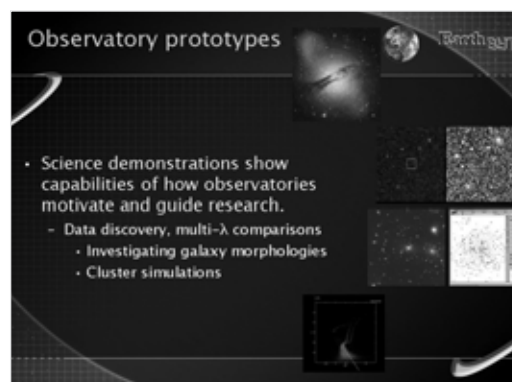
Observatory prototypes have demonstrated how observatories enable research—normal research. People with no access to collecting observations of the sky still have access to data discovery tools and software that allow them to analyse the vast multidisciplinary data that are being collected there.

So, of course, we ask ourselves the question: can we transplant this concept into Earth sciences somehow? Earth observation is a different animal compared with sky observation: there is a vast multitude of different methods of observation. A small sampling is illustrated in this assemblage, and it is a lot more than satellites and space probes.
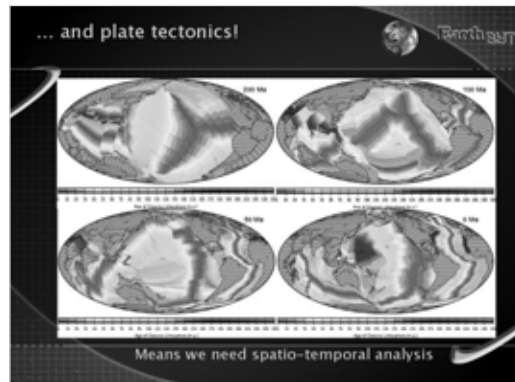
On top of that, we have to deal with plate tectonics because, if we think of mineral deposits, for example, they are formed by hundreds of millions or billions of years of plate motions; so we to have try to put our observations and geological and geophysical data in a plate tectonic context to try to understand these processes, and ultimately predict where we may find ore deposits. The maps on the slide show plate motions over the past 200 million years, in four snapshots, as well as the evolution of midocean ridges (the bright red objects), versus just the plates (the greenish and bluish objects) in the ocean basins. So the midocean ridges and subduction zones are two examples of how certain geodynamic niche environments may create particular ore deposits; unfortunately, I will not have time to talk about that today.

What are the challenges in a mineral exploration context? As far as the first mineral deposits are concerned, they are intricately tied to plate boundary processes. But the GIS tools that we typically use to analyse these data are not temporally aware, so typically we just look at these data in a presentday context and that makes it really hard to capture geological history and geological processes that are ultimately responsible for creating these deposits. Also, the data analysis and knowledge discovery tools that we have available are generally visualisation-based, so they are generally qualitative and limited, due to the vast complexity of the data that we are working with. We have a large number of features to analyse—we like to combine information from geological, geophysical and geochemical data—and there are statistical analysis issues: typically our data is sparse and we might have missing values and noisy data uncertainty. These problems are hard to overcome by purely qualitative data analysis and multidimensional data space.
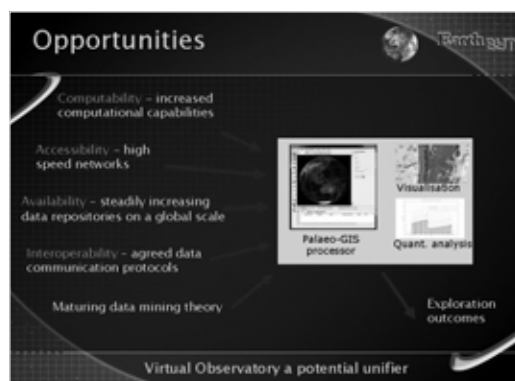
At the same time, there are opportunities in the space in which we are moving. There is the issue of computability. Computing power increases year by year. Even though the processing power of an individual CPU is fairly limited, we are moving into parallel processing. As high-speed networks slowly emerge, there is vast improvement in the accessibility of data—probably several orders of magnitude better than we have now. We have a large number of data repositories on a global scale and already a lot of data is freely available. Typically the problem is no longer in getting access to data but is actually in amalgamating and analysing it in a coherent way. So that brings us to interoperability and usually there are few agreed data communication protocols, so that makes it hard to combine different sorts of data from different sources in a coherent fashion. But at the same time data-mining theory is maturing, so there are opportunities to think of building a paleogeographic information system that would allow us, ultimately, to put all the geological and geophysical data that we are using into a plate tectonic and geological context.

These considerations have brought us to thinking about building a virtual geological observatory akin to the observatories that astronomers have built. What do we mean by that? First, we need a set of standards to share complex data; so we need interoperability. The data standard that we have chosen is called the Geographic Markup Language (GML), which is an international standard for geodata. Other standards have been built on top of that; for example, Exploration and Mining Markup Language (XMML) as well as GeoSciML. We want to be able to analyse lots of different sorts of data: geological maps, stratigraphic data, well data, structural data, potential field data, seismic data—you name it. These data need to be assigned to tectonic plates as we import them into our PaleoGIS, as we want to be able to restore all these data to their positions in the geological past.

This requires a plate rotation model. We need to have a model or alternative models for all the different plates that have moved around through time, and we need easy interactive ways to design these alternative plate models. We also want to be able to work with plate deformation; that will also be embedded in our software within the next year. We want to connect to web services. For example, OneGeology is a web-based effort to deliver geological map data to the community. We would like to have interoperability with geodynamic codes. Also, the type of observatory software and infrastructure that we are talking about should ideally be open source so that it is easily picked up by researchers anywhere in universities, government institutions or industry; they can then participate in extending it and changing it together with us.
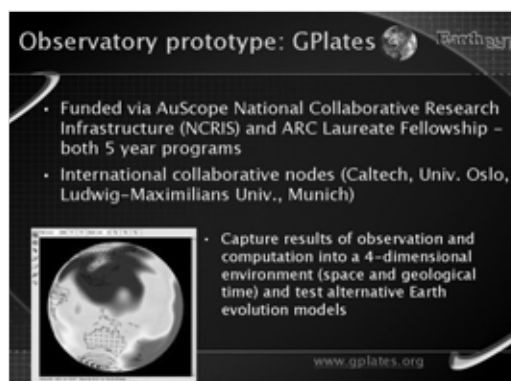
So we have built an observatory prototype called GPlates software, which is funded by the AuScope National Collaborative Research Infrastructure Strategy (NCRIS) project and the ARC Laureate Fellowship; they are both five-year programs. We have several international collaborative nodes, particularly Caltech, the University of Oslo and, since this year, the Ludwig Maximilian University of Munich. GPlates software does not yet have all the capability that I have just described, but it provides a framework to capture geological and geophysical data into a four dimensional, spatial plus temporal computation that will, ultimately, allow us to test alternative Earth evolution models.
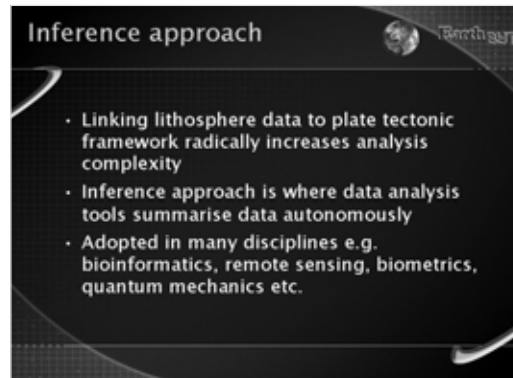
I want to spend just a few minutes talking about an inference approach. We already have a feeling from Neil Williams' talk that there is still a lot of controversy over how we can use positive or negative correlations to make an inference about where to look for the next large or smaller ore deposit. We think that, in order to do that, we need to link our data reflecting properties of the lithosphere's crust to a plate tectonic framework. Of course, that increases our analysis complexity because the adjacency associations of all our data change through geological time as everything is moving around. So this inference approach is useful where we can use data analysis tools to summarise quantities of the data and correlations of the data autonomously—or semiautomatically, if you like. Of course, the researcher must still be there to ask the right questions; the software will never help you to formulate the right questions. This kind of inference-based approach has been adopted in many other disciplines, such as bioinformatics, remote sensing, biometrics and quantum mechanics.
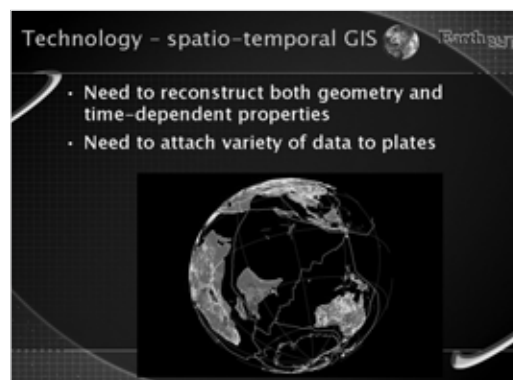
In this environment we need a technology that could be called the spatio-temporal GIS. We want to reconstruct both the geometry and the time-dependent properties of our data, so we need to attach a variety of data to tectonic plates. This slide shows a simplified digital geological map that has been cookie-cut and attached to the different continents that have been juxtaposed to their relative positions of about 100 million years ago.

In this animation, we have taken some published reconstructions and tried to construct a preliminary tectonic model for Australia, which goes back about 2½ billion years, that shows how the different elements of Australia have come together through the closure of ocean basins, and ultimately formed Australia as we know it today. In our PaleoGIS framework, we can cookie-cut these different continental blocks and pieces and display, as in this instance, a magnetic anomaly grid that is cut out and assigned to the different pieces; and we can also superimpose other data, particularly ore deposits, and then investigate the adjacency associations of all these data in a spatio-temporal context. This capability is just now being developed and added to our software. In fact, we expect a major release, which is due to come out some time in the next two weeks, to have much more functionality along these lines.

In order to go from qualitative to quantitative data analysis, we need to explicitly associate data together; it is not good enough just to layer the data, as is typically done in GIS or Adobe Illustrator. We need data that are, in fact, as we say, 'co-registered' in a sensible fashion so that we can analyse all this data together. The output of such analysis would be a 4D spatio-temporal data structure that would be ready for machine learning.
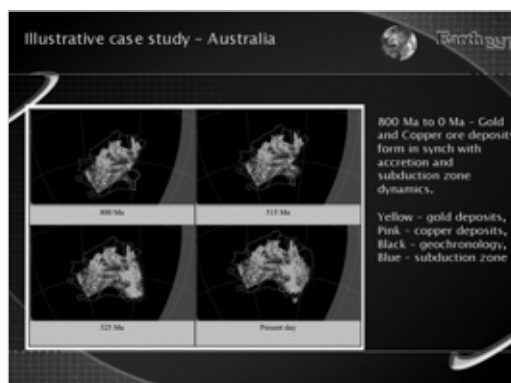
This slide shows four snapshots from the animation I showed you before. It focuses on the time period 800 million years ago to the present. Again, we have reconstructed the Australian Magnetic Anomaly Grid from Geoscience Australia and we have superimposed gold and copper ore deposits on this reconstructed potential field grid. In this context, we can then ask how particular deposits are associated with accretion and subduction on evolution through time.

I am going to show a small sequence of slides to illustrate how data co-registration can help us to ask particular questions, questions that would be difficult to address with a conventional GIS approach. Let's say that we want to ask the question—this is just a simple example: what is the association of particular mineral deposits with the proximity of faults? The beauty of our PaleoGIS is that we can ask this question not only about presentday associations of mineral deposits and faults, but also—as we restore all these different continental blocks, pieces and faults through time—in a spatio-temporal 4D sense.

So, as you can imagine, we can then choose particular datasets to cookie-cut into different plates. Here we are showing Australia, just to make it simple. In this case, we have overlain mineral deposits, which are the red dots, faults, which are in white, and geological provinces—and it is just the blue outlines of these provinces shown here. Now we want to ask the question: how are these mineral deposits related to the proximity of faults? All these bits and pieces of data have geological ages associated with them. This is a sort of *beta* technology that is still under development. We would choose what we call the 'C dataset' that concerns the phenomenon of interest and, in this case, that would be our mineral deposits.

Then we define what we call the 'dataset attribute operator' that defines particular properties that are associated with our C data point; these can be geochemical properties, ages *et cetera*. So we gradually implement the question that we are trying to ask. The operator would be the nature of the association that we are looking for.

In this particular instance, there is one data field that is called 'the ERA', the time period in which particular geological objects, such as mineral deposits, have been formed, and the C points reside within these ERAs. Then in this association we look up the commodity attribute of our C point from the C dataset. The sixth step: we look at the spatial temporal co-registered dataset that you can think of as a 3D matrix. So we have an association of mineral deposits and the distance to faults in a time-dependent sense, not only in a presentday sense, because each data point—a given fault or a given ore deposit—will have a geological age associated with it.
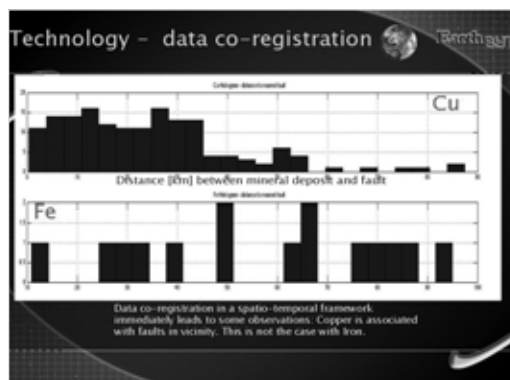
Ultimately, we come up with a histogram of this sort. What we are looking at in this slide is the distance between a given mineral deposit and a nearby fault. This distance, in kilometres, is plotted on the X axis and the upper graph is shown for copper and the lower graph for iron. This is just a simple example, so we can see right away that it seems that copper occurs reasonably closely to faults within 40 to 50 kilometres, whereas there is no such correlation with iron. You can now imagine that you have a multidimensional dataset that might have 50 or 100 properties that you can analyse in this fashion simultaneously.

Just briefly, I want to lead into the discussion points that we will discuss in the breakout groups in this context. We want to address what computational data-management strategies are needed to manage the huge quantity of data that is becoming readily available to us, and to link them to data analysis tools and process models. Once we have uncovered a relationship, using our inference method, the next step would be to perhaps link our plate tectonic model to a geodynamic model, to investigate the process that might produce the relationship we observe. The observatory that we are building is particularly designed to enable links—work flows—between the PaleoGIS and geodynamic modelling tools. Then we want to know how ultimately to link geological, geochemical and geophysical data to analysis and modelling tools. Also, we want to talk a little about what software and hardware are needed in terms of the modelling, to advance these fields in the context of mineral exploration—and, as we have already heard, it is all about giant ore deposits and they are relatively rare, statistically speaking.
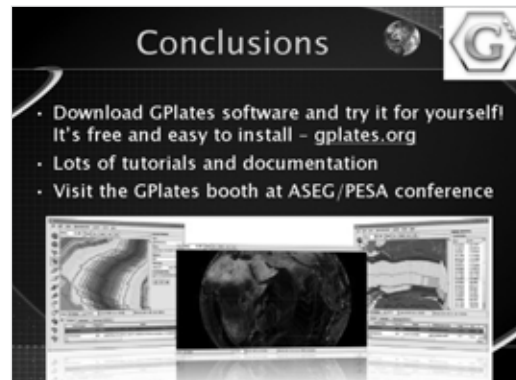
So, in conclusion, we have this GPlates software that is a prototype for a virtual observatory. It is free; it works on any kind of computer; you can download it from www.gplates.org and try it for yourself. There are plenty of tutorials and documentation available.

Discussion

Cam McCuaig, Centre for Exploration Targeting: That looks really fantastic and it is great that, given that you have data, you can put it into this software and query it. I think it is a fantastic advance. What I would like to know is how you capture uncertainty. It came into my mind when you looked at your fault database. You have some faults, and I think we all intuitively know that. But, just because there is no fault map, it does not mean there is not a fault there, and the faults that are there or are mapped have certain uncertainties with them. How do you try to capture that type of uncertainty? As geologists, we are really pretty poor at capturing uncertainty. I think that is going to be critical in information management if we are then going to make decisions off this. It is decision making under uncertainty.

Dietmar Müller: Of course, there is uncertainty due to missing data. That is just about the hardest part of it. I do not think I have a quick answer to this question. The fault dataset that I showed you was deliberately a simple dataset. We could have used a dataset from FrOG Tech that has ten times as many faults; the whole map probably would have been white. I guess that one way to assess this kind of uncertainty is to look at one area that has been very well mapped—say, deep seismic data—where you think you have captured most of the faults that you might find in the crust and then compare that with an area where you have merely mapped the faults using potential field data and geological surface observations. Perhaps in this way, if there are similar terranes, you will get a feeling for what the real density of faults is, versus what you can infer from remote sensing and surface geology.

Katy Evans, Curtin University: It looks great. I was wondering where you draw the line between subjective and objective properties for the elements on the map—because, clearly, you can say, 'This is a copper deposit,' or, 'This has a certain geographical location.' But, if you are looking at a fault and you want to say it is a strike-slip or thrust fault or some kind of fault property, that becomes interpretive; and, if you get that wrong, it preconditions the models. So, presumably, you would draw the line somewhere within that. How does that work?

Dietmar Müller: I would say that, sure, geologists interpret the nature of faults and, on top of that, you might have faults that have gone through a history of different types of faults. You might have a normal fault that you have to recharacterise as a thrust fault or as a strike-slip fault. So, there are probably not even many time-dependent databases that capture this behaviour because it is so difficult to extract these properties from geological observations.

I suppose one way to safeguard yourself from this problem is to make your analysis more robust by analysing large datasets—datasets not just from Australia but also from other continents—and to establish associations. That is what we do with plate reconstructions and marine geophysical data: we identify outliers that way. If 95 per cent of the data fits in a certain way and some data points do not fit, we say, 'Well, they've clearly been misidentified; they're not what we think they are.' So I guess you can use a statistical approach. You can define a confidence limit. If you have fitted parameters in a certain way, you can look for certain associations and then, if something lies outside that envelope, there is always the question: it could be that it means something or it could be that it is just an outlier. But that is why you can never completely automate these processes; you always need somebody with geological knowledge and intuition to look at these tools and make decisions—to go back to the data at that point and look at them.

Giant ore deposits: Why they are important!

Richard Schodde

I would like to begin by thanking the conference organisers for putting on this session and for inviting me to come along. But I would particularly like to thank Roy Woodall for something he did 20 years ago, which was to ask me to join Western Mining Company's exploration group. In the process of doing that, he sparked my passion for mineral economics, which continues today. He switched me from the dark side of engineering to the bright side of geology. To paraphrase: geologists are optimists; they are fun people to be with. On that basis, I will get started with my talk!

My topic is 'Giant ore deposits: Why they are important!' There is one obvious answer: they are big and that is where the money is. But there are a lot of subtleties associated with this and I am going to spend the next 10 minutes or so going through them.

I think the first thing to do is to correct the Think Tank by saying that giant deposits are not the same as world-class mines; really what we should be doing is focusing on the latter because that is where the money is. Just to pick up on that: giant deposits are of academic interest and often geologists tend to focus in on big things, but really where we should be looking, for industry and society, is where the money is being made. The differentiation between the two is pretty obvious. Giant deposits are large accumulations of metal, but they may not necessarily be economic. What you are really looking for are things that can be turned into mines of large size and long life and can actually have an impact on society. So that is really a definition of what world-class mines are.

Different people have different views on what is 'world-class'. If you talk to the general public, it is something of general outstanding quality. Geologists tend to think of the size criterion. Investors are focused on the money aspect. For promoters, it is anything that is big, they are very loose and fast with their definition of 'world-class'. But I like what Michael Doggett said in 2004: 'World-class should be more than just big geologically, there must [also] be an economic consideration. …when economics are considered, there is no such thing as a world-class mineral deposit. There are only big interesting mineral deposits or world-class mines.'

So we have to focus on things that are of economic value, things that can be turned into mines. It is no use finding a brilliant ore body if it is in the middle of a national park – as you cannot mine it. It is no use finding a large deposit 1000 metres down that is too low-grade to mine. It has to be something that is of value to society.

Why do we need to find more deposits? This chart has been well used, and I love using it again and again. It talks about the 100 years of copper production in the world; it has grown from less than half-a-million-tonnes-per-year production to over 15 million tonnes per year now. Over the past 23 years the world has used up half of the metal that has ever been mined. The scary thought is that over the next 23 years we are going to mine all of the copper that has been mined to date. So, basically, we are going to double the size of the cumulative history of the industry. It is a real challenge to fill that gap: where are we going to find the metal and of what quality will it be?
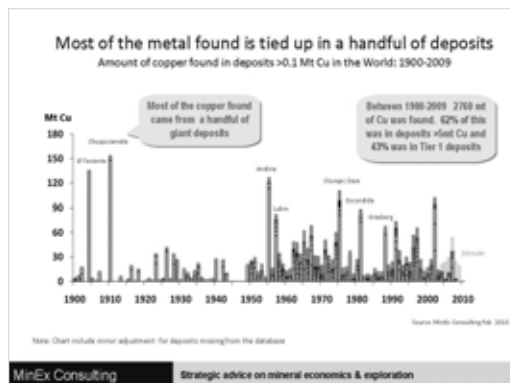
When you look at copper mineralisation in particular, you find that it is a fairly episodic event. This chart shows the total amount of copper that has been found each year for the past 100 years. You can see quite clearly that there are a few peaks there, and much of the copper is found in just a handful of deposits. The names are legendary in their own right: Chuquicamata, El Teniente, Olympic Dam in 1975 and Escondida. When you add up all of the discoveries, you find that something like 2.7 billion tonnes of copper have been found in the past 110 years. Of that, 62 per cent was in deposits containing more than 5 million tonnes of copper metal and, when it comes to tier-1 or world-class deposits, 43 per cent of the metal was in those. So just a handful of the deposits have a large amount of the metal; that is where the value is.

So what are the obvious benefits of world-class mines?

Geologists all want to be associated with a significant discovery; there is a lot of pride and prestige to be gained and money to be made out of them.

What do world-class deposits or world-class mines mean to companies and investors? A company making mines that run for several business cycles makes a lot of money for the investor and the company itself and, more importantly, such mines create a lot of optionality—and this is something that is underappreciated with a mine. It is better to have one big mine than 10 small mines because, when you think about it, as you go through the business cycle with technologies changing and opportunities arising, if you get a large deposit, you can basically grow and grow it. You see that time and time again, in places like Escondida, which has had over a dozen expansions; it is amazing. It is the same with Olympic Dam: when it first started off, it had a production rate of less than 30,000 tonnes a year; now it is over 220,000 tonnes and they are talking about going to 600,000 tonnes. Believe me, when I am long gone, they will be talking about a million tonnes or more for that operation.

The other thing to think about from the government's perspective is that world-class mines generate strong revenues and, obviously, lots of taxes, which are of benefit.

To consumers, world-class mines tend to be the ones that set the price for the industry; and, although it is not good for the mining company, it is good for society in general to have lowcost inputs.

From a societal point of view, having large mines with long lives, which are actually multigenerational, is important for society because such mines create a longterm perspective. They justify and underwrite the infrastructure that is required for Australia. Looking at a map of Australia and seeing where the roads and railway lines go, you will see that quite often they are associated with mining deposits. You can think of Kalgoorlie and Broken Hill as a couple of classic examples in that case. They underwrite our longterm prosperity, which is critical to why we are here today. We need to think about what we will be doing today that will underwrite Australia's society 20 years from now, if not further into the future.
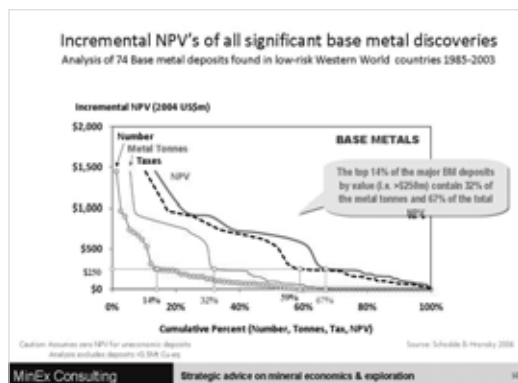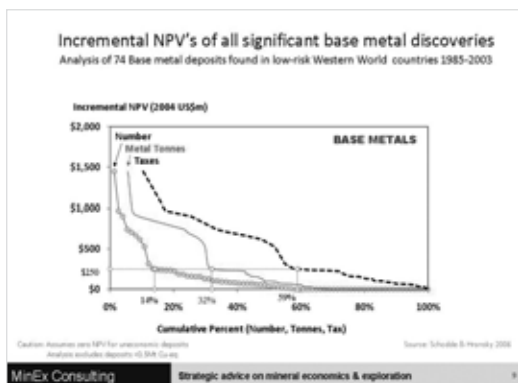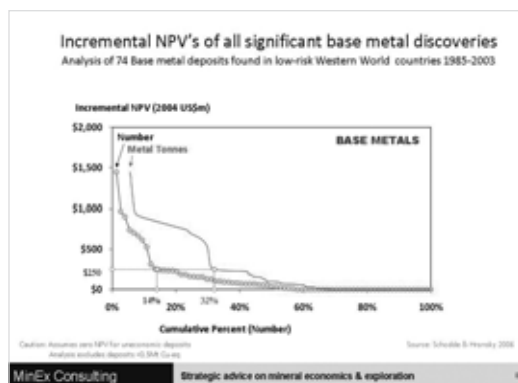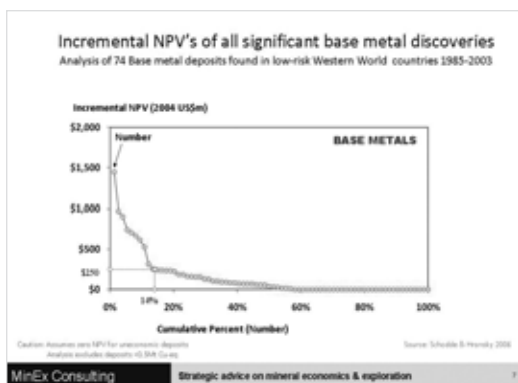
This series of charts explains why world-class or giant deposits are important. I did a study a few years ago of 74 base metal deposits around the world in low-risk countries and looked at how many of those were big and valuable.

The Net Present Value (NPV) chart is now out of date. But, at that time, at lowcommodity prices, I drew a line that said: of those 74 significant mineral deposits that were found in that period, how many had an NPV greater than $250 million? About 14 per cent had an NPV greater than that. Those same deposits contained 32 per cent of the metal; those same deposits had 59 per cent of the taxes paid; and those same deposits had 67 per cent of the NPV. So you can very quickly see that only a handful of the deposits generate much of the wealth for the industry.

One of the characteristics of a world-class mine is that they do have large and obvious signatures. Going back to Neil Williams' question, imagine that you are a giant ore body: 'What are the things that I can't hide under 350 metres of cover?' They do have large footprints, large geochemical signatures and, obviously, large geophysical signatures as well. The challenge that we face is that a lot of the deposits that have been 'at surface' have been found, particularly in so called mature terranes such as Australia. I would actually argue the point that Australia is not mature once you go below 200 metres of cover. It is also becoming progressively more difficult to find these world-class deposits, especially for commodities that have much more subtle signatures and a much more variable grade distribution. In the case of nuggetty gold deposits and uranium deposits, it is very hard to find those things under cover and there are special challenges for those.
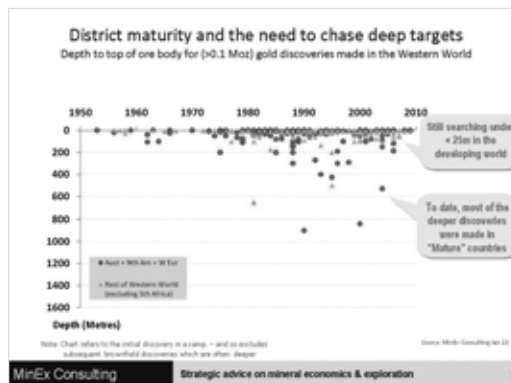
This chart shows depth of cover for deposits that have been found in the past 50 years or so. The green is associated with emerging countries, such as those in South America *et cetera*; and the red dots are associated with so called mature terranes or mature countries with well-established mining areas, such as Australia, Canada, the USA and Western Europe. You can see that, as the industry matures in places like Australia and North America, we have to explore under deeper and deeper cover, and that presents a lot of challenges. But, in emerging countries, people still are swimming at the shallow end of the swimming pool.
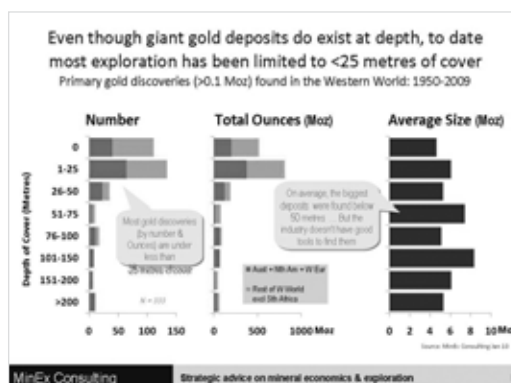
That is not to say that deposits do not exist at deep cover; a lot of challenges are associated with gold exploration in particular. In recent years—this slide is from a study I did a little while ago that looked at this—most of the deposits that have been found for gold have been under less than 25 metres of cover, and that is where most of the ounces are as well. But, looking at the average size of the discoveries that were found at depth, you will see that they actually got better at depth. So that implies or tells you that, just because we have not been finding any there, it does not mean that they are not there; it is just that we do not have the right tools to see them. That is the challenge for you.

World Class Deposits are rare !

- Between 1975-2009 the Western world spent US$154b (in 2009 dollars) on exploration and discovered 59 Tier 1 (ie WCD) deposits
  - ie 1.7 WCDs per year at a cost of $2600m per discovery

- Along the way the industry also found 184 Tier 2 deposits and over 3000 smaller deposits
  - ie average cost of ~$50m per (small) discovery

Analysis excludes bulk mineral exploration and discoveries

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We keep emphasising this; it is almost a definitional thing: world-class deposits are rare. I will repeat that: they are rare. If you add up the money that has been spent over the past 35 years, about $US154 billion in today's terms has been spent on minerals exploration and, from that, we found only 59 world-class or tier-1 discoveries. That means that you basically have to spend $2.6 billion per discovery—and, on average, the industry only finds fewer than two a year. It is a pretty scary thought when you think about it because, when you read the strategic plans of the BHPs and the Rios of the world, they all say, 'We want to find world-class mines.' Everyone is competing for these, but only one or two are found each year. If you step back a little and look at tier-2 deposits—I guess Olympic Dam would be a tier-1 discovery and Prominent Hill and Ernest Henry would be tier-2 discoveries—you find a lot more of those and you actually find quite a large number of other deposits along the way. But, if you add up the smaller and probably less economic deposits—we are talking $50 million or more per discovery—the real challenge is that, if you are a junior mining company with a budget of $A1 million or $A2 million a year for exploration and it is costing you $US50 million on average to find something, a lot of people are missing out. There are a lot of frogs that you have to kiss before you find that prince or princess.

Exploration expenditures and discoveries
Western World 1975-2009

On average less than two Tier 1 deposits are found in the WW each year

Tier 1 deposits are World Class Mines
Tier 2 deposit have some but not all the characteristics of a T1

Source: MinEx Consulting, June 2010

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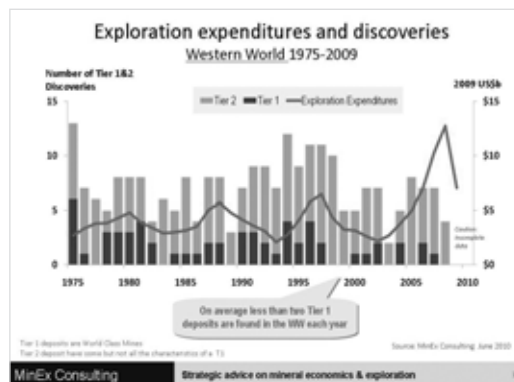
This slide shows some statistics on the frequency of discoveries. They show tier-1 and tier-2 discoveries. On average, fewer than two tier-1 discoveries are found in the western world each year. Exploration expenditures are up and discovery rates remain fairly modest.
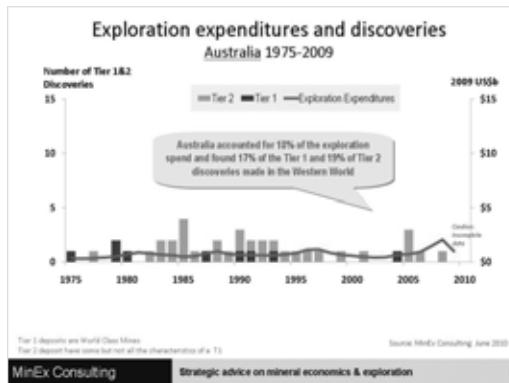
This is the snapshot for Australia; it is even more modest. I guess though that we should not feel too badly about ourselves: in that period of 35 years, we added up to about 18 per cent of the exploration spend and we found about 17 to 19 per of the discoveries; so we were punching above our weight.
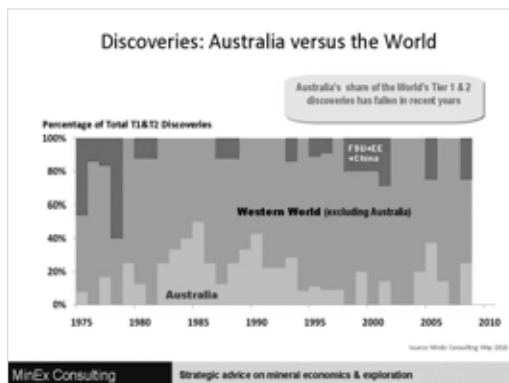
But the concern is that in recent years the discovery rate has gone down in Australia, and I suspect that it is probably because we are spending less money exploring: people are going to other areas. So how can we reinvigorate and excite people to come back to Australia and explore for those targets?
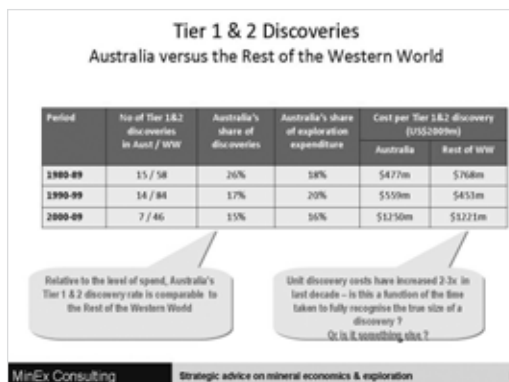
This is a summary of some of that data, in terms of a snapshot over a 10year period. I guess it is saying that we are still competitive when it comes to discovery compared to other parts of the world, in terms of spending our money and the number of deposits that we find; but the scariest thing for the industry in general—not for Australia in particular, but for the industry in general world-wide—is that it is costing us more and more money to make those discoveries; it is becoming much more challenging. Is this a reflection of the fact that it does take time for ore bodies to be found, or is it a fact that we are now getting to where the easy ones have been found. It is costing us over $1.2 billion to make a tier-1 or tier-2 discovery. That is a lot of money.

Sometimes we can "grow" our own WCMs
Tonnes-Grade data for 48 copper deposits
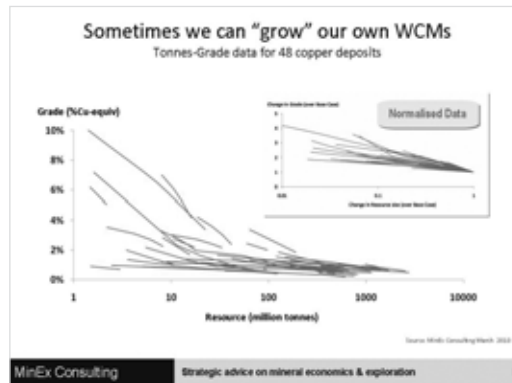
The other thing to think about, when you look at it over 100 years, is that some deposits are made and not found; you can actually grow ore bodies. When you think about copper in particular, there is no such thing as a single 'tonnes and grade'; it is actually a tonnes–grade distribution.

You can normalise those things and, basically, you can dial in an ore body of any size you want; it depends on what cutoff grade you use. The cutoff grade is set by the economics of the mine. The economics are driven by the price; you have no control over that. They are also driven by costs, and costs you do have control over. Engineers can lower costs. Technologists can come up with breakthroughs that make previously uneconomic ore bodies viable.

Economies of scale and new technology helped drive down costs
Cash Operating costs for selected open pit copper mines in USA and Chile: 1905-2007

This is a chart looking at the costs of various world-class ore bodies over the past 100 years. You can see that, over the period of 1915, 1929 and the 1970s through to 2007, there has been a step-change down in the cost structure; there has also been a step increase in the size of the mines. Back in 1905, the world's biggest copper mine had a mining rate of only half a million tonnes of ore a year; today we are talking about 80 million tonnes a year.

So the thing to think about is that, just by the industry growing in size, we have been able to achieve economies of scale and to lower our costs. But, more importantly, what has been happening is that technological breakthroughs have led to a step-change reduction in the cost of mining. That means that we can have lower cutoff grades, which means that we can have larger ore bodies. That particularly benefits copper porphyries because of the diffuse nature of those types of ore bodies. So what I am trying to say here is that geologists should not be independent of the technologists and the engineers; you have to work together as a partnership to come up with breakthroughs. Just think about things like copper oxide ore bodies; people used to ignore those things 50 years ago. The invention of solvent extraction/electrowinning (SX/EW) technology suddenly made them very attractive and people came back in again. In the case of case of Australia, the carbon-in-pulp (CIP) process, which came in during the 1970s, suddenly reinvigorated the gold mining industry here. So do not just wear a geologist's hat when you are looking for ore bodies.

The Key challenge
How can we improve our discovery rate for WCMs ?

1. Have to be in the "right" area
   - Need to be innovative and innovative in area selection

2. Have to be effective in testing the target
   - Need cheap and efficient ways of exploring

3. Have to be smarter at extracting the ore
   - Geologists working with Engineers and Metallurgists can "make" WCMs (for example, bauxite in the Darling Ranges, large-scale iron ore in the Pilbara, SXEW for copper, ISL for uranium)

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In conclusion, these are the key challenges that I see. There are three things that we need to do at least to improve our discovery rate of world-class mines. First of all, we need to be in the right area. It is no use exploring where there are no ore bodies. Secondly, you need to be innovative. You have to be efficient and innovative in area selection. Also, you have to be very effective in testing those areas. You have to have the tools to be able to explore those things effectively. Finally, we have to be smarter at how we extract the ore. This is the point that I was emphasising before: geologists need to work together with engineers and metallurgists to make ore bodies, and there are lots of examples of that.

Giant ore deposits: How do we target them better?
Seven things that aren't in the textbooks

Dr Jon Hronsky

Thank you for giving me this opportunity to speak to you about a subject that I am passionate about, which is from, fundamentally, a practitioner's perspective. I am here because my day job is targeting and looking for giant ore deposits and I am very interested in the things that I can use that will help me to do it. But, before I start, I would like to pay tribute to Roy Woodall and the intellectual heritage that I and many others from Western Mining inherited from him and to thank him for his leadership, which I think has made a profound impact on the Australian, and perhaps the global, exploration industry in terms of how to think outside the box, how to look at things at the right scale and how to focus on the ingredients that really make a difference in targeting giant deposits.

I have subtitled my talk 'Seven things that aren't in the textbooks', because I do not believe that the current economic geology textbook or the various volumes that we have are particularly helpful to me in targeting giant ore deposits. The point I will make about the textbooks, which is quite interesting, is that, as far as I am aware, in this century no one has written an economic geology textbook in the English language; I am aware of one in French. So there is a lot of catching up to do.

The fundamental problem I think we have with the textbooks and with the science of economic geology is that perhaps, more than many other sciences, we are terribly stricken with this problem of 'availability bias', which is a term that psychologists use. 'Availability bias' means that you study the things you can study and not necessarily the things that are important. We have typically been very focused on things like, if we want to find out about giant ore deposits, we think we need to go and describe giant ore deposits, and that is actually a very small part of what we need to do to help find giant ore deposits.
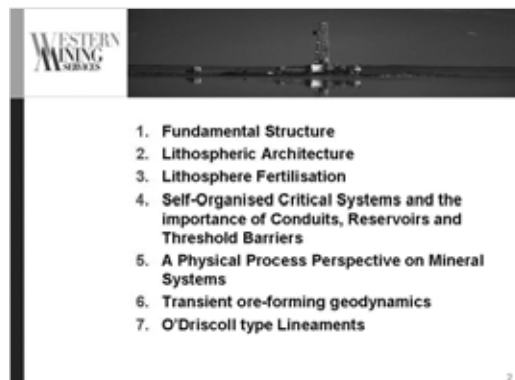
I am going to talk about seven things that I think are not in the textbooks. They are listed on the slide in approximate order, from the things that I think are broadly accepted in the industry and a fair bit of the academic community, down to those that I think would be considered pretty fringe. I think these are all things that we do not normally talk about in economic geology research, but they are absolutely essential to targeting. There are other issues that are important, like the secular evolution of the Earth, hydrosphere and so on, but I am not going to talk about those issues because I think they have been in the textbooks for a little while.

Sierra Foothills Gold Province (California): Example of an Ore-Hosting Anastomosing Fault Zone developed above a Fundamental Basement-Boundary Structure (inferred from gravity gradient) Source: Bierlien et aln (2008)
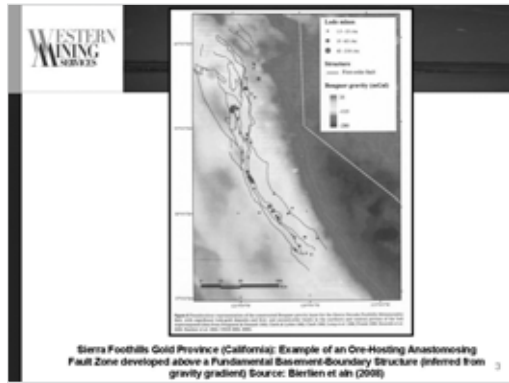
This diagram is from the Sierra Foothills Gold Province in California. It is a really nice example of what is a fundamental control on just about any giant metal deposit that you want to find—and that is that they will always be associated with fundamental lithospheric scale structure. But these structures have a couple of characteristics. One is that they never manifest themselves as major faults in the nearsurface environment. So, if the geological survey has gone there and mapped a big black line on the map that is not the type of structure that will host ore. They always have a cryptic signature or a more complex signature, at least at the surface erosional level. That is the first point. As for the second point, there was some conversation before about thrust faults, normal faults or whatever. Inevitably, if they are going to be important ore-hosting faults, they will have moved in just about every direction you can imagine and they will have very complex histories. But you do not have giant deposits without these things. I think this is a fairly well-established concept, certainly in the industry.

Great Basin, USA :Paleozoic Sequence
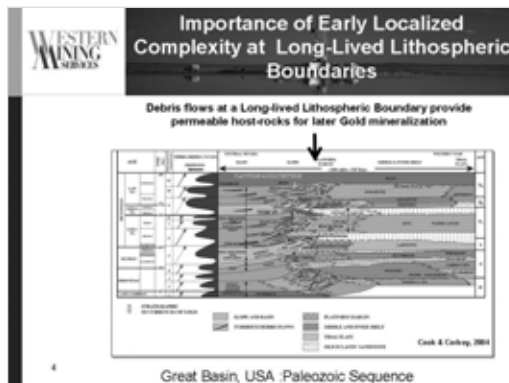
As I have said, these structures have very, very long histories. This slide shows an example from the Great Basin in the USA and the structural corridor that hosts the giant Carlin Trend deposits, which are Tertiary-age deposits. But the key point is that they are forming above, and associated with, what was a major lithospheric boundary in the Palaeozoic, a major transition between the shelf sequence and the deepwater sequence, which represents fundamental underlying tectonics. Time and time again we see this pattern in the structural environments that host giant ore deposits.
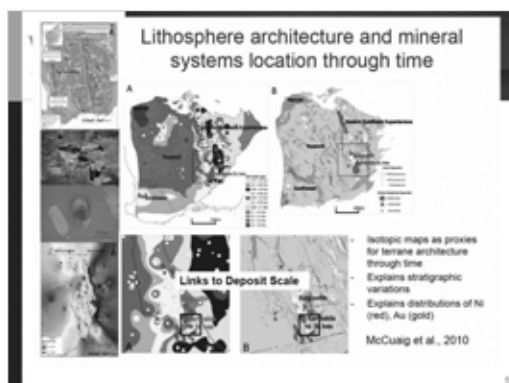
The structures that I have just been talking about are a component of lithospheric architecture, but we also see the importance of lithospheric architecture at other scales. People like Graham Begg have really been driving this over the past decade or so, but now we are also starting to get some innovative datasets that are enabling us to map the lithosphere in ways we could not previously. This is an example from the work of the Centre for Exploration Targeting (CET) at the University of Western Australia that clearly shows the correlation of both major nickel and gold deposits with the edge of a paleo-cratonic block. We could speak about any of these topics for quite a long time, but I think it is pretty clear that we see these controls and we are getting increasingly better at improving the resolution of these features in our data.

SAMTEX MT Survey:
Red dots = diamondiferous Kimberlites
(Jones et al, 2009)
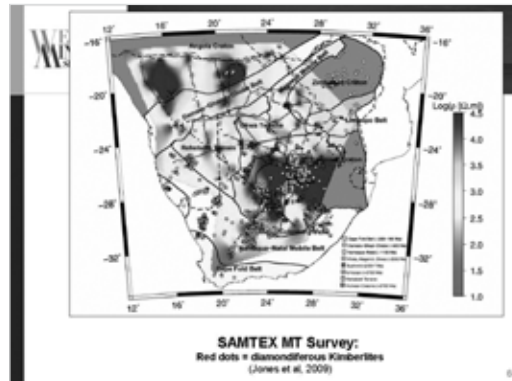
This is a dataset that I really like. It is probably the best high-resolution dataset we have anywhere in the world of the lithospheric architecture, the upper mantle, and it comes from this South African Magnetotelluric Experiment (SAMTEX) magnetotelluric (MT) survey, which was a big, collaborative industry research effort carried out in southern Africa over the past few years, primarily for diamond exploration. It shows very clearly the relatively resistive areas, which represent what we believe are the more harzburgitic, more depleted parts of the upper mantle and, of course, the regions that host diamonds. It is pretty clear that you can see major structures in these data but you can also see the importance of diamondiferous kimberlites clustering around the edges of these particular blocks. These are the sort of data that I think are going to be very important in underpinning exploration as we go forward. We probably need to try to get those sorts of datasets for Australia, as a priority.

Sillitoe (2008)
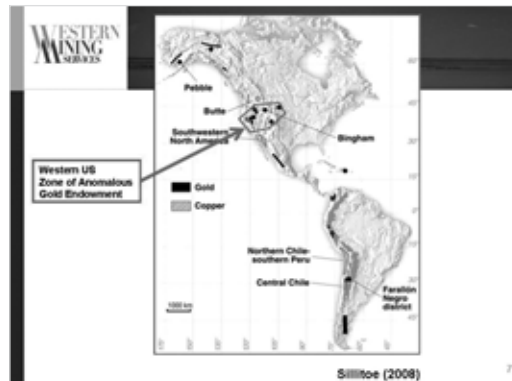
One of the things that has been recognised for quite a long time is that we have provinces that have fundamental fertility. Our current models for economic geology tend to see metallogenic events as the property of a particular tectonomagmatic event; so Olympic Dam is seen as a property of the 1590Ma Hiltaba event, for example. But, when we look at things on a bigger scale, we see that metallogenic fertility must be a larger-scale property; it must be the property of larger-scale domains. This has been very elegantly summarised by Dick Sillitoe in his paper a couple of years ago: his summary of the gold endowment of the Americas. He points out that, when you look all along the 20,000 kilometre extent of the American cordillera, lots of the same sort of geology goes on but there are only a few areas that really get the gold endowment. In particular, I am going to focus in on this western US superprovince because it is quite instructive to look at the characteristics of something like this.

Western US Zone of Anomalous Gold Endowment:
Multiple Events – Multiple Deposit Types
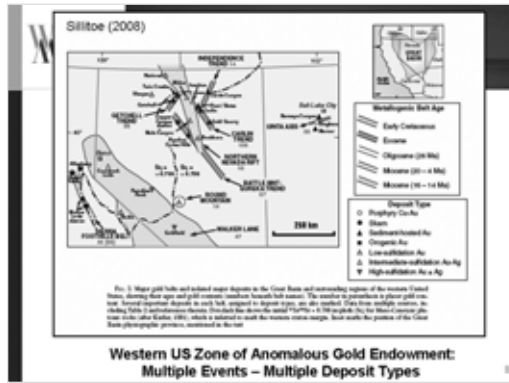
I do not need you to pay attention to the details of this slide; but what I need you to realise is that in this superprovince, first of all, we have a range of metallogenic belt ages from Cretaceous to Miocene; and, secondly, we have a vast range of deposit types from porphyries to skarns to sedimentary-hosted gold to orogenic gold, but they are all formed in this one environment. Clearly, the only explanation for these sorts of patterns—and we see them in many other places in the world—is fundamental lithospheric fertility.
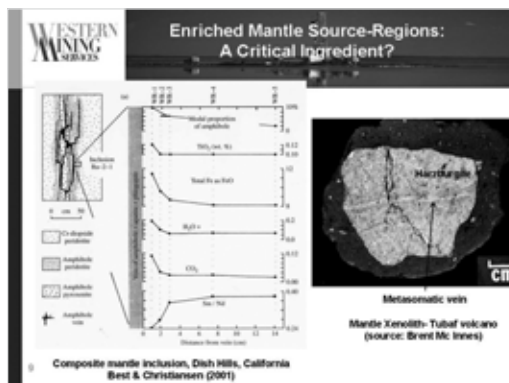
We are now getting some understanding that this is all about veining and altering the mantle. Here is an example from a mantle nodule that was dredged from a submarine volcano just off Lihir, from Brent McInnes's work, where we can see the altered metasomatised veins in this underlying mantle, which we believe has been remelted to make the alkalic melts, the Shoshonitic melts, which the Lihir deposit is associated with. So this might be what these enriched mantle regions look like. We know that these things are enriched in metal.
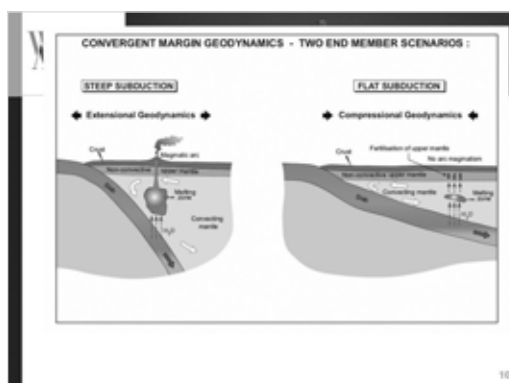
I think it is really important that we think about dynamics—just some very simple concepts. We see most metal deposits associated with convergent margin scenarios, certainly in the copper and gold space, and we really have two end member scenarios. We have the steep subduction that goes on most of the time, with extensional geodynamics, but then we have these anomalous environments of flat subduction and compressional geodynamics. The way I would summarise it is: steep subduction is most of the time and flat subduction is the most important time.

UPPER MANTLE FERTILISATION PROCESS
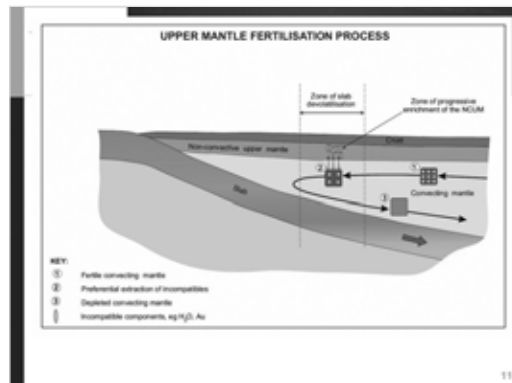
I think flatter subduction is a very favourable environment for metasomatising and enriching the upper mantle. This is a firstorder process. What we are trying to do is partition incompatible elements—and gold is one I am particularly interested in—from the convecting mantle into the upper mantle. The best way to do this is in a situation where the thermal structure of the mantle wedge enables us to just partially melt this material so that it is enriched in gold and then concentrate it in a volume of lithosphere, which is non-convecting. So the key thing is partitioning from the convecting mantle to the non-convecting mantle. I actually use the term 'non-convecting upper mantle' rather than 'subcontinental lithosphere' because we now know that these domains can occur in fairly complex accretionary orogens and end up underlying juvenile arcs, so the term 'sub-continental' does not seem appropriate. So it is important to make that distinction.

A General Model for Ore-forming SOC Systems
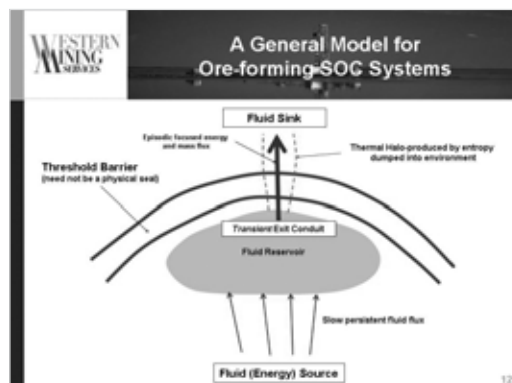
The next point that I would like to speak to is this concept that ore-forming systems can be considered as self-organised critical systems—and I use the term 'self-organised critical system' in the sense of the Bak *et al.* 1987 seminal paper on these systems; it has been a very important concept in the physics community. Perhaps this is an example of what Phil McFadden spoke about regarding the need to translate ideas and concepts from other disciplines. It is a funny thing because complexity science, in my view, is probably the most exciting science in the physical and natural sciences. As economic geologists we have largely ignored it, yet the primary example that physicists use of self-organised natural systems is the Earth's seismogenic crust in the Gutenberg–Richter relationship. I do not have much time to spend on this, but the key point is that, if we have a slow and persistent energy flux—energy here is mediated by fluid—and if we have some sort of threshold barrier, we can organise that into a focused conduit; and the hypothesis is that these focused transient conduits of energy output and mass output are, in fact, what form our ore bodies. The very important targeting implication out of this is that the critical and essential ingredient in our models must be the presence of a threshold barrier; it may or may not be a physical seal. It is a central element to the model but has been totally absent from economic geology thinking until now.
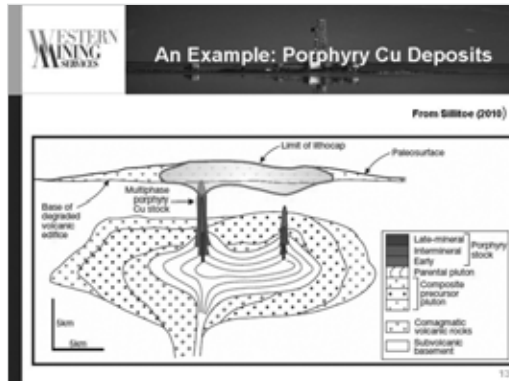
Here is what I think is a really nice example: porphyry copper deposits, which are some of our best studied deposits. We can view them simply as a tank, an over-pressured reservoir, with the threshold barrier being physically the carapace but more broadly the geodynamic scenarios that keep those magmas down and prevent them erupting in extensional events and big eruptive events, and then the episodic and transient exit conduits, which are these porphyry stocks, which represent the exits—the 'avalanche events', to use the terminology of the physicists.

If we then think about threshold barriers and related over-pressured fluid reservoirs—as I have said, they are critical new elements in our model that are implied by this—I can think of three scenarios that are very common, and empirically we see them all the time, that have to be an essential element of our targeting model. The first is an antiformal seal, which is a very obvious way to get an over-pressured fluid reservoir. Anyone who works in orogenic gold knows that any significant orogenic gold deposit is always associated with an antiformal culmination. It is a very robust empirical parameter in that model.

If we look at basin-hosted mineralisation of all types—sediment-hosted base metals, uranium—we all know that being on the edge of some sort of horst block is a critical targeting ingredient; so I am not just talking about a major fault but a major fault on the edge of some sort of horst block. It seems to me that, if you have some sort of permeable aquifer unit overlaid by some impermeable unit and impermeable basement, this would be a very good way also to produce over-pressured reservoirs which then feed ore systems higher up. Then, of course, intrusion carapaces will also depend on the geodynamics to keep those things down there.
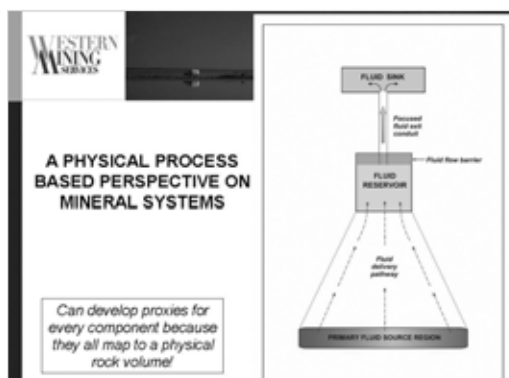
I think another concept that we need to continue to focus on or to focus more on is the mineral system idea—and many people have advocated that over the past decade or so—but I think we have been a little confused between the chemical and physical processes. What I think we need to do is to focus on a framework to depict, describe and anchor our understanding of mineral systems that is fundamentally founded in physical processes; and I would argue that there are only six elements that represent, for pretty much any metal deposit that you can think about, the generic physical components of that system. The really important thing from a practitioner's perspective is that, in principle, you can develop proxies for every one of these components because they all map to physical rock volumes. That does not mean that chemistry is not important—and we will come to that in a moment—but the point that relates to this is that, in terms of targeting, we have to start off with the big picture and come down to the small picture. We can spend a lot of time trying to understand the deposit, but what we really need to know is: what is this fluid delivery pathway system that is delivering fluid to our deposit? What works for us here is that these systems are actually very big.
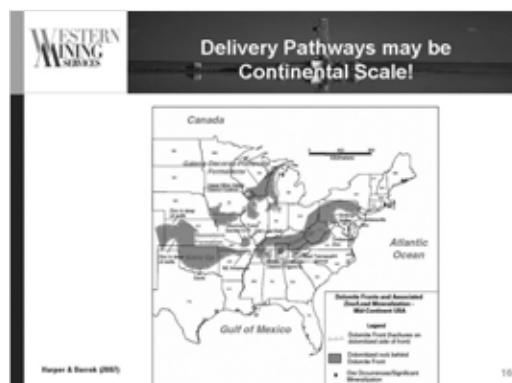
If we look at an example from Mississippi Valley leadzinc deposits in the US, you can see that all the known deposits, which are almost invisible at this scale—Mississippi Valley deposits—occur at the edge of these very extensive dolomitisation fronts, which clearly represent the signature of very large-scale fluid delivery systems. So, if you are a national geoscience mapping agency, you should be trying to map these systems out because they are very big. This applies also to 'red beds'. What are 'red beds'? 'Red beds' are just the signature of oxidised fluids flowing through sediments. The rocks did not start off red; red beds are the signal of the fluid delivery system. So you have the fluid delivery system and you map it to the architecture, and then you can say very significant things about the targeting.
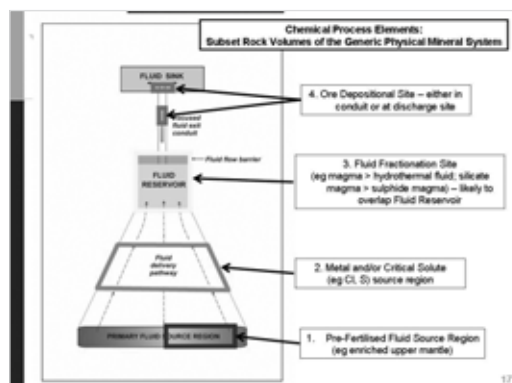
In terms of the chemical frameworks, I think the best way to handle them is that any chemical process element can still be mapped to rock volumes but they will represent a subset of the generic physical mineral system.
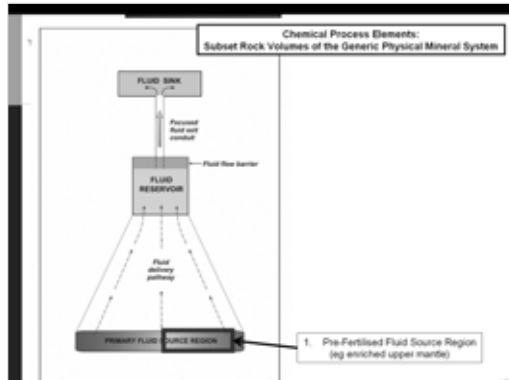
So we could have pre-fertilised source regions. I used the example of the upper mantle before.
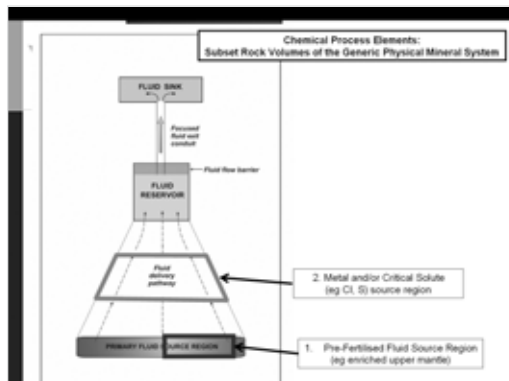
We could have some critical metal or solute source region—for example, evaporitic sediments.
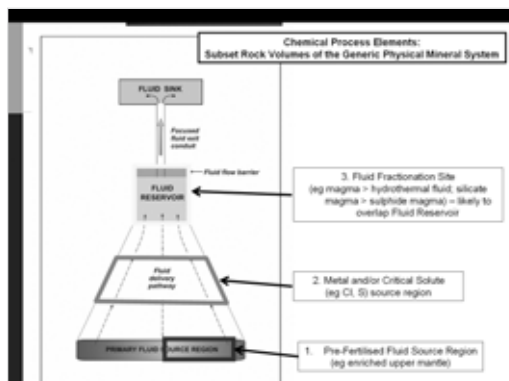
We may have what I call a fluid fractionation site. In porphyries, this is the magma chamber where we have a transition from the picritic melts from the mantle to a hydrous copper-bearing fluid or from a mafic melt to a sulphide melt, in the case of nickel sulphide systems.
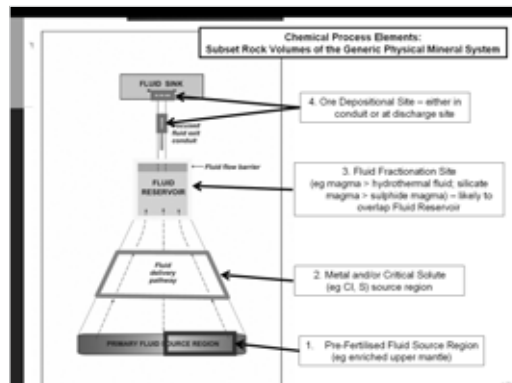
And, of course, finally the fluid exit conduit. Then we need an ore depositional site and that is going to be either in the conduit or at the discharge site.
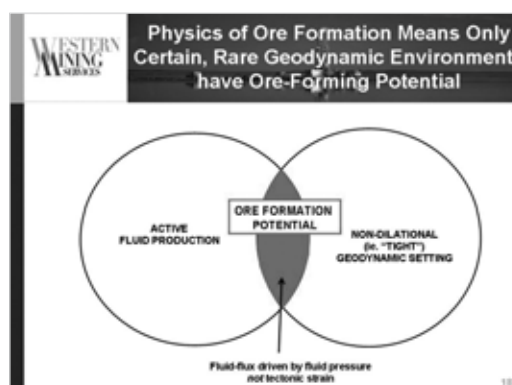
There are a couple of other things though. If we think dynamically and think about the physics of ore systems, we realise that there are only certain very rare geodynamic environments that have ore-forming potential. They are going to be where we have the intersection between an environment with active fluid production and an environment that is what I call a 'non-dilational' or a tight geodynamic setting. The reason is that it is only in that intersection of those two spaces that our fluid flux will be driven by fluid pressure, not tectonic strain; and it is only in that space that the fluid flux will organise to make an ore deposit.

I think those scenarios are rare, but I think the four main scenarios are: incipient extension; transient compression; switches in far-field stress, which are very important—the reason that the switches are important is that, as you switch from one stress state to another, you transiently must go through a neutral space and it is in that neutral tectonic space that the fluid pressure can organise; and, lastly, the very terminal stages of an accretionary orogen. So it is a very small subset of our geodynamic history.

Example:
Tampakan District, Mindanao

Red area = amount of convergence partitioned into intra-plate shortening during subduction reversal. From Rohrlach (2002)

A really nice example is from Bruce Rohrlach's work on Tampakan, where he resolved the convergence across Mindanao and the complexity of plate movement there. Anything that he could not assign to plate movement—which is in red—he said must be compression. Also, he showed very clearly that the timing of the mineralisation clearly correlated with the peak of compression.

O'Driscoll Lineaments
Map of image-diffused Bouguer gravity contours (O'Driscoll, 1986)

This or a similar slide has been shown before by Neil Williams, and as Neil said, it was controversial, but I think we really have to go back to this topic. These are O'Driscoll lineaments or the lineaments that Tim O'Driscoll focused on that were relevant to the targeting of Olympic Dam. As I have said, I am a practitioner; not a theoretician. I do this work for a day job using the most modern up-to-date technology—seismic tomography and all the datasets that we have—and, when I work in, say, Central Asia or north-west Siberia, I still need O'Driscoll lineaments; they are there and they are controlling the giant ore deposits. I have perhaps been sceptical at certain times in my career; but looking in areas in Central Asia, where there are the super giants, you can see that they are being controlled by these features. So I do not think we can continue to brush this under the carpet. In fact, I am going to suggest—and it is just a speculative hypothesis—a model that reconciles this with our current framework.

But I would highlight just one point. The critical thing about O'Driscoll's lineaments is that when your data get smoother, the appearance of the lineaments gets sharper and you can see them better. So remember: it is a characteristic of these features that they are sharper when your data get smoother. You might think that, if you could just get deep seismic tomographic data or whatever, they would become sharper—but, in fact, they do not. The higher the resolution of your data, the more they start to disappear, and that is important.

In summary, I have to say that these things are not just the deep tapping structures that I talked about before, though they may constitute some of these things as segments along their elements. They have two key characteristics. The first is that they transect orogenic collages where there clearly has been significant differential motion between blocks. That was the big problem for Tim and plate tectonics, because he felt that he could not reconcile the two, and I actually think you can; they are not simply some fundamental feature in the basement. The second characteristic is that they become more obvious in diffuse datasets.

So the bottom line is that they simply cannot be just the manifestation of a single deep structure at depth. I am going to propose an alternative hypothesis, once again borrowing from complexity science, which I think has a lot to say about these things. I am going to propose that these lineaments represent emergent patterns of self-organisation in complex tectonic environments. In other words, if you can imagine a complex accretionary collage—most ore deposits do form in very complex tectonic environments and not in simple continent–continent collision-type environments, and everything is jostling around and the blocks are constrained: they extend and they come back and whatever—there may be patterns of organisation in how those blocks behave once seeded, perhaps very early in the Earth's history, that then continue to propagate and organise those patterns throughout geological history; and I suspect that the actual process which might link those patterns of organisation to ore formation may be enhanced mantle convection at slab tears.
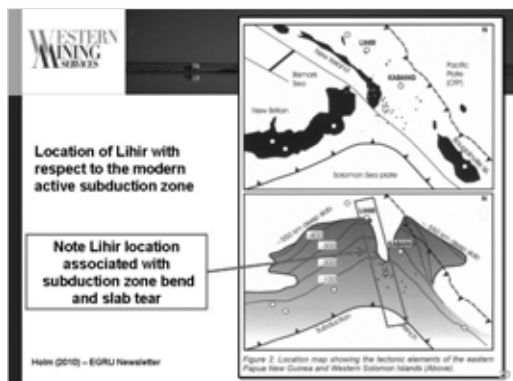
This is just to show you an example of a Lihir deposit—we keep coming back to Lihir because it is almost forming today, so it is our best example—and to point out that the deposit is associated with the bend in the subduction zone and a slab tear; so it is a lineament in formation.
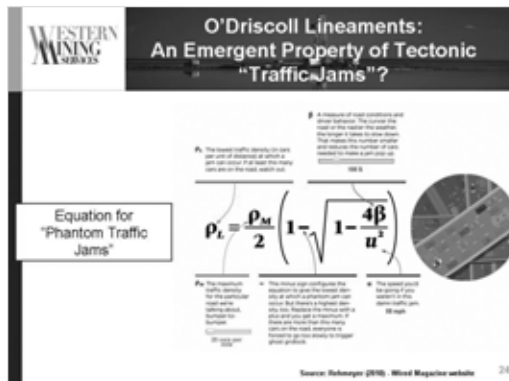
The analogy might be phantom traffic jams, which we understand are emergent properties of the complexity of cars on a highway. Are O'Driscoll lineaments the product of tectonic traffic-jams?

Anyway, I seem to have run out of time, so hopefully I have provided some food for thought for our discussions.

Discussion

Tim Baker: Richard, when you show that information about the cost of a tier-1 deposit being $2.6 billion, is the reaction from mining companies to say, 'Well, maybe we should focus that money into technology advances rather than looking for high-risk mineral deposits'?

Richard Schodde: No. Their response is usually to go and buy somebody else's discovery. It is scary when you see $US2.6 billion for a discovery. You really have to do the economics and the sums and say, 'Well, am I getting $2.6 billion worth of value out of my exploration activities?' The answer is that you do get some second and third prizes along the way and they pay for some of the costs. But the main game and the main value is associated with those tier-1 discoveries. So the real challenge for us is how do we get the cost of discovery down from $2.6 billion to something a lot more reasonable than that? Companies tend not to think about technology, and this is an unfortunate thing as well. I do not want to talk about individual companies in particular, but a lot of them basically look at each other and say, 'We want someone else to invent the next breakthrough; we want to be followers rather than innovators.' I think that is a broad challenge for the industry.

Jon Hronsky: There is one comment I would make on the $2.6 billion. Remember, whenever you see those datasets, they are bimodal. So what you have is a few people who do it well; as for the rest of the industry, it is infinite, effectively, because they do it very, very poorly. So these averages are relevant to the scale of Australia or whatever; but, from the corporate decision-making point of view, it is bimodal: you are either on one side of the fence or you are on the bigger side of the fence, where pretty much you are wasting every cent.

Steve Micklethwaite: You had those three points, Richard. The first one was that our exploration has to be innovative and efficient; and the second one, I think, was that you wanted exploration to be cheaper. I know that we have a CRC that is exploring very effectively at the moment, but I wonder whether the biggest stimulus for exploration would be cheaper technology in mining to enable mining to a 5kilometre depth rather than to a 1- or 2-kilometre depth, as there is in Australia at the moment. In the Witwatersrand it can get down to 4.5 kilometres

Richard Schodde: This is a complex issue. But, when you think about the discoveries of copper and other deposits, a lot of deposits get found and then it takes 30 to 50 years before they actually get into production. That is not really a good use of your money as an explorationist. What you have to look for is deposits that go straight from discovery to development. How do you shorten that lead time? The best way to do that is with the quality of the deposit. A lot of deposits get found—in the copper case you have 0.3 to 0.5 per cent copper—and then sit on the shelf for 30 years, waiting hopefully for technology innovations to come along to fix them and also hoping for a business cycle where someone is optimistic or silly enough to build the mine. But you will notice that the projects that go to the front of the queue are those with the best grades and largest tonnes. Really, as explorationists, the challenge is to make sure that the things you focus on are in that end of the curve; so quality always rises to the front of the queue. So, as an explorationist, sure, technologies can lead to new openings-up of deposit styles, but at the end of the day you still have to focus on quality deposits.

Innovation and new technology

Current issues for the future of innovation and new technologies in minerals exploration

Dr Tom Whiting
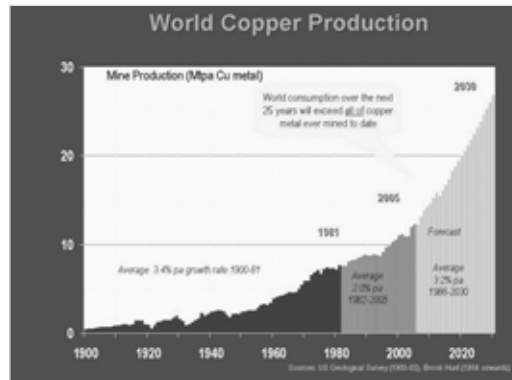
This is a good slide to start with because it is demand arising from the industrial development of China, and to an extent India, that is really driving the minerals industry today; and what is driving the minerals industry is also driving technology development and innovation in the minerals exploration industry in Australia today.

The current boom in commodities demand is very good for Australia. Currently, minerals exports account for roughly 50 per cent of all Australian exports; however, 80 per cent of that production comes from discoveries made more than 30 years ago, prior to 1980. In effect, the industrialisation of China and India is driving a massive production expansion; but the production expansion, as we have already heard today, is from known world-class deposits. That has been driven by successful brownfields exploration discoveries, which we have been very good at. I have to say—brownfields exploration has saved our bacon over the past 10 years—along with innovations in mining and processing technologies. However, this is having a dramatic impact on the existing resource inventory of the country and its quality, and that is due to the interplay of increasing commodity production rates and the longer-term decline of greenfields discovery rates for world-class mines. So the challenge for us today and tomorrow is obviously to look at new technology and innovation with the aim of not just sustaining Australia's market share but also to capture some of this future growing market for our commodities.
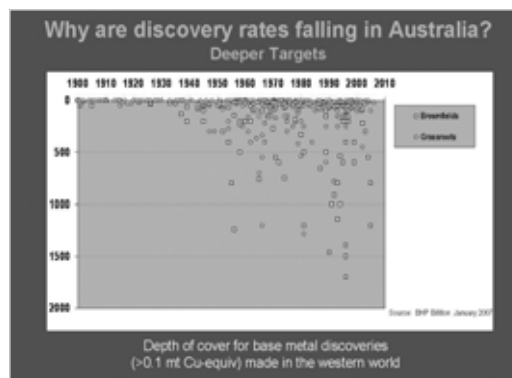
In order to continue to make discoveries, particularly in the western world, the search is going deeper and it is focusing increasingly on brownfields settings at the expense of greenfields exploration. As you go deeper, all the factors that led to post-war exploration success in shallow terranes are much less effective. At depth you no longer

have comprehensive geological maps to help you determine prospectivity. Rapid reconnaissance geochemistry no longer works to focus onto the search zone and onto the target. Also, geophysical targeting tools are less effective as you go deeper, as most techniques have rapidly diminished resolution with depth. And, probably worst of all, it is more expensive to test deep targets and exploration concepts. The tendency is to drill less and to drill fewer targets. If you do not drill, you do not discover, and you can see that in our statistics. The effective drilling per dollar has dropped off markedly over the past decade. The other effect is that Australia is losing ground versus the rest of the world as a lower proportion of global dollars is being spent here.

Of course, our industry is responding to these challenges and, over the past few years, I have had the opportunity to canvass industry via an Australian Mineral Industries Research Association Limited (AMIRA) project, which eventually led to the formation of the new Cooperative Research Centre for Deep Exploration Technologies (DET CRC). This process highlighted what industry currently sees as its priority areas for new technology and innovation to help make the necessary breakthroughs to address the issues outlined in the first couple of slides. By the way, all of the companies and groups associated with the CRC are listed here and the picture is of Richard Hillis, who is the CEO of the CRC, which is based in Adelaide.
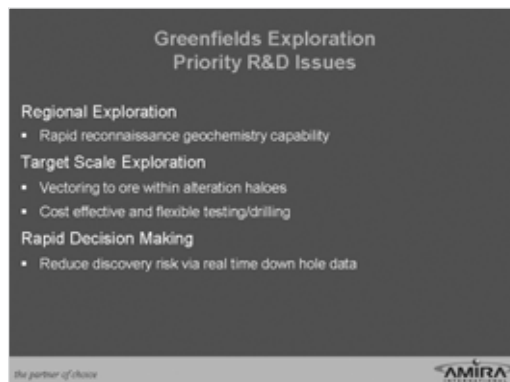
I am going to break these priorities into two areas. The first area is priority issues for R&D in greenfields settings. I think Jon Hronsky covered quite a few of the regional issues about how you focus onto a prospective area, so I am not going to talk much about that. In fact, if you look at what industry feeds back to us in the engagement that we have had with them over the past few years, probably the regional tool that they miss the most is the lack of ability to rapidly focus in on a target area using geochemistry. If you have a very thick transported cover or barren overburden, you just technically cannot do it. I will say though that industry is fatigued in this area. It has spent 10 to 15 years testing surface techniques for everything from partial leach to everything else and nothing has really worked; they're saying, 'Well, we'd really love to have this stuff, but we're exhausted; we're kind of at the end of the road.' It is a big area. The CRC is going to look at this area; but I am not going to go into the details of what is proposed there, because we do not have time.

At the target scale of greenfields exploration, vectoring to ore within alteration halos is a very high priority. Think about it: if you drill a deep target in excess of 300 to 500 metres through barren cover and you hit an alteration system, you have just spent hundreds of thousands of dollars to get that hole and you have some alteration.

The question is: 'what does that mean; where do I go next?' Do I have to drill another 20 deep very expensive holes?—which, typically, history shows that you have to do, or can I be more effective in determining where to vector to the ore body?

Another key issue with target-scale exploration, is cost-effective and flexible testing and drilling, and that is very much related to the last issue. If we could do that cheaper and more cost effectively, we would have a major leap forward in our ability to drill out interesting alteration systems and make discoveries.

Related to this is the other area of major interest to industry, rapid decision making; which effectively would cut discovery risk. One of the key things facing the industry in Australia at the moment is slow access and rising societal and bureaucratic hurdles. These are driving the need for real-time data to enable rapid decision making, particularly from down-hole information.
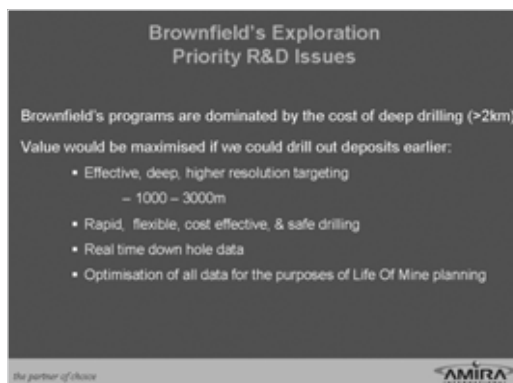
In the second area, the brownfields area, the priority R&D issues are really driven by mining technology innovations that will allow much deeper mining. Those innovations are happening now, but they need to be matched by exploration technologies to discover deep deposits. Brownfields programs today are dominated by the cost of deep drilling, often in excess of 2 kilometres. This is being driven by the current high commodity demand and the fact that we are going through massive expansions of existing world-class deposits; for example, Escondida is in its 13th expansion. This is taking mining of these deposits much deeper. Value would be maximised if we could drill out deposits earlier. Olympic Dam has been talked about a lot here today and the expansions that it is going through. We still have not found the economic edges of that deposit 35 years after its discovery and the mill is about to be pulled apart and shifted. How many times do you hear of that happening with a world-class deposit? It would really increase shareholder value if we could understand the full extent of deposits earlier. So, effective deep and higher-resolution targeting, typically to 1000–3000 metres, is seen as a very high priority. Most of the techniques that we are using now do not have sufficient resolution at those sorts of depths. Rapid, flexible, cost-effective and safe drilling is also extremely desirable as is real-time down-hole data, again, to make faster decisions. Another is the optimisation of all of these data for the purposes of life-of-mine planning so that that becomes far more efficient.

I would like to show you a video that really captures the vision of the new CRC and some of these issues. It is a vision of how we do things now and what things might look like in the future The video largely focuses on the drilling and real-time data acquisition parts of the wish list from industry rather than on regional targeting. I would like to acknowledge Barrick who helped put together this video.

Well, how do we do it now? The first example starts off with a fairly remote mountainous area where we have defined a greenfields target, probably derived from an inversion model and we have to test that. Currently this is a very slow, clumsy and dangerous process, with high potential impacts associated with the initial drill hole. If the initial drill holes intersect economic mineralisation we have to drill the deposit out; that means putting drill pads all over it and drilling through a lot of barren rock in the process. A much better way to do it would be to have an innovative rig, such as a coil rig set up in one spot. This would potentially involve drilling one mother hole with many multilaterals off it, and collecting real-time data down these holes, which would allow us to assess the potential faster. This would be achieved by sensing around and between the holes and sending this data off in real time to a remote site for processing; subsequently updating the constrained inversion model and looking for extensions and, in a very rapid time frame, being able to test those extensions and, thereby, drilling out the target at a much faster rate.

The second example is more relevant to Australia. In this case we have a greenfields target around a historic urban

centre such as an old mining town or a salt lake where access is difficult. The target is deep and under barren cover rock. Again, we want to minimise drilling through the barren cover, which is a waste. We want to get the data in real time to know whether our first hole is of interest or not. We want to sense and update the model and drill possible extensions or maybe vector to ore faster.
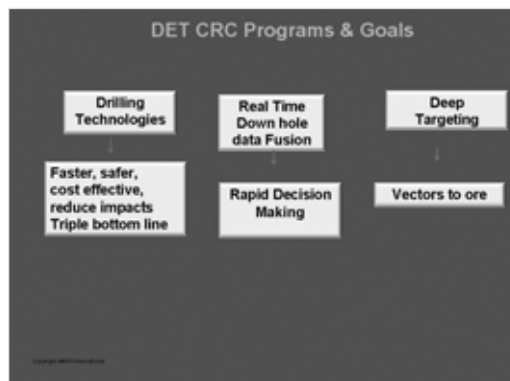
The DET CRC comprises, pretty much, three programs. They are focused on faster, safer and more cost-effective drilling technologies—reducing triple bottom-line impacts in the process; real-time down-hole data fusion to help make rapid decisions; and deep targeting, largely focused around vectors to ore.
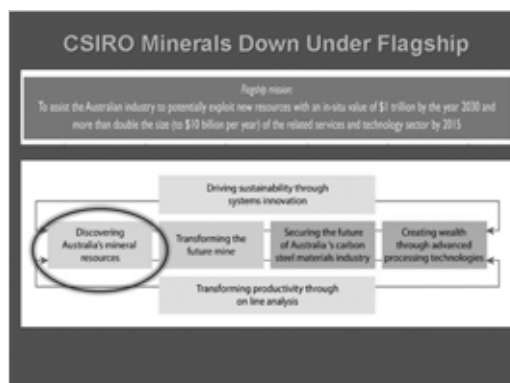
Of course, the DET CRC is not the only initiative currently underway in Australia or, for that matter, in the world. There are many other important research initiatives involved in technology and innovation that are well thought through and focused on industry's concerns. A major one is CSIRO's Minerals Down Under Flagship, which has programs right through the value chain from exploration through mining technology , processing and even sustainability issues. Programs include 3D imaging and target generation at depth based on predictive modelling, which has a different focus from the DET CRC but is related. Other programs are focused on new technologies, both geophysical and geochemical, to see through barren cover. There is also a very important program in global leadership of precompetitive geoscience data, which links in with yet another initiative, AuScope, which is a national data-sharing infrastructure project, the aim of which is a geoscience and geospatial system to transform our understanding of the structure and evolution of the Australian continent. They are not the only initiatives happening in this country, as many universities are involved in new technology and innovation in this space: for example CET at the University of Western Australia and the ARC Centre of Excellence in Ore Deposits (CODES) at the University of Tasmania.

The question is: will these R&D initiatives ensure success in the future? I would contend that ensuring a flow of information results across all these initiatives and organisations involved in minerals exploration new technology and innovation in a systematic and strategic way will be central to success. This will really involve open innovation; in other words, it will involve the sharing of information in a very open manner. Lots of smart people are spread across multiple institutions, disciplines and industries, globally. Open innovation is permeating new business models everywhere, blurring the boundaries between individual companies and research and development efforts. I know of a company whose mantra for its R&D development used to be: 'plagiarism from within and plagiarism from without'—in other words: leverage ideas from anywhere and anybody and make them work. Whatever works! That is open innovation in its truest form. Hopefully, if we take that model, it will lead to a new era of collaboration, which I

think we are starting to see the beginnings of, and ensure success from these numerous related research initiatives.

For the workshop this afternoon, we need to address a number of questions. One is: there is both new technology and then there is innovation; it is important to think of the two as related but separate. New technologies come from invention, so an obvious question is: where are the gaps in our current effort in terms of technology? On the other hand 'Innovation is a change in the thought process for doing something or the useful application of new inventions or discoveries'. That leads to the question: 'are there existing technologies that can be adapted to our needs?'
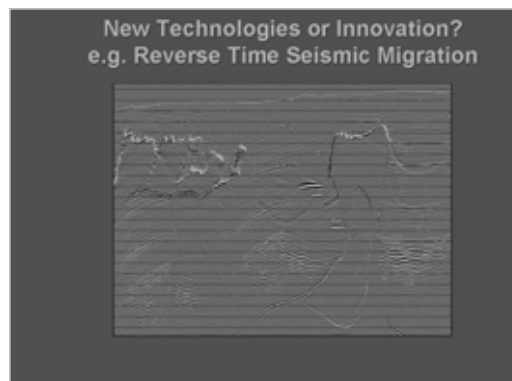
I think there are some obvious examples of where there are opportunities to adapt existing technologies. We do not have to look very far; we only have to look at the oil industry to see who has become very adept at higher-resolution imaging of the top 5 kilometres of the Earth's crust. As a minerals industry, we have always thought, 'Well, yeah, they've got nice layer-cake flat geology and soft rocks and seismic works well on that.' But, looking at the latest information—this comes out of the deep-water Gulf of Mexico—you will see some of the structures there are very complex 3D features that they have a very high success rate in imaging in great detail. With vertical interfaces such as the ones that we deal with, they use techniques called reverse-time seismic migration. So can this technology be adapted to hard rocks? 3D seismic is actually an important part of the new DET CRC.

Another is drilling innovations. I have mentioned coil drilling and this is a coil rig; they exist and are widely used in the petroleum industry. They are used for deposit drill-out, which involves mother holes with extensive use of multilaterals—often flat drill holes. Could this represent a step change? Also, this technology is being used increasingly in the coal-bed methane industry. I think a good analogy here is that, if our regional technologies do get us into the right areas and targets, perhaps we can start to behave more like modern surgeons: we know where the targets are so can we go in with keyhole technology such as coil drilling to test and drill out the targets in a more effective manner rather than our current slow, laborious testing and drill out procedures that are both inefficient and can make a large mess. But can these technologies be adapted to the hard rock environment? I acknowledge it is not an easy problem to solve but then that is the purpose of new technology and innovation research and development—to solve the necessary hard problems.

'Innovation is invention implemented and taken to market'. That definition is from the Harvard Business School. In other words it is new technology in use. There have been significant changes to the mining industry's structure over the past decade such that a lot of functions that used to happen in the mega mining companies, like BHP Billiton and Rio Tinto, are now handled through the services sector and provided by service companies. In fact, service companies are one of the most rapidly growing and important sectors in technology use and delivery in the minerals industry today.

This now requires new innovative business model or models to ensure success in the actual implementation of new technology. A lack of such a model or models is often why great sounding technologies never see the light of day; they get stranded because you do not talk to the right customer, that is generally today, service companies to the mining industry.

We have another example here in terms of how to solve the problem of technology transfer. We do not need to go much past the oil industry again. Oil research seeded very large global services businesses, such as Schlumberger, Halliburton and Baker Hughes. They are orders of magnitude bigger than those of the minerals sector service companies. That may be somewhat related to the oil business itself, but I think there are some lessons in how they have managed to become extremely efficient in the way that technologies are taken to market. Can this be replicated in the mineral services industry? Of course, many other industries have similar technology and delivery systems that we could learn from; the medical and defence industries are cases in point.

Delivering Minerals Industry Innovation
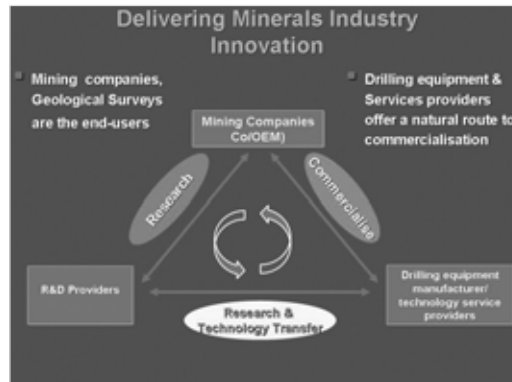
In terms of delivering minerals industry innovation, I think we need to get a model somewhat like what is represented in this triangle diagram—and this is the model being used by the DET CRC. We have obvious end-users, such as mining companies and geological surveys. We have R&D providers such as CSIRO and the universities. The traditional connection for technology development has been between the mining companies and the R&D providers. But given the evolution of industry structure that has taken place we do need to pull in drilling equipment manufacturers and technology service providers, who are the source of the services to the mining companies and the more obvious customers for commercialisation.

There are some good examples of where this has worked. Falcon, the world's first airborne gravity gradiometer, was one that used this model: BHP Billiton was the mining company, the R&D providers were Lockheed Martin/Bell Aerospace and the service providers were Fugro and Sander Geophysics. That equipment is out there flying today; it is available to the industry now. Delivery of this extremely innovative technology to market was very efficient because it involved all three key components in the development and delivery of new technology to the mining industry, i.e. the mining industry end-user, R&D providers and service provider. Possibly the innovative leap in terms of Falcon was that the Falcon technology was brought to the market with an innovative business model as well, which sought to do joint ventures with the technology. It has yet to deliver a major world-class discovery and you might argue that perhaps a better way of implementing the technology would have been to have had a continental-scale high-resolution mapping project using the new airborne gravity gradiometer technology. I have no doubt that that would have led to discoveries as the key was always to cover prospective ground on a grand scale.

Finally, where to from here? I guess that is what the rest of the day and tomorrow is about.
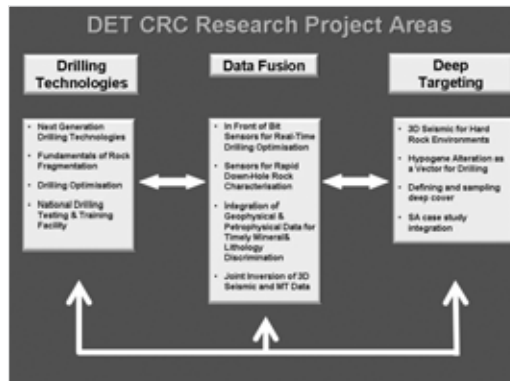
As you can see, we are not finding enough new mineral deposits; our plan is to find giant ones under cover—and it is over to you.

Exploration policy – the way forward

Society and exploration: Considerations for now and into the future

Peta Ashworth

I want to get the lay of the land and to learn something about the people in the room, so I would just like you to put up your hand to answer the following questions. If you have ever ridden a bike without a helmet, put up your hand. There are a few risk takers in the room. Is there anyone who smokes or has smoked in their previous life? Okay. What about having sent a text while driving or perhaps used a mobile phone without your hands free? Some of you are honest! What about having driven just a couple of blocks home when you might have thought, 'Ooh, did I have too much to drink or not?' Hands up. I just want you to hold that thought because, really, what we are exhibiting here is our ability to take risks within society. We all do it on a daily basis.

Let me tell you little about our group—the Science into Society group within CSIRO's Division of Earth Science and Resource Engineering. Our early research focused on the emergence of carbon dioxide capture and storage as a mitigation option for coal fired power stations. The CSIRO was keen to understand the social perceptions of risk about this new technology and whether it was a technology that researchers within CSIRO should be focusing on. Since then our group has grown from three to 18 in the past five years, as we have looked at many of the complex issues that Australian society is grappling with. We use a mix of qualitative and quantitative methods, which many of you would be familiar with. But I think the big thing that our focus is on is how to deliver information to best effect. We tend to use a participatory action research approach to engaging stakeholders. Depending on the issue, they can be anything from policymakers to indigenous groups to lay citizens anywhere in society. We try to ascertain their concerns based on the particular issues and where appropriate translate that back, not only to policymakers, but also to the technology developers and so on.

The value of social research and communication

- A major risk to technology adoption if there is no appropriate engagement with stakeholders during the development process.

- Public attitudes to new technologies can change over time however, once formed they can be slow to change

What is the value of social research, especially in the Division of Earth Science and Resource Engineering? We are quite a distinct little group, alongside all of the technical and engineering folk that we work with. However, despite our differences, I think we work quite well together. Much of the success comes from the first point, and I think we would all admit, that there is a major risk to technology adoption if there is no appropriate engagement with stakeholders during that process. The other thing that I have really learnt and focused on through lots of different experiences is that we know that public attitudes change, but once formed they are very hard to change. So what I am going to try to encourage is that, the earlier you can get in and start having conversations with key stakeholders in the community, the better it is. That little cartoon on the side came from a colleague, Jeremy Kranowitz, from the Keystone Centre, which is all about negotiation. I am hoping that, going forward with projects, you don't use that approach and that we are confident in the outcome because we have engaged stakeholders effectively.
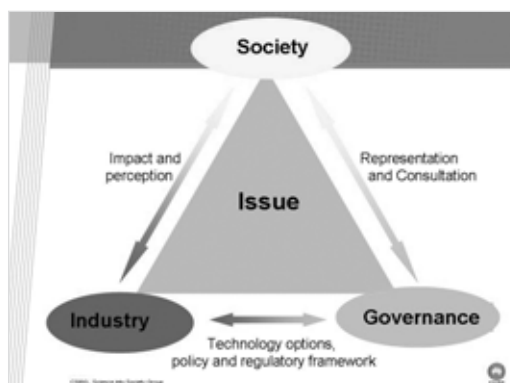
I think the triangle is a really nice way of looking at the issues. We have society, industry and governance as the three elements on the corners of the triangle. In the middle of the triangle, there is an issue: is it a new technology; is it a new industry; is it just a new process that is going to use all sorts of new chemicals that people do not necessarily know about? What we really need to be aware of is that making a change to any one of these three will impact on the others. So for new technologies or new processes all three need due consideration. I recently wrote an article that looked at the role of the regulatory regimes for mandating stakeholder engagement. There is a critical question about how much should we legitimise engagement through regulation or how much should organisations go beyond compliance and engage because it is the right thing to do?

NIMBY: not in my backyard; PIMBY: please in my backyard. These are two concepts that we come across quite regularly. I want to take you on a little journey. Imagine you live in the Hunter Valley in New South Wales and this is your wonderful farm house; it has been in the family for years. In fact, your children are the fourth generation to live in this house. Your parents are still alive, but they have moved down to a smaller, more modern house on the farm nearby. If asked, you would probably describe yourself as a cattle farmer; but over the past 20 years, with the growth in the Australian wine industry, you have diversified—at great investment I might add—and planted several hectares of vines. These have recently become quite productive and you are excited at the prospect of the income that they are going to bring. However, last week you were listening to ABC Radio and you heard that the Australian Government has announced that a new geothermal power plant is planned for your area and exploration is due to start very soon. It has not been confirmed exactly where the location will be, but it could be on your farm. After the announcement on ABC Radio, there was a flurry of callers with concerns about impacts on water, seismicity—'wasn't there a great earthquake at Newcastle; are we at risk here; what does that mean?'—and subsidence: 'Does that mean my vines are going to go; what will happen to our lovely farm house? It has been in the family for years.' So your concerns begin to rise: what is it going to mean for you, your friends and your livelihood? So you pick up the phone to ring the local mayor.

I just wanted to use this example because I think too often that sense of place and prior experience can be overlooked by the fact that we are familiar with our process: 'We know it's safe; we're just going to come in and get the job done.' But I think we need to take into account the considerations, perceptions of those in the community who will be the recipients of the new technology, process and so on.
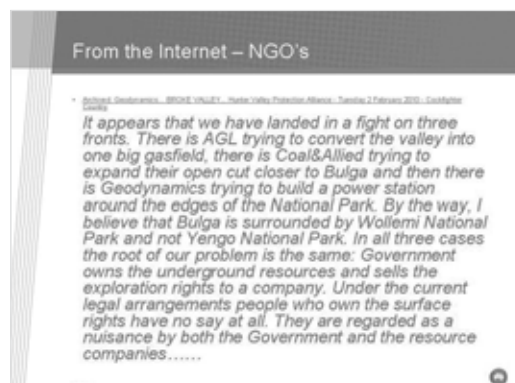
This is just the very top part of an article that came from a group of people who were concerned when a geothermal plant was announced recently and I thought it would be worth sharing how they are reacting in real life.

'It appears that we have landed in a fight on three fronts. There is AGL trying to convert the valley into one big gasfield; there is Coal&Allied trying to expand their open cut closer to Bulga and then there is Geodynamics trying to build a power station around the edges of the National Park. By the way, I believe that Bulga is surrounded by Wollemi National Park and not Yengo National Park. In all three cases the root of our problem is the same: Government owns the underground resources and sells the exploration rights to a company. Under the current legal arrangements

people who own the surface rights have no say at all. They are regarded as a nuisance by both the government and the resource companies…'

These are valid concerns that people hold. I think what is being characterised by any new emerging issue or emerging technology is that quite frequently NGOs, community organisations and other groups may form a collaboration to voice their concerns. However it is important that we recognise and acknowledge their concerns. And the big, critical thing is how we go about addressing those concerns.

If we go back to that question about risk, it really is about perception. Think about the old penny farthing: when it was newly invented, were people brave enough to try it? Alternatively, I don't know how many people here snowboard regularly. It all depends on what is within your realm of safety. What is the risk you are prepared to take? What is the risk you are prepared to live with?
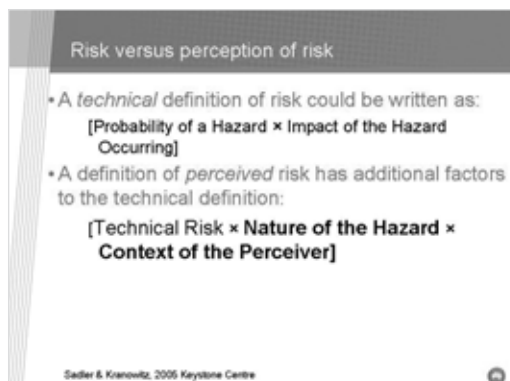
All of you, I am sure, are very familiar with the definition of 'risk'—the probability of a hazard versus the impact of the hazard occurring.

We need to think about the perceived risk in there as well. So what is the context of the perceiver? This can be anything from the fact that you have lived with the coal industry, you have lived with oil and gas and you have lived with mining in your area for some time and you have a respectful relationship with that company; or you have had someone come in who has not done it right and you have a negative view; or you know nothing about the technology or process being proposed. All of these things are going to play on how successfully these new technologies interact with society, and we are seeing a lot of that now with several of the industries that we are working with.

Risk perceptions

- Stakeholder positions about new ideas and technologies are arrived at through a series of decisions that are made when assessing the risks and benefits of a technology, as well as its moral acceptability.
- Perceptions of risks are heightened when the risk is
  - unknown,
  - catastrophic,
  - felt immediately,
  - uncontrollable, and
  - can harm other people (Slovic, 2000)

There is some well-known literature around risk and risk communication. For example, Slovic identifies the critical questions about whether something is seen as risky or not will be impacted by the following questions: is it controllable; is it unknown; are there likely to be catastrophic events or perceived catastrophic events; could the effect be felt immediately; and what effect is it going to have on my friends and family? All of these things will impact on how that new technology or process is perceived. I think the important thing is to recognise and treat each of these as valid concerns.

Management of the social risk

- But, *management* of risks is the critical factor for public acceptance
  - How can we **have a say** in what happens?
  - Will the process be **fair** and will anyone **listen** to us?
  - Can we **trust** the project developers and government to take care of problems
  - What have our **previous relationships** with these entities shown us?
  - What is the **benefit** to the community
  - How does the project fit or **improve** our way of life?

Bradbury, J., et al. *The Role of Social Factors in Shaping Public Perceptions of CCS: Results of Multi-State Focus Group Interviews in the U.S*

With carbon dioxide capture and storage I work with many social researchers around the world and we find similar results around the world. One of the things that emerges as important is the process that is used to engage and how it is managed. When some colleagues in the US—Judith Bradbury and others at Battelle—were looking at the work they have done with the Carbon Regional Sequestration Partnerships, there were strong similarities across the seven regions. The things that were of critical concern were: can we have a say in what happens?; will the process be fair and will anyone listen to us?; can we trust the project developers and government to take care of our problems?; what have our previous relationships with these entities been?; what is the benefit to the community?; and how does the project fit or improve our way of life? So one of the things we found is that taking the time to have the conversation to find out what communities prioritise as needs can help you frame the benefits that a project, new technology or new process might bring; it is a critical consideration for public acceptance.

Critical Issues: Time, Trust, The expert

The other thing that we have found is very basic: we are all time poor and, to engage effectively or to involve stakeholders, we need to find adequate time.

Trust is critical. So here I have used a mother and a baby because, if you ask people whom they trust, you will find that they tend to trust friends and family, their peer groups and so forth.

Also, I think the role of the scientist or the expert is critical. Obviously you would not go out with your white lab coat on; but I think it is critical that, when new processes and new technologies are being introduced, people know that there is someone they can go to for the latest, and most independent, answers.

When we are thinking about how to communicate, we start to think about what is the best way to identify the different audiences.

I classify one group as 'influential stakeholders' and it is with these people that you need to invest your resources. For example, perhaps they are the local mayor or politician and will be the ones most likely to receive lots of calls about an issue; so, if they understand what it is all about, they can give the facts to the callers to allay their concerns somewhat.

Local communities are also very important and quite often it is better to hold small-group meetings, which can be held through the schools or at local council offices if appropriate. Education is also a critical way of providing information about new processes and technologies. That can mean anything from universities down to schools, but also using other forums such as museums and science institutes. From a project perspective you also need to identify who are the influential citizens within your local community? Is it the local footy star? Is it the head of Rotary? Identifying that person or persons means that, if you engage them, and the newspaper wants to do an article, they might get some coverage on the front page and you will have a bigger impact. So it is a much easier way of getting your message out there.

The other important thing—this may not be new to many of you, but I think it needs to be considered—is to look at the stakeholders through those different groups and see who they are. Are there specific individuals that we need to think about? What is their level of interest in the project—is it low, medium or high; but also what is their level of influence? Often it can be NGOs or a journalist; it can be one individual or a group of individuals. By starting to think about the segments, you can start to work out: 'How best to engage with them?' This is another way to approach it. Once you have plotted that out, you can look at it on the spectrum of their potential to influence versus their level of interest. As for what you can then do, obviously there will be those who need the greatest effort and you can start to focus in on them.
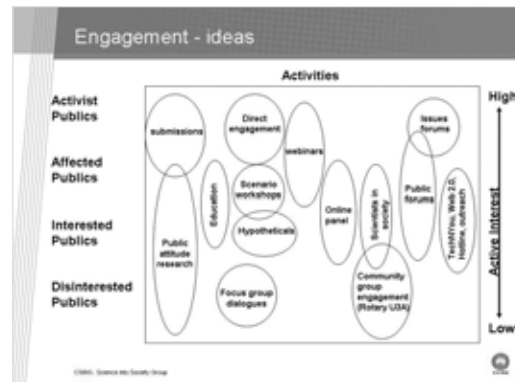
This is from a colleague, Craig Cormick, who has done a great deal of work with emerging technologies such as nanotechnology and biotechnology, and I show it because it is an interesting way of segmenting. Obviously there are those who are active, the active public, those who are affected, those who are uninterested and those who are interested. This is just a range of different engagement types that you might choose to use, depending on what the process is and who the audience is. So I really put those up just as a thought, I suppose, to think about. There is a range of ways to engage communities, but it will depend on their level of interest and where they fit.

So why should we engage stakeholders? I think it depends on the organisation, the culture and the technology and where it's at in its development. But I think there are two views. You could engage to understand the concerns of stakeholder groups and improve the social value of the organisation's business, so you see it as an exercise in partnering. But there is this other view, which is really to manage or influence the stakeholders and, hence, improve the ability to operate and reduce the risk of failure. So really you are exercising power.

In the first view, you are seeing the stakeholders as a respected source. And perhaps in the second you are seeing them as a potential interferer. How we go into those relationships will establish the way forward and influence how you end up engaging that community.

But I just want to put in a little cautionary note because, regardless of the quality, it does not always guarantee acceptance or endorsement of the project. So there are times where you could have the best engagement, the best stakeholder consultation, and I can give you an example. In Greenville, Ohio, Battelle wanted to do some exploration and seismic testing for potential storage sites, but that community did not believe in climate change: 'So why on

earth would we support the government spending billions of dollars on something that is going to mitigate climate change? We are farmers; give the money to us.' So a decision was made not to pursue that, because fundamentally it just did not work within that community. But, regardless, I think the most important thing is to start early because, remember, once opinions are formed, they can be really hard to change.

Breakout group presentations

Group A: Computational, information management and modelling advances

Rapporteur: Dr Thomas Landgrebe

I am going to start with a summary of the most important points that we made yesterday. The consensus of the breakout group was that ongoing developments in Australian computational information management and modelling advances will lead to enhanced exploration methodologies, once brought together, and we are going to touch on that point. We put a few practical scientific ideas together, as well as complementing technical requirements. Non-technically, the most important discussion points were keeping the current momentum and breaking some restrictive barriers.

Regarding the *status quo*: what currently exists? The consensus of this group was that many of the subcomponents required are maturing and are already in place. We can look at useful public datasets that are readily available, such as potential field data, geological data, geochemistry, geochronology *et cetera*. So substantial datasets exist, but this is of course an important ongoing process. Also, data is increasingly accessible and interoperable; one needs to bring together all these important factors. Facilities for large-scale computation exist and, importantly, software and simulation tools are maturing.

Issues in existing infrastructure/capability becoming effective tool

□ Group believes that the integration of all these components will lead to advances in mineral exploration...
  ■ however the various components/ resources should be allowed to mature – many are still in progress
  ■ Risk – if any "link in the chain" is discontinued/not allowed to mature, essential components and critical mass may be lost
  ■ Return on investment regarding the current infrastructure will not materialise unless the combined system matures
□ Essential to have continued support

How do we get a return from this infrastructure; and how does Australia reap some return on investment regarding these things? As I have said, the group really believes that integrating all these components will lead to advances in mineral exploration; however, the various components should be allowed to mature. A lot of them are close to completion, some are still in progress and a substantial amount of work has gone into them. We strongly believe that ongoing support is required to ensure continued momentum, and for the opportunity to be given for all these different technologies and developments to be brought together. The risk here is that, if any link in this chain is broken, an essential component may be lost, and critical mass may be compromised. Thus the most important point made here is that it is essential to have continued support going forward.

Issues in existing infrastructure/capability becoming effective tool

□ Action is required regarding computational/numeracy skills for geoscientists
  ■ Group felt numeracy education should be encouraged – should consider rewards or incentives for students excelling in this area. Need to decouple education from short-term industry fluctuations.
  ■ Current skills shortage – other disciplines? Cross-discipline pathways? Incorporation of more technical components into curriculum
□ Ensure knowledge transfer to industry and end-users

Another issue that was discussed quite extensively is regarding the increasing demand for computationally and numerically skilled geoscientists. The group felt strongly that some practical steps need to be taken here. In particular, numeracy education should be encouraged in the geosciences. The group discussed some practical steps, such as considering rewards and incentives for students excelling in this area or even choosing this area. Another important point made was that this is a longterm vision and, when it comes to education, one needs to decouple the education strategy from short-term industry fluctuations. Skill shortages are a related issue, which was also mentioned. We discussed crossdiscipline pathways as a possible way of getting the necessary multidisciplinary skills into the curriculum. Ensuring knowledge transfer to industry and end-users: it is absolutely essential to have these types of numerate skills in order to ensure this.

Issues in existing infrastructure/capability becoming effective tool

□ Discoverability of data (and software tools), especially by industry
□ Interoperating not only with data, but also with model outputs – consider updating e.g. GeoSciML
□ Setting expectations, and tangible outcomes – if potential users not aware of applicability/value of a technology, it may be in vain
□ Collaboration between various Australian groups could increase critical mass, and help develop the bigger picture. Support CRC's etc

As a lot of new data and software tools come on line, we need to make sure that the data is discoverable. Interoperability has been a hot topic over the past few years. We also want to emphasise that an essential component behind this type of research is that models are generated and the outputs of models are fed into the input of other processes. Interoperating with model outputs is something that is missing at the moment. We talked somewhat about practical methods that can be used for communicating this type of information, and suggested that information modelling and GML dialects, such as GeoSciML, could potentially be extended to cope with model outputs.

Another issue that we discussed a little was the importance of setting expectations, especially regarding industry, to ensure that we create tangible outcomes. It is important to note that, if potential users are not aware of the applicability of new technology, even if a nice piece of research has been done and some nice findings have been found—if industry is not aware of the applicability or value that this new technology can provide—it may all be in vain. The final point we made amongst ourselves was that we should all collaborate more closely because geoscience frontiers are suggesting that all these processes need to be brought together. Collaboration is really essential to get everyone's input in designing this kind of unified system.
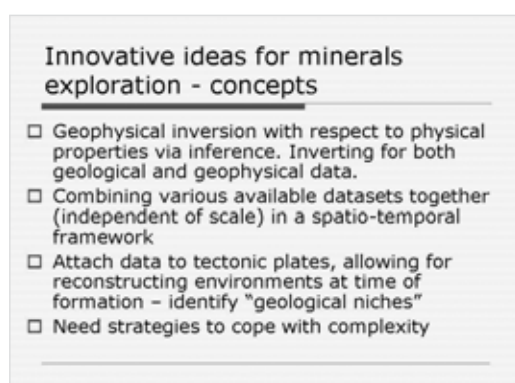
I am going to talk about some innovative ideas we had for minerals exploration. First of all, the group acknowledged that current qualitative approaches were obviously very useful for exploration, but ultimately understanding the interactions between the various geological processes may result in paradigm shift improvements in methodologies and understanding; this is the longterm goal. Importantly, there will be and should be progressive milestones along the way.

Existing data. This is a very important point, which we acknowledged after debating it for quite some time. Existing data contains a lot of unrevealed information. So we have all this data, but we have not exploited it enough. So the next step for us is really to combine and analyse the data that we have in a more unified framework.

Understanding. We spoke a little about the fact that the observations made are inherently uncertain and we also spoke about the importance of understanding the nature of that uncertainty and how it propagates through models. This is really an essential component, especially for Australia, where one has an extensive geological record stretching far back in time—and, the further back in time one goes, the more uncertainties there are. So one needs to carefully consider this data and ensure that it is analysed in an appropriate fashion.

Here are some scientific concepts that we discussed. They are quite new ideas that we believe will result in some tangible outcomes.

The group discussed the concept of geophysical inversion with respect to physical properties via inference. This data would then be inverted for both geological and geophysical data.

Possibly the most important topic that we discussed is the opportunity we see of being able to combine these various available datasets, independent of scale, in a spatio-temporal framework. Then, as Dietmar Müller discussed yesterday, a framework in which we can analyse all this data in a unified fashion would involve attaching the data to tectonic plates. This allows data to be reconstructed back in time. We then can look for examples of it. We can go back in time to when an ore deposit formed and look at the geological setting. It is this type of process that one would follow to identify geological niches, and that would just be the first step in the knowledge discovery process. Once something interesting is found, one then would do follow-up scientific studies involving geodynamic and geothermal modelling to validate geoscientifically in order to get more confidence about these niche conditions. That could result in a new predictive capability behind this type of technology.

A very important part of taking this next step is the requirement to cope with a lot of complexity. We are talking about a lot of datasets in bringing all this data together and it is fraught with a lot of complexity.
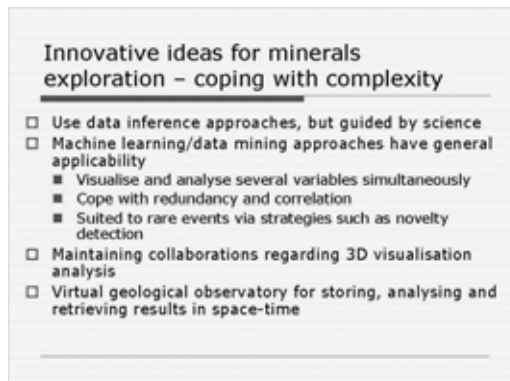
For example, data needs to be analysed in space and time, so we have three-dimensional space and we have the temporal domain, i.e. a 4-dimensional data space. Further compounding the complexity are other factors such as large numbers of attributes (increasing the analysis dimensionality), redundancies, correlations, noise *et cetera* that represent various aspects of the underlying geological processes. One of the things that we are trying to do is to find out which aspects of these complex processes are the most important ones. Topics like data inference are really important here because they allow us to escape somewhat from trying to model restrictively complex processes.

Machine learning and data mining should certainly be mentioned as they have a general applicability in this domain. There are a few things one can do with such tools: visualisation and analysing of several variables simultaneously; coping with redundancy and correlation that exist inherently; coping with the nature of statistical distributions (e.g. not everything has a simple distribution); tailoring tools to rare events—one can employ strategies such as novelty detection to look for rare events as opposed to classical approaches. So these kinds of machine learning and data mining advances should form part of our strategy.

We also spoke about maintaining collaborations regarding 3D visualisation analysis; that is a very important component. In addition, the virtual geological observatory that was discussed yesterday by Dietmar Müller is also a very good opportunity to manage the knowledge discovery process: look at large datasets, concatenate datasets over time and make that information available to the outside world.

Innovative ideas for minerals exploration – scale and sampling

☐ Analyses need to be done at all scales, locally, regionally and globally
☐ Global sampling:
  ◾ Statistical confidence in results often depend on data availability – group discussed the fact that studying data outside Australia (or pooling data) may help increase confidence.
  ◾ We may also generalise results from elsewhere locally e.g. where geological record is better preserved, but geological setting is similar.

I want to mention two related topics: scale and sampling. Analyses need to be done at all scales: locally, regionally and globally. As we heard in talks yesterday, these ore depositions involve factors at both very local and global scales that really count, so our analyses should work in this entire dimension.

I will say something about sampling. This is something that has not come up too much: statistical confidence in results depends on data availability. Yesterday we discussed the opportunity of potentially studying data outside of Australia. This may allow us to pull data from similar geological settings. So, if we do not have quite enough data, we might be able to increase our confidence by pooling it from elsewhere—of course, done responsibly. Also, there may be similar geological settings elsewhere in the globe but where the geological record is more established. That is also a good opportunity to try to generalise the findings to Australia.

Integration with other ThinkTank topics

☐ Giant ore deposits – identifying geological niches
☐ Innovation and new technology – tools and infrastructure can directly capitalise on data from new technologies for better models. Software already exists to attach arbitrary GIS data to combined framework.

Integration with other Think Tank topics: in regard to giant ore deposits, the main concept that we came up with was identifying the geological niches that result in finding giant ore deposits. We really believe that bringing together the infrastructure, the data and the various software and modelling tools will allow us to identify these geological niches and better understand the complex underlying processes. This would hopefully result in predictive tools in the future for identifying giant ore deposits.

Regarding innovation and new technology, it should also be understood that the various technologies and infrastructures that have been developed have been developed have kept flexibility and extensibility in mind. For example, if a new technology comes along, in many cases we can integrate new data into the data grid. Many of the software tools are flexible too, so we can update the software tools, read in these new variables, update our models and make better predictions based on new technology.

In conclusion, I will state the primary points once again: computational information management and modelling advances have come quite some way and are starting to pay dividends; it is essential to maintain the current momentum for an optimal return on investment; and existing Australian data is awaiting exploitation via the unified geoscientific analysis framework that we talked about. We also talked a little about technical and scientific ideas that were put forward, primarily involving analysing general GIS data in a tectonic framework and using quantitative techniques to visualise and analyse results. We believe that the identification of geological niche conditions by looking back in time will lead to exploration dividends.

Discussion

Jon Hronsky: I wonder whether your group contemplated the fact that the modelling needed to take the next step was missing some critical observational data at all sorts of different scales, data that you might not have at the moment. There did not seem to be any reference to that. As I understand it, there is probably a lot that we could add from having some inputs: subduction zone behaviour, large-scale plate convention and all sorts of things.

Thomas Landgrebe: I suppose that one could come up with quite a detailed answer to that, but I suppose in our first steps we have quite a lot of data; for example, our plate models, subduction zones and, thanks to Geoscience Australia, ore deposit locations, geochronology—

Jon Hronsky: You are not missing anything? You have everything that you want?

Thomas Landgrebe: I am sure that we do not, and we will always be hungry for data. Actually, the most important data for us to achieve is ageing-coded data. For example, we would be very interested in looking at data on such things as faults and how they may have evolved over time and when perhaps they were active and not active; volcanic datasets: what types of volcanos they are and when they appeared; and stratigraphic data as a function of time. So I suppose what I was getting at primarily was that the datasets that we currently have are sufficient to enable us to take our first few steps. But, of course, we anticipate that in the future, as we gather more confidence in our processes, we will want more data than that. For example, it would be wonderful to have more detailed geochronology data, some information about seafloor ages in certain spots and the thickness of the crust and so on. But it will be an ongoing issue. I suppose that another of the reasons that we invest so much of our time in building interoperable capabilities into our tools is that we want to be ready for whatever data comes, whenever it comes. So, if Geoscience Australia updates its database, for example, we want to get that information.

Mike McWilliams: Earlier in your presentation, you talked about the various components that make up the modelling work flow and you described some of them as needing time to mature and others as essentially finished. Could you give us a couple of examples of things that need more time to mature? Secondly, if you look back on the history of science, it is kind of bold to say that something has really finished. But would we really look at it that way in 10 or 15 years from now; would we still say that same thing?

Thomas Landgrebe: That is a good question. There are things that are partially finished but that add value. An example is the GPlates software; it has a huge amount of functionality. But, of course, we have grander visions, for example, of putting the quantitative data analysis into it. Other technologies, such as GeoSciML, are mature and connected to the data grid. You might argue that the community out there has not been given enough time to get

familiar with it in order to start using it. Software tools have not been given an opportunity yet to be updated and to have the information models updated, and we believe that there is positive feedback that it will come about. That is why these things need to be supported, acknowledging that it will take some time. Yesterday we used the Google Earth example. Google Earth came along and offered this free service and a handful of guys started playing with it. In the end, it has become quite an essential tool for many organisations and a useful tool for people. In the same way, you can argue that infrastructure, data and software tools that exist, all need to be given the opportunity to reach that mature state.

Nick Rawlinson,: I want to respond to Jon's earlier question about what data we are missing. I know that it is slightly self-serving of me to say this, but I think we are missing passive seismic data. For example, if we were to cover the whole Australian continent with seismometers at a spacing of about 50 kilometres—okay, it might cost $50 million or $100 million—that would give you a massive new dataset and you could also deploy magnetotelluric (MT) stations at the same time so that you could get this massive seismic/MT dataset. There is so much that you can do with that. Jon, yesterday you talked about looking at lithospheric boundaries. I think, with a dataset like that, you could come up with quite a detailed map of the whole of the Australian continent and the significant lithospheric boundaries, and I think that would be a very big difference from what we have at the moment.

Breakout group presentations

Group B: Giant ore deposits

Rapporteur: Dr Rob Hough

One thing that is really striking when thinking about giant ore deposits is that, clearly, Australia's future is down under, which is basically about peeling that skin off the outer surface and how we see through that skin; people have talked about that a lot. But what is the key surface? Once you get past that surface of the Earth, we really need to be looking at that to understand where world-class mines would reside.

So, in the 20th century—very successfully, I think—we mapped the Australian surface. What we are looking for is something really punchy in the 21st century: to map the Australian lithosphere and to understand large-scale ore-forming systems. That really is the kind of headline that came out of our session, and it is all about seeing through that skin.
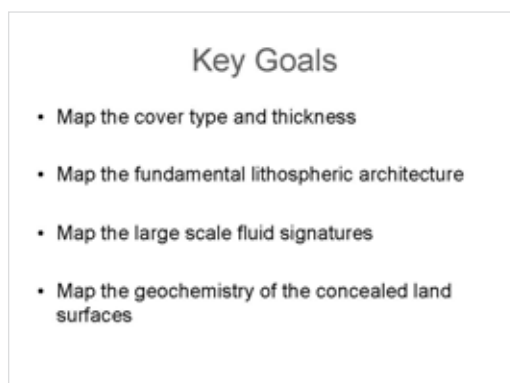
Then, within that, there are some very key goals, such as mapping the cover type and thickness. I think one thing that was really striking yesterday, in the talks by Tom Whiting and Richard Schodde, was this argument of being able to tell the location of the deposits that have been found in the exploration success that we have had recently. Really, how deep do you have to go to find new ore bodies? In talking about that cover, do we still have a challenge in Australia in terms of just seeing through 10, 20 or 30 metres of cover? It is not always about trying to see through 300 or 600 metres of cover. What became really striking in thinking about that was: well, what do we really know about the thickness of the cover in Australia? So mapping the cover type and mapping the thickness of that cover across the continent is a very important strategy that we believe needs to happen, so we can start to have better targeting exercises around key areas. Where can we apply different methodologies? At the moment we do not really know because we still do not know the depth of that cover and the type.

Once we get through that and have mapped that, we can start to think about mapping the fundamental lithospheric architecture. We heard a lot yesterday about the different features that might reside within and, for that matter, below the lithosphere that we need to understand better. There are lots of components within that that we might undertake to try to break that down, and I will say a little more about that in a second. But also, within that framework, obviously you then have to map the large-scale fluid signatures. So understanding that kind of fertility and the plumbing within that lithosphere is very, very important. But we also have to understand just what are normal geological signatures. I think we still struggle with that in a lot of areas because we have had a big focus on studying ore deposits. What we have very rarely done is to go away from the ore deposits and ask what is that kind of distal signature, the distal footprint. We think that the distal footprint idea is a very key concept that, as a research community, we should be targeting.

Roy Woodall referred to mapping the geochemistry of the concealed land surfaces. Exploration programs in Australia have been very successful over the years in doing surface geochemical mapping—soil geochemistry is a great example—in great detail. Effectively we have to take that same methodology, but now we are doing it at depth.

So we are finding those ancient land surfaces and sampling those different surfaces as a new exploration sample media, if you like. That has the potential to use the same kinds of methodologies and targeting that we would have done at the surface but to use them at depth, as long as we have done those things here that we have done beforehand.

Key Innovative Strategies

- Technology roadmap (AMIRA model) approach to guide the overall strategy
- National map of cover depth and character
- Innovative new technologies for mapping the lithosphere (MT, seismic, Sm/Nd, other..)
- Strategic groundtruthing by deep drilling (?Crustal drilling program)
- National Distal Footprints Program
- National Exploration Research Network
- National Embedded Researcher Program

So we need strategies within some of those frameworks to really decide how we drive that: what things do we look for to really undertake this kind of program? As a start, maybe we need to look at the AMIRA model—which I think was the drilling road map before the Deep Exploration Technologies CRC got up—and have some kind of exploration technology road map to try to develop that strategy over the next couple of years, in thinking about how we really would pull together what we are talking about in terms of getting past that surface skin. We need a national map of the cover depth and character, as I have said, and to understand it, so it really drives what we do next. If we understand where it is relatively easy to go, we can start to set new areas to look at—and not be driven by any ore deposit models, so not be driven by an understanding of what we think today are key fertile areas. How do we find the 'black swan'? We will do that only if we are not driven by our preconceptions. We believe that taking this kind of national approach is the way to do that.

So, once we get past the map of the cover depth and character, really it is about those innovative new technologies, like MT surveys and seismic surveys across the nation—assuming that here we are dealing with mapping—to be able to understand that lithospheric architecture. In fact, with the MT surveys, one of the things that we really felt that the community needed to study was MT and its properties. What in the rocks gives an MT signature like the ones we see? Do we know enough about the petrophysics of our rock samples? Do we know enough about the effects of geochemistry on the geophysics, for instance?

Strategic ground-truthing by deep drilling: it is almost like a sampling program. Rather than calling it just a drilling program, it is about sampling the subsurface skin that we want to start looking at in detail. Think about the ocean drilling program, which has been very successful, and some of the continental drilling programs, and we could have an Australian scheme with some very targeted areas where such an Australian government-funded program might allow us to tap into key areas to understand that in more detail. But we could also have a national distal footprints program, with this idea of basically stepping out of some of our large deposits. Perhaps we would have transects going through our deposits but going very much into the background. So perhaps we could have some research programs focused on looking at those distal portions—and we are not just talking about alteration mineralogy or geochemistry. We are talking about things like brecciation. We are talking about changes in the kinds of physical and chemical properties of the materials that are constraining our geophysics, for instance, and saying, 'Well, how far out of the system do you have to be? Where is the smoke of a giant ore deposit?' At the moment, yes, we go and study a giant ore deposit or we all want to go and study something like Olympic Dam, but perhaps we should all be studying things that are 10 to 50 kilometres away from Olympic Dam and thinking about how we might target into a deposit like that. That is the kind of information that explorationists would then be able to use to have confidence that, when they are end-drilling programs and might know that they are getting close, they know the kinds of signatures of a world-class mine.

What is very critical, I think, is a national exploration research network. In the EU they very successfully have had these networks which are all about communication. We have just heard from Thomas Landgrebe that one of the things we do not necessarily do very well in the exploration community is to capture the knowledge that we have and all get together to have discussions like this. This is the first time that I have been in a room with all of you. I have met a lot of new people in the past 24 hours and we all have common aims in trying to understand and support exploration

in Australia. So we need a national network, to foster us getting together, maybe with an interchange of researchers going through different laboratories, to try to identify synergies. In terms of the modelling, for instance, there could be the identification of people who, on a day-to-day basis, are collecting data that could be fed into or used to drive models, and that might make a real difference very, very quickly. For those areas, it is very important that things do not happen in isolation. The power we have in Australia is the integration of our different capabilities. So how do we make that happen? A national exploration research network might be the very mechanism to start to do that; possibly not needing a huge amount of funding to support that activity.

What is also very critical is a national embedded researcher program. One thing that we talked about quite a lot was: well, how do we get that twoway street between the researchers and industry and how do we get that happening a lot more rapidly? One thing that has been successful in the past is having research scientists sitting with companies on a daytoday basis as part of their normal operations. In that way, the research that is being undertaken and the access that is being given to different researchers across the country can really be fostered by people who know what is going on in the community and attend the conferences and the networking meetings and communicate that to the company on a daybyday basis. But also, and very importantly, communicating with those young exploration geologists—graduate geologists in a lot of cases—who have a problem understanding key concepts or have questions that really need addressing and which make a difference to that company in terms of exploration.

In that respect, education is also very important. We identified—as talked about by Jon Hronsky—that we are very good at producing graduate geologists but not necessarily exploration geologists. That key element of training for young exploration geologists is very important and often the companies themselves find it hard to find the time to free up the mentors that are necessary for those people. But we all have a key role to play by offering training programs to exploration geologists, particularly in the junior sector. Some institutions are looking at mechanisms to partner with the junior sector. The Association of Mining & Exploration Companies (AMEC) in Western Australia, which represents a lot of the junior companies, is a very important mechanism for doing that, and we believe that we should look to partner with them more strongly around training programs. That feeds off that national network idea of us all basically working together to create those kinds of training courses rather than just being one institution. A key point is that we realise there are centres that are very strong in Australia for exploration and they can be quite large, but there are also very strong individuals residing in universities and other places—in industry, very critically—that often do not get together with those big centres. Having the network is a mechanism to foster that, we believe.

As for the outcomes of this big initiative, obviously one is new exploration frontiers really creating a new generation of greenfields exploration. We believe that those new exploration frontiers, once we have removed that skin, will foster the discovery of new world-class mines and not necessarily the ones that we would expect—that kind of 'black swan' scenario. It will also unlock other advantages for Australia in terms of the geothermal potential and deep groundwater resources. If as part of that lithospheric mapping you undertake a hydrogeochemistry exploration study across the nation, then you will also understand the water quality across Australia, with the added benefit that you might identify things for exploration targets. There will also be a better understanding of intracratonic earthquakes because of the systems that you have put in place and the data that you have collected. I think these are key things for the nation in terms of exploration: that we show how we add value to other sectors and not just to the mineral exploration industry.

Finally, there will be Australian world-class leadership in the deep Earth sciences. One thing this group was really looking for—and we would welcome feedback—was how to inspire the young generation to get involved or to stay

in the Earth sciences. Other sectors have done that very well by linking to planetary science, astronomy, life sciences. Maybe for us it is about that leadership in deep Earth sciences. It is about the evolution of the Earth: how did the Earth form and how does the Earth tick as a planet? We need that hook, not just for the young people coming into science but more generally for the public to understand what we do and to support more exploration in Australia so that we can support the exploration industry to find new resources and wealth creation for the nation.

Discussion

David Giles: I really want to emphasise something that has direct relevance to Thomas Landgrebe's talk as well, about the importance of deep drilling for ground-truthing ideas. I think it is terrific that you can build the continent and even the Earth in a computer. But, if we are going to make new discoveries of deposits that we do not even know the appearance of yet and in areas that we do not even know the geology of yet, we have to generate new data and we have to generate observations, and we can do really smart things with those observations. But we have to go under cover. We have to drill to get the samples. It goes into all of the things that you were talking about: the prospecting on those horizons and what have you. You have to drill. And it cannot all come from industry; the government has to help. There has to be some level of co-investment in a strategic way to generate that data; otherwise we are not addressing the problem that was raised yesterday with great emphasis, which is that we are not changing the search paradigm: we are looking for the same things because they have the same signature that we have registered in the rocks that we know, in areas under cover, where we do not even know what the rocks are yet. So, if we are looking for courageous ideas that need to be done, which do take a lot of effort and a lot of convincing in government, I think we need to get behind this idea that you have to sample it, and it is going to cost a lot of money to do that.

Rob Hough: As a group, I think we are in violent agreement. We talked about the concept of redrilling Australia and basically, if you pattern-drill the country, for instance, what kind of level of information you would get and how much that would cost. You would get to a calculation of the order of $40 billion; but, at the end of the day you may have found five or ten world-class mines. So, around this kind of deep crustal drilling program, we could put in something akin to the Ocean Drilling Program model.

Sue Meek, Chair: I was interested in your reference to embedded scientists. One of the things that the Academy was arguing for during the election campaign is that we should have more scientists embedded in government departments in order to create those links. Having one chief scientist to accommodate the entire public service is a bit of a stretch.

John Miller: Years ago geological surveys actually had drill rigs. The New South Wales Geological Survey had a drill rig and, when they did their mapping programs and had things that they did not understand, they could test them with the drill hole. Then that was removed from them and from other places. So there has been strategic drilling done in the past to understand maps. It is a concept that I think we have to reinvigorate and get moving again.

Rob Hough: One of the things that became clear when we started discussing it is that obviously we have not sampled—as David Giles said—that zone before, and it really is back to first principles of collecting that first generation of data. For feeding into things like models as well, that is exactly the kind of data that we need to be collecting.

Graham Begg: I would just like to support those comments about the deep drilling; I think it is essential. We have to characterise our basement. The discussion by Nick Rawlinson about the architecture is pivotal. Seventy to 80 per cent of our continent is below the crust and we know very little about it. It is clearly a major player and is where the big deposits are. So we need to be (a) imaging it and (b) understanding how the crust interacts with it.

I think we need to be able to make sure that the computational stuff develops to the point where it can model coupled mantle crust systems; so it needs to be able to model process and examples of process. I think it is good to use the plates computationally, and move things around. But that is only relevant for very recent times. So, for the more ancient terranes, which are most of what we are exploring, we need to characterise just what occurs in the interaction of tectonics and what those interactions and crust and mantle interactions produce in the datasets we have available to us and give us the signatures that we see. We just need to interpret 'environment'. So I would like to see the computational side going that way. It needs to be supported obviously by, first of all, collecting the data, as you are saying. We have to characterise these terranes.

Breakout group presentations

Group C: Innovation and new technology

Rapporteur: Dr Katy Evans

Essentially, this presentation will follow the structure of the questions that we based the discussion around: 'where are new technologies well utilised?'; 'what stops us from using new technologies?'; 'what do we need?'; 'what do we think the key innovations will be?; and 'how do we facilitate uptake and turn knowledge into innovation?'. These examples are not in any particular order. It would have been nice to rank them, but I think that would have taken considerably longer than the time that we had.

We all have great admiration for the way that service companies in the petroleum industry translate knowledge to innovation. They have their own research departments, so they can develop things like new drilling technologies, without IP problems, and then they are much in demand and the financial model works really well. Another example is the software packages that have been developed either in-house or in a university like Glitter by Gemoc, ER Mapper or GeoModeller software, where these are marketed by spinoff companies outside universities. Again, these have been successful. Then you have geochemical techniques, such as Terranechron. What they have in common is that they have been built on available knowledge and then marketed, and there is a distinct return on a fairly short timescale.

We have other examples from the geotechnical field, where we have things like the laser scanning of pit faces and geophysical fields—things like GroundProbe and EnABLE techniques. Again, these examples build on new technologies that may have come from other fields. Then they drive success on a short timescale, which drives more investment. An example of where this has driven exploration success is the shallow exploration under cover in Yilgarn and Mount Isa in the 1980s and early 1990s.

Impediments to technology transfer

- IP issues
  - Cultural differences
  - University and CSIRO commercialisation departments can be slow and ineffective
- Timescale of development
  - Problems particularly with 6 to 10 year timescales (market failure: role of federal research groups?)
- Lack of basic physics/chem/maths in Australian graduates
- Financial disincentives for overseas and Australian graduates

So why doesn't it always work like that? This was quite a lengthy part of the discussion yesterday. We have IP issues. Basically, there are cultural differences between universities and industry. That means that commercialisation can have a whole load of barriers that it does not have when it is happening, for example, in an inhouse department in a service industry. We have problems particularly when there are technologies that require development on a 6- to 10year timescale. The term that came up in the context of this sort of issue was 'market failure', where other research groups that may be federally funded have the role and the capacity to take on this kind of research problem.

What has come up in the other presenters' discussions is a lack of fundamental knowledge of physics, chemistry and maths in Australian graduates. Without the graduates to feed into PhD projects and into industry, you do not have the people who are going to turn the knowledge into innovation. You can try to get graduates from overseas but, certainly from an academic point of view, the overheads on an overseas student are much, much higher. So basically there is a financial disincentive to taking that strategy. From a different point of view but with a similar effect, you have financial disincentives for an Australian graduate, which is simply the differential between their wages if they go into academic research versus their going into the mining industry, which is calling out for our geology graduates.

Impediments

- Innate conservatism favours incremental over quantum leap improvements
- **Network failures within and across the different groups
- **Lack of data release e.g. high resolution geophysics data, drilling data, exploration data
- Deep Giant Ore Deposits
  - Hard to engineer: intermediate scale data required
  - Extremely expensive to drill to JORC compliance

Further impediments are an innate conservatism and a disinclination to take risks, which can favour incremental improvements over the quantum leap that may develop what we really need. On the slide, I have put stars next to 'network failures within and across the different groups' because this basically relates to the communication that other people have talked about. It is something that could potentially be solved, or at least improved, by the kind of strategy that Rob Hough was talking about with his embedded researcher program. Essentially, we are talking about cultural differences between academia and industry and the difficulty of communicating the great ideas. If you look at places where there have been excellent successes in transferring knowledge to innovation, you will probably see people who are very good communicators. They may or may not be the same people as those who have the ideas and transfer them into the knowledge that then turns into innovation.

Data release: again this runs in parallel with topics brought up in the other talks. If the existing highresolution geophysics drilling data and exploration data were to be released, we would have an order-of-magnitude increase in the information that we need to build up these pictures of what is going on under cover, shallow and deep.

The last point on the slide is something that I had not heard before, so I am going to emphasise it because it is particularly relevant to the deeply buried giant ore deposits that we are focusing on to some extent. Basically,

the engineering challenges for a deeply buried giant ore deposit and the costs that it takes to even demonstrate the viability of, for example, a block cave in an 800metre deep ore deposit are simply not proportional to the depth; there is a slightly more highly-geared relationship. So we need better ways to find intermediate length-scale data, mine-scale data, to enable those facilities to be engineered. Again, if projects need to go to the Stock Exchange and get funding, the expenses of drilling to JORC compliance (compliance with the Code for Reporting of Mineral Resources and Ore Reserves of the Australasian Joint Ore Reserves Committee, JORC) for a deeply-buried giant ore deposit is a substantial disincentive to developing that kind of thing. It puts such development off into the much more distant future than if there were some other way to do it.

I will move on to what we think may be key innovations. First of all, I will briefly summarise the requirements that have come up both in yesterday's early presentations and through the discussions that we had. These are the outcomes, if you like, of what we want the innovations to provide. We want quicker cost-effective drilling; faster research outcomes to enable decision-making; onsite assaying, again, to produce faster decision-making; and down-hole data analysis to reduce the costs and the time taken. Basically, this is the context in which we are looking at our innovations, but then again we are also trying to think outside the square.

Basically, the innovations are split into those that are available now or will be available soon and those that are not available because a key piece is missing but that are technologically plausible.

We are looking at things like cycling exploration data all the way through a mine life. So you take your exploration data and use it to inform your mineral processing decisions and to inform your mine closure and environmental mitigation strategies. That is efficient and that is a smart thing to do.

We have talked about onsite assaying; those tools exist. We have portable x-ray fluorescence (XRF) capabilitiy. We have infrared tools that will walk themselves up a core and give you information. These still require an operator, but they can be used on site. Something that is very exciting and potentially powerful is the combination of geophysical methods and joint inversion, to increase the information we get. So we are looking at things like combining gravity with airborne electromagnetic methods; we are looking at combinations of seismic and gravity with magnetotellurics; and we are looking at things like a national database for electromagnetotellurics. We are looking at the fact that we have improved geophysical methods available, such as ambient seismic data processing and the 3D and 4D seismic

for hard rock, which has come from the petroleum fields, using reverse-time migration strategies. Again coming from petroleum, we have 3D visualisation techniques where you can see the ore deposit or the inferences of where the ore deposit is around you.

Intermediate

- Downhole geophysics to get intermediate (mine-scale) architecture
- Passive seismic around existing mines
- Downhole MT
- Comprehensive crustal architecture models and geochron maps of Australian continent

On the intermediate timescale, down-hole geophysics and down-hole magnetotellurics sound very promising because they give you speed and cost effectiveness. Again, with similar benefits, there are things like passive seismic surveys around an existing mine. So you are using the fact that a mine creates seismic signals continuously to develop a detailed picture of the mine-scale architecture. From a geochemical, and much bigger, point of view you are looking at developing comprehensive nation-scale crustal architecture models and geochronology maps of the Australian continent. If you are going to explore under deep cover, then having some idea of what is under there is essential.

Future

- Remote drilling drones
- Remote sensing drones
- Miniaturised nano-machines to collect information down holes (hydrofracturing)
- In-situ solution mining

In the future it would be so cool to have remote drilling drones. You would drill out a pattern by setting these little machine guys up and then, when you came back, you would have the data. Remote sensing drones: they can fly lower and carry less weight. Potentially, using miniaturisation technologies, you could have machines to collect information down holes. So you could hydrofracture to give yourself space within an ore deposit and, by some means as yet undiscovered, collect that data. Then there are things like solution mining, where, instead of mining the ore as one gram per tonne, you pump it out as a solution and leave the waste rock in the ground.

Incentive for knowledge to innovation

- Goldcorp challenge – took a mine and offered prize to whoever showed extensions to the ore body. Tremendously successful. Won by Nick Archibald with 3D fractal type software.
- US Defence force: prizes for technology and autonomous vehicles

What are the incentives? An American company called Goldcorp offered a prize to anybody who could show them the extensions to their ore body. This was hugely successful for the mine and for the person who won the prize, Nick Archibald; he would have got big benefits from winning that prize. Also, there is an annual competition held by the US Defense Force with different yearly focuses on technology. So prizes are a good incentive. You don't get the prize until you have done the research though, which does not make it easy for everybody.

How will investments facilitate innovation?

- Incentives for small explorer research
- Research quota for overseas exploration companies
- Cross-company research levy for long term goals (e.g ACARP)
- **Open competition innovation prizes
- Fee waivers for foreign PhD students
- Government think-tanks

Most of our suggestions revolved around the fact that we need more government money. Obviously, if that is going to happen, proposals need to be very well argued and very tightly targeted. For example, there could be things like tax incentives for small explorers to do research and a research quota for overseas exploration companies. For the longterm goals that were identified as being problematic and associated with market failure, something like a cross-company research levy similar to that used by the coal industry was proposed. Also proposed were open competition innovation prizes; these could be from government or from anybody else. Another proposal was to have fee waivers for foreign PhD students, which would deal with some of the skills issues. Also proposed were government think tanks, similar to this one, where you would bring people together from industry and academia. That would deal with some of the communication issues that we have been talking about.

Investments

- High resolution databases
- Sliding scale ECR Linkage grants
- Pre-venture capital type funding
- Tax incentives for 10 year research projects with fundamental aspects
- Tax incentives for greenfields exploration
- Changes in university funding policies to produce the graduates that Australia needs
- Recognition of applied research in ARC funding models and provision of salaries.

Highresolution databases came up over and over again as being essential, and that concept has run through all three talks that we have had so far. Getting linkage grants for early-career researchers could be addressed by a sliding scale, where an early-career researcher would not be required to obtain quite so much money; some people in our group felt that a type of pre-venture capital funding would be useful; there could be tax incentives for longterm research projects for greenfields exploration; Australia could be persuaded to produce graduates with basic physics, chemistry, maths and computing skills; and, generally, recognition of applied research is needed so that people can do applied research more easily within university environments.

Non-investment drivers

- Early release of high resolution data
  - Massive simultaneous data release
- Better communication
  - Government, academics, industry
  - Chemists, physicists, geologists
- Better University commercialisation departments or other commercialisation pathways (e.g. private)

There are drivers that do not require investment, such as the early release of highresolution data. In the petroleum industry, there is quite a different model and the data is released; I think they can hold it for three years and, after that, they have to release it. Better communication came up as an issue over and over again. University commercialisation departments do not always help, but other commercialisation pathways exist and it may be a good thing to utilise them.

Pick three

- Education
- Data availability
- Rapidity
- Commercialisation pathways

We asked the group to pick the three most important issues that we had discussed. We came up with four: education, data availability, the speed of response, and commercialisation pathways. Those things will help us to turn knowledge into innovation.

Discussion

Jon Hronsky: If you look at the geophysical sensing technologies that we use in mineral exploration, all of them are based on physical principles that a well-educated physicist in, say, 1900, would have been able to understand, yet we have had a fair bit of development in our understanding of fundamental physics since then. Did your group contemplate completely new sensing technologies and, in that regard, was there any discussion of the work that the Canadians are doing right now using cosmic-ray muon tomography to image deposits? There is a study going on at the Myra Falls volcanic-hosted massive sulfide (VHMS) deposit using that approach. To me, that is a potentially really exciting technology that deals with your big problem of giant ore deposits because, in principle, you could drill a few deep holes, put the cosmic-ray muon detectors at the bottom in a grid and then, over time, build up your rock volume mass in a very highresolution way. In Japan, they have put these detectors in tunnels in a mountain and been able to recapture the entire overlying topography of the mountain from the cosmic-ray muon tomography. That might just be the tip of the iceberg in terms of all the potential sensing technologies out there from 100 years of particle physics.

Katy Evans: We did not discuss muon ray technologies, but they sound very interesting. We touched briefly on remote sensing from satellite data. But we did not really come up with anything that is fundamentally new, like the things that are you discussing.

Chris Yeats: I would like to thank you, Katy, for giving me a nice segue into the group D presentation because you dwelt pretty heavily on government investment in innovation. I wonder whether you had much discussion around other avenues of investment. Do you really believe that the government is the only agency that will invest in innovation, or is there a responsibility on the private sector to do so?

Katy Evans: We did discuss the private sector, but the private sector is market driven. Where the private sector is going to work, then it is working, if you like; returns on a short timescale are working really well. The places where you have the market failure—and, therefore, what we focused on—are the longer-term knowledge-to-innovation questions. I don't think we were talking specifically about government investment but about using government to help companies invest, with different kinds of tax breaks. So that is not saying that the government should give the money; it is saying that the government should be encouraging. If we want this research to be done—and it is not being done because people are finding it easier to go to South America—then shifting the tax burden so that research is encouraged is the thing that came up over and over again as being a mechanism to allow this to happen.

Anya Reading: I just want to respond to Jon's question. I am a member of the innovation and new technology group and we did touch upon some of the new technologies, like quantum interference detectors. I would put muon detectors in a different area of physics but in that class of modern physics detectors. I have a really strong sense that innovation is not blocked by a lack of good ideas; innovation in Australia is slowed down by some of the things that Katy was raising. I think the key is releasing university researchers so that they can interact in a fast and effective way with industry people who will put those innovations into practice. It is almost a tragedy to have new technology that you still cannot get through because of these same impediments.

Steve Micklethwaite: This is really to support what Anya has just said. I think there was quite a strong feeling in the group that, from a researcher's perspective, you are short of time and often there is a disconnect between the ARC funding system and your ability to take an idea to an actual commercial venture. Katy did raise one point there: the idea of pre-venture capital. What we meant is that there is a gap: there comes a point where you cannot attract funding from the ARC system to develop an idea any further but neither is it ready to attract venture capital for it to be developed and you as a researcher do not have the mechanisms and the time to go to industry and say, 'Well, look, here's an idea that you might want to invest in.' So we really need some mechanisms to enable someone perhaps to be marketing our ideas. One idea that came up was to have a national conference where you would link industry and researchers together. You could have things like the talks being focused on here, 'Here's an idea; does anyone out there want to fund it?' You could have workshops on IP. In effect, you would almost be reversing the current conference model in that the people doing the trade stalls would be the researchers and the people attending the conference would be the industry representatives.

Sue Meek, Chair: In no way are the issues that you are highlighting restricted to this area of research. In fact, other industry areas are shifting to that sort of model where you do the fast sell, bringing people together to identify researchers and potential investors *et cetera*. So, yes, that is not unreasonable. But it is a challenge; the dreaded valley of death in terms of investment is a challenge, because some of the structures in government funding programs also do not really address that either.

Breakout group presentations

Group D: Exploration policy—the way forward

Rapporteur: Dr Chris Yeats

We stepped back a little and asked the question: 'what is the value of the minerals industry to Australia and how do we sell that to the Australian public?'. There is the obvious direct economic benefit: the massive export earnings that underpin our economy. There are also flow-on effects to communities. That sort of regional benefit argument is a little harder to make when we live outside of those communities. The fly-in fly-out workforce particularly has tended to dilute that argument, taking the community up and down; it does not help. So we then asked: 'do we really need deep discovery?'. From an economic point of view, if you look at it in terms of export earnings, iron ore, coal and natural gas dominate export earnings. Around those commodities—those are fairly 'bulk' commodities, for want of a better term—we have some pretty good resource security. For example, deep discovery certainly is not an issue for iron ore; we are not drilling deep to find iron ore deposits. So you need to make a more subtle argument, which is around the triple bottom line. A good example of that is the gold industry in Western Australia. In Western Australia there are communities that rely on the gold industry; if you take that industry away, those communities will cease to exist. But that, again, is a difficult argument to communicate to people who live outside those areas. So there is a problem of perception around the industry, and I will come back to that in a moment.

We were asked to outline current policy, but we did not do that at all; we probably do not have the expertise to do it. But the next question we needed to ask was: 'is there a problem with current government policy?' We have heard over the past couple of days that there is a huge technical risk involved in exploring in Australia. There is a lot of cover, and there is a poorly defined basement geology. The outcome is that exploration is expensive, technically difficult and time consuming, and that turns companies off. But are they the only things that are turning them off?
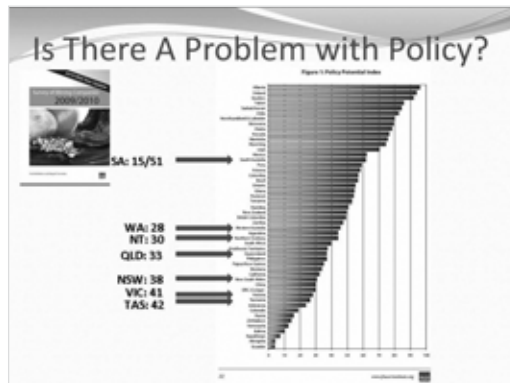
Coincidentally, in my emails last night I received an update of the Fraser Institute report. This came out in the throes of the mineral resources super profits tax so Australia had a depressed result as a consequence. This report asked companies about the influence of policy on their exploration decisions. Being realistic, if I were an exploration manager and was asked whether such-and-such a policy would affect my decision to invest in a given area, I would have in the back of my mind the technical difficulties involved in prospectivity; but this was asking questions about policy. South Australia, ranked at 15th, is judged to be the best area in Australia to find and develop mines. Tasmania, ranked 42nd, just beats Indonesia and is below Papua New Guinea, followed by the Philippines and then Argentina. Basically the answer we are getting from these figures is: yes, we do have a problem with the policy; so we need to do something about it.

However, the fundamental issue faced by the industry is public perception and attitude. This slide is a rough summary of how 'Joe Public' and certainly, based on the debate around the resources super profits tax, the Australian Government sees the mineral industry—they have not helped us here. Some of the perceptions are: mining 'pillages' Australia for offshore profits; it does irreparable environmental damage - they dig massive holes in the countryside and then leave them there; the companies are insensitive to cultural and social issues; and there is minimal return to the community and the economy, which was the argument for the tax in the first place. Also, you have to deal with NIMBYs: 'not in my backyard'; NIMSs: 'not in my state'; NICs: 'nowhere I camp'; and NICDARRs: 'nowhere I can drive a Range Rover', which I made up last night after some red wine. So this attitude is deeply ingrained in the Australian community at large. Until or unless these perceptions can be changed, there will be little appetite from government because there are few votes to be had from investing in the minerals industry. So it has to be changed.
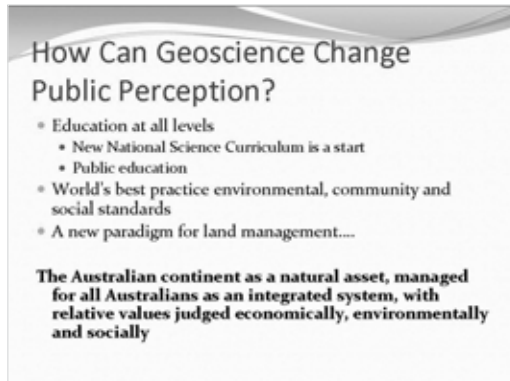
How can geoscience change public perception? The fundamental underpinning issue here is that we need education at all levels. The new science curriculum is a start. Geoscience is one of the four core sciences in the national science curriculum, so that is a good start for us. But the reality is that we need public education: we need to educate the public on the benefits of the minerals industry, but we also need to give them an industry that they can be proud of—and that means having world's best practice in environmental, community and social standards. If you have one bad environmental incident, the whole thing goes back to square one again and you can lose 15 years of good work by the entire industry.

And just thinking a little bit outside the box, we are looking for a new paradigm for land management. That means looking at the Australian continent as a natural asset quite holistically. It should be managed for all Australians as an integrated system, with relative values judged economically, environmentally and socially. That is not an easy thing to do, but perhaps it is the only way that you can get communities to believe that a minerals industry is an important part of how we manage the Australian continent.
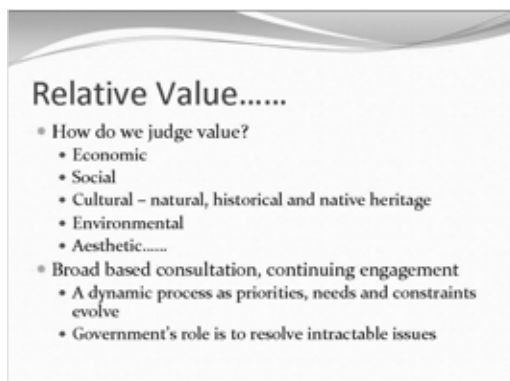
So how do we judge this relative value? Economics is never going to sell these things on its own. You have to look at social values and cultural values—the natural, historical and native heritage; environmental values; and also simple aesthetic values. People want to look outside their front doors and see something that looks nice; they do not necessarily want to look outside and see a pit. The only way that you can do this, we believe, is to have broad-based consultation with all stakeholders, and you need continuing engagement. What we are seeing here is a dynamic process as priorities and needs change and constraints evolve over time. So we do not go out there and say, 'This area is going to be a national park,' then do one heritage assessment of it and leave it for all eternity. As priorities change and other pressures come to bear, you go back and have another look at that decision.

The ideal case here—and perhaps it is a bit of a pipe dream—is that various stakeholders can come to an agreement amongst themselves. The government here really is the umpire; its role is to resolve intractable issues. We would hope, perhaps unrealistically, that there would not be too many of those; but that is the dream, if you like.
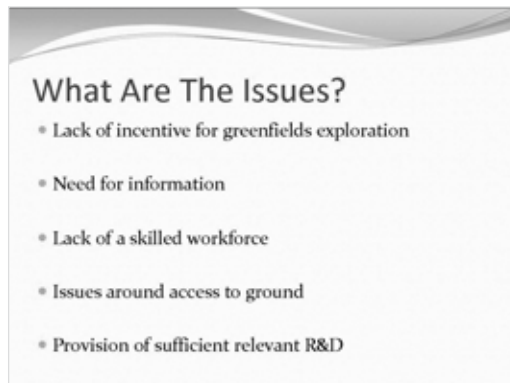
Given that we could get community agreement that we need a minerals industry, that we need more mineral exploration in Australia and that we need to find deep ore deposits, then what are the issues? We have split them into five key issues. Basically, there is a lack of incentive for greenfields exploration in Australia. Part of that is that there is a need for new information, and we have also heard that from the other three speakers today. There is the lack of a skilled workforce who can provide the necessary expertise to address these difficult problems. There are issues around land access. Finally, perhaps there is a lack of sufficient relevant R&D within this industry.

Lack of incentive for greenfields exploration: Like the other groups, we believe that government needs to share the risk, and it is in the national interest for it to do so. That might mean things such as flowthrough shares, for example, as they have in Canada—and Quebec is a nice example of that—and drilling co-investment, which we are doing already on a small-scale at state level in Western Australia, South Australia and, I believe, in Queensland. One idea that was put up was government co-investing in greenfields explorers in return for equity. That was not by any means universally supported, but it is an idea to throw out there.

Need for information: The fundamental issue is the surveys—and I guess the fundamental custodians, if you like, of our geological heritage are the state and Australian Government surveys. What tends to happen in those surveys, as you would be well aware, is that they get programmatic funding; they might have the offshore energy initiative, for example, or the Exploration Incentive Scheme in Western Australia. They are all finite schemes; they ramp up, come back down again and then sit and wonder what they are going to do now. So we need coordinated, stable and long-term baseline funding for those organisations. But the reality is that we are looking at defining the unknown, going into areas where we do not have the information, but then getting it and providing it to explorers to encourage them to invest in Australia.
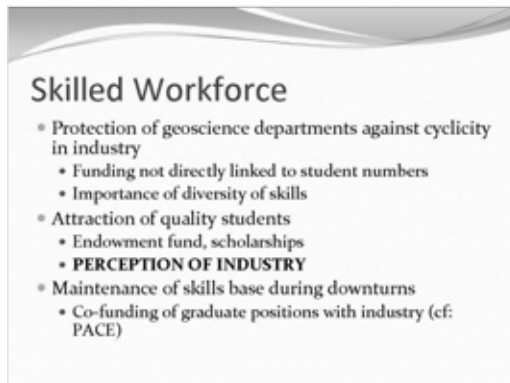
Lack of a skilled workforce: There is an issue around the cyclicity of the industry and the fact that geoscience departments are impacted by that. You need to decouple the university funding model where you directly link funding to departments with student numbers. If you do not do that, university geology and geoscience departments are always going to fluctuate and will eventually atrophy. The other important issue is that a diversity of skills is required in our geoscience community. As you downsize departments, you lose that diversity and you lose the ability to teach those skills—and they can be lost to the country forever. We need to attract quality students. A possible policy mechanism to do that is to produce an endowment fund or scholarships for students who work or intend to work in high-priority industries like minerals exploration. Probably the fundamental issue though in attracting students is the perception of the industry again, both in the community and as an employer. It is a cyclic industry and it sacks half its workforce every five or six years, and it does not look like a good career move to go into it. We also need to put in place mechanisms to maintain skills during downturns. They did that in South Australia recently: a group of new graduates came out in the middle of the global financial crisis and the Government of South Australia's Plan for Accelerating Exploration (PACE) co-funded them as graduate geologists with companies. So it can be done.
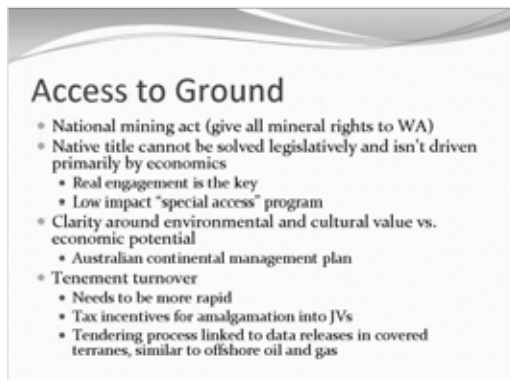
Issues around access to ground: It would be great if we could have a national mining act. Realistically, the only way that it is going to happen in Australia is if Western Australia controls it and the government relinquishes control of what they have got. The native title issue is a very difficult one. I would not go so far as to say that it is an intractable issue, but it is a very difficult issue. Also, it is not driven primarily by economics; it is driven around cultural issues. Real and ongoing engagement with the community is the key. The idea we discussed here was that potentially you could remove a lot of pain and a lot of unnecessary negotiations with native title landholders if the national surveyors could negotiate some way to carry out low-impact regional exploration programs, with the idea primarily of sterilising the ground that is not prospective. There was some diversity of opinion in our group as to the applicability, usefulness and practicality of that, but it is an idea to put out there. We need clarity in Australia around environmental and cultural values versus economic potential, and this harks back to this integrated management idea that I spoke about a little earlier.

The other issue that we need to talk about is tenement turnover. Juniors constantly complain about lack of tenement turnover; they want it to be more rapid. It is not just about turnover though, it is also about the fragmentation of land holdings. So a mechanism that could be put in place is tax incentives for juniors who are working in greenfield areas with adjacent tenements to go into joint ventures together. This would enable them to get a larger package and, therefore, increase their chance of success. We also spoke a little about going into a process similar to the offshore

oil and gas process, where you release an area of land linked to a data release and you ask for a tender to explore that land. There are pros and cons to that but certainly it is a slightly different way of looking at these things and it is something new for the minerals industry.

Provision of sufficient relevant R&D: I would postulate that the minerals resource rent tax represents an opportunity to set up a mineral industry research fund similar to the Australian Coal Industry's Research Program (ACARP) or, for example, Australian Wool Innovation (AWI) Limited for the wool industry. That is where a portion of that tax is set aside to reinvest back into the industry which is generating the revenue. That has the potential to provide longterm base-level funding for minerals research in Australia. The other issue we have in applied mineral industry research is the way that it is assessed. If you look at the ARC process, there is almost a sole reliance on traditional metrics—that is, if you like, the publication record. Although it would be very difficult to quantify and difficult to measure, there should be some sort of recognition and reward given for measuring the relevance to industry of things like spin offs and new technologies; and perhaps rewarding academics who collaborate directly with industry rather than academics who stay within their own little bubble. Also, one of the comments made in our group was that you cannot, by any means, publish everything you know, but the tacit knowledge you have that you cannot publish may be as valuable to the industry as what you have published. How you would measure that I have no idea, but it is certainly relevant. The final point about R&D is that we have the national research priorities but, let's be honest, they are very vague. Almost any proposal that you want to put forward you can tie to a research priority. So we would like to see the government setting funds for specific areas of strategic importance—hoping, of course, that this area is one of them.

So, summing up, these are our key initiatives in addressing these issues. With the lack of incentive for greenfields exploration, government co-investment and sharing the risk is the key; I think there is no getting past that. Also, you need to provide the key information to allow companies to explore successfully in greenfields terranes. The lack of a skilled workforce: we have to fund Earth science and science teaching sustainably—and I mean 'science' in the broader sense here, perhaps even including engineering, although I shudder to say that—and attract good students to the field. The issues around access to ground: our underpinning idea here is the new paradigm around integrated land management. Finally, with the relevant R&D, we believe that there really is an opportunity around the minerals resource rent tax. The industry is going to complain about paying an additional tax but, if they are already paying the tax, we can get them to lobby to spend some of it on themselves. But underpinning all of this and probably underpinning the future of the minerals industry in Australia is the public perception issue; that is the key issue for the industry in this country. We, as researchers working with that industry and in that industry, need to be aware of that.

Let's MOVE FORWARD

"The future belongs to those who can see possibilities before they become obvious, and who effectively marshal resources and energies for their attainment."

Theodore Levitt, The Marketing Imagination
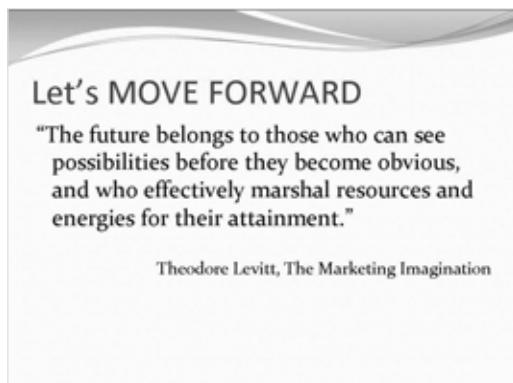
I would like to finish with the quote on this slide. I think it is relevant to this particular forum. Another way of putting it, of course, is: let's move forward.

Discussion

Jon Hronsky: There was a lot of contextual stuff about the Australian public not considering the mining industry to be significant. I wonder whether that is a bit out of date. I was informed recently of a survey that said that 96 per cent of the Australian public agreed with the statement that the mining industry is important or somewhat important to Australia. They might not agree with all aspects of it, but I suspect the reason why the resource tax in its previous incarnation did not get up and, in fact, probably led to the end of a prime minister, was that the Australian public do think the mining industry is important. I am not saying that there is not a lot we can do in that communication space—I think there is an enormous amount—but perhaps things have changed over the past decade as it has sort of doubled or tripled its share of our GDP.

Chris Yeats: Yes, that is a fair comment, Jon. Perhaps I oversimplified things, but I certainly think there is a fair way to go.

David Giles: We did discuss that in the group, Jon, and I think we agreed that the Australian public sees mining as an important thing; it is something that they have to live with because economically it is vital, but they do not see that they are involved in the process of managing this resource or that they should feel ownership of it. That is what we were trying to get at with that land management issue. It is different; these two things are not the same. Recognising that it is economically important does not get you anywhere on the NIMBY debate, for example; you still have to say that it is important and we are engaged in extracting that wealth in a socially responsible way.

Chris Yeats: I think perhaps David put it best in the group. He talked about managing the mineral resources for the good of the community rather than looking at it as mining them for the good of the country. Maybe that is a change in mindset that we are looking at.

Steve Micklethwaite: You put a point up there right at the beginning of your talk on the idea of reassessing projects as you go along. So the environmental report at the beginning is not the only report; you revisit it as the project develops. I am just a bit worried about that because I can imagine a scenario where a mining company develops a mine and has an eightyear projection for the development of that mine; it is only going to make a profit after seven years and, if it has the rug pulled from under it halfway through the process—you know, four years further on—it means that it has a level of uncertainty and might be less willing to commit to projects. Could you unpack that for me a bit more?

Chris Yeats: We were not looking just at the case of a resources project; we were looking at land management more broadly. The situation that we have at the moment is that, if you have a mine, you put in a mine plan and you have eight years to mine it out; then you have a rehabilitation plan and then you sort of walk away. If you have a national park, on the other hand, you have it for eternity. There is a disconnect there. Once you have submitted a project plan—unless it is a 50year project; but if it is a 10- or 20-year project—there is no reason to reassess it during the course, unless you are just reassessing progress against the planned outcomes. What I am trying to say here is that, just because at the moment an area's heritage significance is considered to overrule every other consideration, it does not mean that 30 years hence, as society evolves, Australia's needs evolve and national priorities evolve, we do not need to look at that again and say, 'Well, hey, maybe'—because it is sitting on a massive uranium deposit,

for example—'we have to reconsider how we use this land.' So it was not about making projects stop and start once they are underway; it was more about being more dynamic about how we manage the land as a whole.

Frank Reith: Just on that point of having to be more dynamic: I suppose you can stand on either side of that debate, but I think that would be an absolute public relations nightmare. If you were going to say, 'Let's assess the national parks situation in terms of mining rights,' and so on, you will kill the mining industry in the public's standing for a long period of time because that is, I think, an issue that Australians feel very strongly about—and, in my opinion, rightly so—in that these national parks are put aside and probably for all eternity because, once you have deforested half of Tasmania, it will not regrow.

Chris Yeats: I do not want to focus overly on national parks. I am also not saying that we are going to do it for mining either. That is the whole point of the exercise—that at the moment we do. You put in an application to mine or explore somewhere, and it is just for that. I am saying that we need some sort of plan in there. We have multiple land-use pressures anywhere you go in Australia and it varies depending on where you are. That is why there are more mines in Western Australia: there are fewer people and so there is less pressure, irrespective of prospectivity. So I am saying that you need to manage these things in a flexible way.

It may well be that 100 years hence—I am just throwing out numbers here; they are random numbers—unless we move to nuclear fuels, the lights will be going out across our cities, for the sake of argument. However, if you are living on the edge of a national park where there is a massive uranium resource, you can bet your life that you will be getting pressure from the rest of Australia to reconsider those park boundaries or to find some way to work within the national park without having too much impact while still extracting those resources. These are the sorts of things that we have to consider and this is what we are trying to throw out there: an idea where you can be flexible, move with the times and move with the priorities around land use and be more holistic. It is not just about 'let's mine or let's not mine' or 'let's lock it away or let's not lock it away'. It is about how we deal with all those conflicting pressures and it is all about consultation and bringing all the stakeholders on board. As Peta Ashworth said yesterday, if people have made up their minds before they start, it is very difficult to change them. But the idea is that it is a long process. You may lay the groundwork for this 30 years before you need to do it, but you will bring a generation along and hopefully they will be more amenable to not having a knee-jerk reaction and to considering the more holistic picture.

Mark Tingay: I want to follow up on the topic of education. I really liked some of the points you were making on trying to change perceptions through education. I think one of the best ways that we can change perception long-term is through better education, in primary and high schools, of sciences in general and of the minerals industry and geosciences in particular. I know that already there are quite a number of good initiatives that are being done. CSIRO is doing a brilliant job through its public relations section and through things such as the Scientists in Schools program and I know there are changes in the science curriculum for high schools, but do people have other suggestions for perhaps improving our communication and relationship with kids so that, when they grow up in 10 or 20 years, we will have changed their perception in a longer-term and more fundamental way?

Sue Meek, Chair: I cannot resist putting in a plug for one of the activities that the Academy has been heavily involved in. It significantly pre-dates the decision to implement a national curriculum for science and other subjects, but the Academy has been working very hard with all of the state and territory governments to put together a program for teaching kids science in primary and early secondary schools. I am pleased to say that the program has been successful in getting into at least 50 per cent of primary schools so far, when we have not really marketed it yet. It is not about perception shifting; it is about getting kids engaged and interested and, hopefully, continuing to be interested in science.

Open discussion

Chair: Dr Phil McFadden

Nick Williams: One of the themes that came through quite clearly in our discussions in group A was that, to paraphrase Pete Betts who was also in group A, we need an Earth system geologic process modelling capability to model all of the different disciplines that we are experts in. Sure, that is a beautiful vision to have, but how do you implement something like that?

We have tremendous expertise in all of the different capabilities that are part of that. We have the geodynamic and spatio-temporal framework modelling capabilities; we have the fluid and chemical modelling capabilities with structure; and we have the physical properties and the geophysics and how they relate. They are all easily solvable problems and there are commercial packages available to do all of them, but what is missing is linkages between each of those based on knowledge of the geological processes. For instance, you could take a geophysical dataset and invert it for its direct parameter of interest, which is physical properties; but then you could take it further and say, 'Well, the physical properties are controlled by the mineralogy.' We could do that link, do that inversion and do that modelling. But then we have the mineralogy; that tells us something about the chemistry. We could take that further and model all the way through. But, with every step we take, the uncertainties get bigger and bigger and bigger. It is doable, but the uncertainties get bigger. So we need more data. We need to draw on the other disciplines to support that. So, if we are doing an inversion from mineralogy to chemistry, we need to know something about the isotopes or the geodynamic system; we need to feed that in there. A lot of those links are clear now; we could do them now, if we had the support to make that step. But then we could draw on expertise on giant ore deposits—and Rob Hough asked for more technological advances in our understanding of the linkages between different datasets and the phenomenon that we are observing. Katy Evans also pointed out the need for new technology to provide better data quicker, and that will support these grand visions of inversion. It is all possible. What is necessary is the linkages and the collaboration between interdisciplinary silos on how to make these things happen. It is completely doable. I think an Earth systems modelling vision is a useful one because, if we get these things working correctly for ore deposit research, they will also work for mapping groundwater resources or other geoscience issues that are important to government and to the Australian people.

Phil McFadden, Chair: I think Nick is making a very strong point and I would reword it in a slightly different way— maybe I am not quite as polite as Nick: the days of reductionist science only have gone; we now need to understand the system. That means that we have to take a cohesive, coherent and holistic view and we have to integrate it, in order to be able to get the knowledge that we want. I think that is a strong message to us as scientists, but I think there is also a strong message that needs to go to government about the implications and consequences of that. There are massive implications with this for data management. This is an issue that is facing all sciences, but I think it is one that is going to be absolutely massive in this area: we really do have to get a handle on holistic, cohesive and coherent data management, because that is the thing that will facilitate what you were saying. That, of course, has big implications and it has big implications that go much broader than just the Earth sciences because a lot of work is being done by a lot of other people and we really need to learn from them. We also have some wonderful things going on—and I think this is a point that we need to make—in the Earth sciences where we have solved problems that other people have not, and we need to be expansive about that and help others as well.

Rob Hough: Going on from what Nick was saying, one of the things that we have talked about lately is a kind of workflow of characterisation around the materials that we all study. People here are using various different techniques and approaches in how they study ore deposits or exploration samples, but how often do we do that on the same kind of material or, really, the same material?

One of the things that comes out of that is that the CRC structure is an effective way of having a national study of different research providers and industry of specific case study sites whereby you could operate a workflow that did capture that kind of information. Then, when you talk about data management, if you change behaviour so that from the very start you are thinking about some of the structures that the rapporteurs were talking about earlier in terms of information management, you do have the opportunity at the end to roll all of that stuff together. At the moment we do it all very disparately. We are doing it on different materials and there are excellent analytical facilities around

the country doing work on different materials. So, as part of what we were talking about—that is, once you get past that cover and you do have a case study site where you have done the drilling and you do have the material—having that kind of 'workflow', for want of a better word, around specific case study sites to pull all that stuff together is a very effective mechanism of taking that 'team Australia' approach to maximise the benefit out of the samples that you do have and out of the size that you are trying to do.

Phil McFadden: You have touched on something there that has come up several times in the presentations this morning: the need to have the broader discussion. I think two of you commented that you had not been in discussions like this before and that they are really quite important in order to get a broader range of ideas coming in, and that is something that is up to us as a community to do. So are there any ideas out there about ways in which we could keep the discussion going and growing?

Rob Hough: The national network that came out of our group discussion got quite a lot of discussion as to what kind of form it would take. It is an opportunity to have an event not just annually but perhaps more often than that. Quarterly workshops, for instance, are held by the EU networks. It's about having a network like that, which promotes far more regular discussion and invites the industry to attend; I think it is absolutely critical that industry people are in the room. One thing that came out very strongly in our discussion is that we have a bunch of researchers and a few industry people. There are some very clever people in industry who have lots of opinions and interests and it is important that we capture them in our research community.

Phil McFadden: Not surprisingly, there are some incredibly smart people hiding away in industry—and I say 'hiding away' not in a derogatory sense but in that there do seem to be separate pools of thinking. Are there any suggestions about ways we can build stronger and better integration between the real thinkers in industry and the thinkers in academia?

Jon Hronsky: I want to address that point more generally because, if we are going to do anything really powerful as a national initiative here, I think we have to engage the decision makers in industry. We have had a conversation about exploration policy, but at the end of the day it is AMEC and the Minerals Council of Australia (MCA). In this room, we do not have many representatives of the groups that would be the most important stakeholders in any conversation about exploration policy. In terms of the R&D space, I think we need forums that engage the industry decision makers with the researchers. I think the closest thing that we have to that in Australia—and I think we are quite lucky to have it—is the AMIRA Exploration Managers Conference. I think we need to build on forums like that that are prestigious and do attract the very busy industry decision makers; they do mostly find time to go to the AMIRA conference. But they need to come together and have these sorts of discussions around some sort of technology road map so that you get that uniformity of approach—because one of my concerns is that this group, the Academy of Science or whatever, could go off in one direction; but, if AMEC or MCA are going in a completely different direction, the chance of getting the traction that we want probably is not there. So I think it is really important that we bring AMEC, MCA and the senior decision makers in the industry into this through key forums.

Phil McFadden: Jon, you just mentioned something there and I have heard the phrase several times over the past two days: 'road map'—to some extent, I guess, a strategic plan about where you are going. But one of the things that we are missing is a road map that ties in a lot of the work that is being done by the academic researchers and the industry researchers and a plan for where we are going ahead. I go back to NCRIS. Twice we put in the effort of building road maps, which have really had a big impact upon directing where we put investment into science. But not only that, they have had a big impact on getting investment through government decisions. So my question to you as a community is—and do not forget that most of you still have a long time to go in this game, so you have the opportunity to make decisions and choices that will really impact upon your future careers—who is willing to get involved in building a road map, working together with the people in industry to build a road map of where we should be going? I am quite certain that, if we were to do that, it would have an enormous impact upon our ability to have a really genuine outcome.

John Miller: This is a follow-on point about having a national research network. When we say 'researchers', we do not mean only researchers in universities or CSIRO or wherever, we specifically mean that researchers in industry should also be involved with that network. One thing I have not seen come out this morning is that, if we are going to have innovation and think outside the box, we also need people who are not geoscientists involved in these sorts of think tank meetings. So we need to get in some biologists and physicists and people who are outside the box. So having Chris Yeats's group talk about policy when that is not necessarily what they do is actually a really good thing because they have probably come up with some ideas; whereas, if you got people who just do policy, they would not be

thinking in the same way. So I think we need to have some way of exploration science integrating with groups that are outside that space, because we have no idea what they will come up with. I do not think I have really seen that mentioned specifically in any of the presentations that have been given today, but it is something that I think we need to do if we want to have innovation in geophysics or remote drones or whatever it is.

Phil McFadden: You are dead right: bringing in people with a different perspective has enormous benefits. Look at Robert May, he was a physicist at the University of Sydney and decided to start applying his physics to biological problems. He then had a massive impact. He was President of the Royal Society and became Lord May because, by bringing a different perspective, he was able to bring a whole new way of doing things.

Peter Betts: Just listening today, I am getting two very different themes. The first theme is the need for a new generation of data, which was presented by the giant ore deposits group, and the second is new technologies. Both of those visions could form that road map and could run in parallel. The issue is that they are longterm visions. We are not going to map the continent in 10 years. So, to me, it seems as though there is a fundamental problem with the way we fund Earth sciences. We do a project base, so it is three years, then another three years and then another three years. You might get something like NCRIS, which is five years. But it is all short term. As a group, when the next opportunity comes up we digress off the path. So we never can follow that road map, unless we change the way we go about it. So, as a group, we need to say, 'That's where we're going,' and then we all have to go in that direction together. Until we behave like that, it is a bit like, 'Let's go up our road,' and then every five seconds we hop into a different taxicab and go a different way. To me, that is the big vision that we need to come up with.

Phil McFadden: Can I just endorse that? If we look at the astronomers, they have a decadal plan, which is a live document, and they keep it going. They come to an agreement within the community about what is important. They have built for themselves a strategic perspective: a road map of what matters and where they should be going. By that process, they get over many of the problems that you were talking about, such as *ad hoc* funding, because they use every funding opportunity that comes along to fund the next step that they have identified. Furthermore, they behave quite differently in ARC funding processes from the way that the Earth science community does. They have already made decisions about where the science needs to go. They make applications to the ARC and those applications go out to reviewers who then come back and say, 'This is fantastic science; this is wonderful; this is going in exactly the direction in which astronomy needs to go'—and the ARC gets the impression that astronomers do good science. The Earth science community, this community, needs to behave that way as well: make collegiate and community decisions about what matters and where it should be going and then provide support to each other in the funding process. By doing that, I think you will find that you can get over a lot of the issues that occur because of the *ad hoc* and disjointed funding mechanisms. So I would support that strongly.

Tim Baker: Just following on from that, one of the things that I am involved with is the AuScope2 steering committee. I am just wondering where this fits with what is going on in that space, because you run the risk—which Peter is alluding to—of having two types of decadal plans and, if they are not aligned, they may both appear in front of the Australian Government at some point. Government will look at the two documents and say, 'Well, this group is completely split,' or 'There are no links between the two.' I am just wondering how we can make sure that those sorts of links and plans are collaborative or in the same space.

Phil McFadden: You are quite right, and that is why I used the word 'community'. I did not mean just the people sitting here; I meant the Earth science community. I think what is happening in AuScope is important—and I am glad that you have mentioned that because one thing that is a little bit surprising to me is that, in terms of data, I have not heard anybody mention the National Virtual Core Library (NVCL) that is being created in AuScope and whether those sorts of initiatives are going to be valuable in the future.

Tim Baker: If you get into the detail of what we were doing, particularly in the giant ore deposits group, it was that the NVCL would be a critical component of the distal footprint mapping and the subsurface mapping through legacy drill core. So I think it definitely was on our agenda, but we just did not get down to the details in terms of what we have discussed today.

Phil McFadden: Fair enough. Let's get back to the presentations that have been made. In terms of the discussions that you had in your breakout groups, were there any burning issues that any of you want to put into the mix that did not get covered in the presentations?

Jon Hronsky: In terms of policy, from the view of my colleagues in the junior exploration sector represented by groups such as AMEC, we would see the whole access to land through the impediments of the heritage system as

an absolutely critical issue and one of the major difficulties impacting on greenfields exploration. The group talked about native title, and it is important to draw a distinction between native title and heritage because they are two very different things—without getting into the technical details. But as for policy around streamlining that whole process—and there are a lot of technical issues we could talk about—I do not think you can make a meaningful contribution to this debate if you do not try to address that issue, because it is one of the major sources of Australia's current competitive disadvantage. There certainly are innovative possibilities, I think, for dealing with that.

Campbell McCuaig: I think the giant ore deposits presentation really hit it on the head: a nice clear vision. Within the exploration policy group, I think we struggled in that we did not have expertise in actual policy creation, but I think we have come out with some useful things, particularly around land management as the overarching theme and changing public perception as the main driver. With data management, I think one of the key things that stops us is ourselves. In managing data, one of the key issues is the human factor and human behaviour. You have your stochastic uncertainties, which are incomplete data, and there are ways that we can recognise that and get around it. But then there are systemic uncertainties in that (a) we will all come up with a different interpretation of the same data and (b) we kid ourselves that we understand more than we do about how these mineralising systems work. I do not have the answer, but we need ways to capture that human element in there. The way I like to put it is: we want to produce tools that maximise the power of the computer but also maximise human intuition and minimise human bias. I think we have to have some sort of vision about how we are going to do that—and it is not easy; as I say, I do not have the answer. But one thing I wanted to see more of from our group was: if we could crack how to capture uncertainty better, it would also drive us to what data is required. Where is the sensitivity? What is the dataset that would resolve it best and basically resolve the two camps?

Phil McFadden: I think you are making a very strong point about us as people and the way we interact. I would just like to pick up a point that Neil Williams made but perhaps make it a little more forcefully than he made it. He used the example of Carstensz, who pitched up and said, 'Hey, listen, it's all flat. There's no metal here; we can be sure of that,' and that was built on the concept that they understood that minerals occurred in mountains and hills. So you go and look in mountains and hills and, yes, every now and again you find some minerals; therefore, you are right that minerals occur in mountains and hills. So you search some more and so on. That means that you totally contaminate your data acquisition process by going around in this tight little circle. I have no doubt that in 30 years we will look back at what we are doing now and say, 'You see, we did exactly the same thing.' So I think you are trying to target mechanisms to try to avoid that contamination in the way that we acquire that data and also more blue-sky thinking in the way that we target the question of what are the right datasets to answer the critical questions.

Campbell McCuaig: Also, in any data management model—we are really getting great advances in computing power and how we combine and fuse data—how we capture human uncertainty and propagate it through models is one of the key issues, I think.

Richard Schodde: I just want to clarify a couple of points. The audience for the outcome of this Think Tank session is ultimately the prime minister, so we really need to be quite clear about the sort of policy or recommendations that we are putting up. I saw a lot of confusion regarding the role of industry and the role of government. If you could unpack that, I think it would make our life a lot simpler. For example, I thought it would be very useful to look at public perception. I think that is a role that the AMECs and the MCAs of the world should take on, rather than the government. I just feel that, if you take that out of the equation, it simplifies the story a lot.

We should also be focusing on the outcomes. It is one thing to have a shopping list of good ideas that are relevant for the mining industry and, in particular, exploration; but it is also important to talk about the community-wide benefits that are associated with the activities and the proposals that we are putting forward. In particular, just to pick on the computational modelling side of things, we are talking about complex models that deal with information that comes from other complex models and how you make all of those systems talk to each other in order to get the maximum value out of that data. I am not a computer type of person, but I got the sense that you are trying to talk about a universal language translator that helps you interface that information from one database to another or one model to another. That has application universally across all systems; it is not just something for the mining industry. So, if you can sell the story that developing those sorts of interfaces and coming up with a common or universal language will have a very powerful or beneficial impact on the rest of Australia's industry and society, it gives you a much stronger leverage for when it comes to talking to the prime minister.

When it comes to putting up recommendations to government, we should also be talking about the national interest as well. In the case of, say, new technologies or innovative thinking, we should be thinking about things that have

a special application to Australia rather than a universal or global application. It is one thing to come up with a 'you beaut system' for finding ore bodies; but if it happens to be finding ore bodies in Canada rather than Australia, then we really are not doing ourselves much of a service there. So I feel that there is a bias here—or my bias would be things that lead to local benefit, such as getting detailed data on deposits. The interface of the regolith and lithosphere in Australia has direct application to deposits here and you can make the case that there will not be much leakage outside of Australia of the commercial application of this knowledge.

So really my point is that we are asking governments to assist us in finding the next generation of world-class mines, but the actual exploration is going to be done by the companies themselves. What we are really trying to do is put together the information, and open access to that information, that is going to lead to those discoveries, but the actual discoveries are going to be made by the companies themselves.

Phil McFadden: I think it is very helpful to make those distinctions to help clarify our thinking. I agree entirely with Richard that it is going to be up to the private sector to do the exploration, but we are seeking here to come up with suggestions for government whereby, in their role in providing the environment in which that can happen, they will come up with some of the better solutions and remove some of the impediments that we see—because sometimes they have impediments in place that they do not see but we do.

Chris Yeats: Just picking up on a point that Richard made there around interoperability and models talking to each other, one thing that we did not hear much about in the data session was the AuScope Grid Project, which of course is a major project to do just that. We have Ryan Fraser, the AuScope Grid Project Manager, here and I wonder whether he would like to make some comments. I guess that I am asking where we are at the moment and where you see it going in the future.

Ryan Fraser We have been making some progress towards making the geological surveys' data available, mostly the precompetitive data, focusing on some of the geological information such as coverage data and Earth resource information. We are making a start on that, and that is all coming out via a standardised format; GeoSciML is an interoperable standard. They are also taking that up in the EU: there is a project called Inspire, which is mandating that all the geological surveys over there funded by the EU exchange their data via the same format. It is also occurring in the US. So we are following down that same path. The only thing that the EU has over Australia is that it has a mandate and it explicitly says that the geological surveys must exchange their data in this format. So AuScope Grid has been funded to enable that process to occur within Australia with the geological surveys and now with Geoscience Australia. We are also now venturing out into other domains—in particular, the Bureau of Meteorology and various other departments. We are funded for five years and will be completing at the end of this financial year. We are looking at the AuScope2 bid being followed up by possible NCRIS bids. Bascially, the intention then would be to deliver that to a larger scale and make more datasets available, listening to industry and to researchers to see what datasets are of significant interest and to make them the highest priorities.

Phil McFadden: Perhaps I could just add a comment to that. In AuScope they have, at the theoretical level, solved a lot of the issues that have gone to true data interoperability. That has been achieved within AuScope largely through the group run by Rob Woodcock in CSIRO. The point I make is that is actually a genuine addition to the national innovation system. It will have an impact that goes well beyond the Earth sciences. I just use that as an example because there are so many instances where, in the Earth sciences, we are dealing with a large—and I use the word in its correct sense— 'complex' system rather than just a complicated system; we are dealing with a genuinely complex system and we are solving problems that add to the national innovation capability. I think we need to make the point that the issues we are dealing with here are big enough, complicated enough and complex enough that, when we solve them, they have broad application across the whole of the sciences so that, in fact, doing top quality research in the Earth sciences has major spin offs into a whole pile of other areas.

Ryan Fraser: That is true. Our research, which has been aimed at the geosciences and Earth sciences, now has applicability in other areas. We are also looking at demographics and we have just received an additional $2 million worth of funding to take that into other areas, such as Aboriginal heritage information. The applications in the services and software that we developed primarily for the geosciences and Earth sciences have now had applicability into other areas.

Phil McFadden: I would like to focus the discussion in a slightly different direction. Richard Schodde, I think, has made a useful separation between industry and government; but I am going to add to that academic research ability, and then I think we have the three sectors. I want somebody to stand up and say, in terms of the interaction between the academic community and the industry community, what is the most critical thing that we have to do to improve our

ability to find giant ore bodies?' Also I would like to know what you think is the most important message we could send to government about a genuine policy change that could impact upon this problem? I think we need to be able to show that we have been thinking about these things and genuinely have some suggestions.

Tom Whiting: I think, on that point, there are a number of benefits for the country which need to be emphasised in the report. One of those is that there are a number of growth mechanisms and, obviously, finding new resources is one. But, along the lines of your question, the other one is that one of the biggest and fastest growing sectors and a sector of great importance to the country is the minerals services sector. So we should be emphasising that, if we do this correctly and commercialise the results, it should grow that sector, and that would be of major benefit to the country. In terms of your question about how that enforces the link between the academic world and industry, I think that is the missing link at the moment. That is why a lot of our technologies do get stuck, because the link is strongest between the mining industry and the academic world and not between the services sector and the academic world. We have to make that triangle work better. The payoff is in growing the minerals services sector, which is a payoff to the country—because, if we want to have the best Earth sciences foundation, we have to build not only the R&D sector but the services sector, which after all supplies the services to the mining companies—and the surveys.

Jon Hronsky: Firstly, taking up Tom's point about the service sector, I think an idea that came out of one of the groups— they did not use the term 'incubator' but, I think, 'preventure capital'—was that it might be important to have that sort of incubator type approach, which is used in high-tech industry, to be joint industry –government funded in order to build that interface between the outputs of the research and, potentially, the next generation of service sectors. But the point I would make is that the critical thing about engaging with industry is to engage with the decision makers and get the input at the right level. I think all too often what happens with the research communities is that the engagement is horizontal, from people doing the research to people in the companies who might be interested in the research and champion it but who are not necessarily decision-makers. So a lot of the engagement then really depends on the power and influence of those individuals, which can be variable. I think there is this concept—we talked about it a lot when we tried to get funding for the DET CRC, which I think was successful— of the zipper model of engagement, which means that you have multiple points of contact. So you do have to engage at the level of the technical gatekeepers in the company, but you also have to engage at the strategic level—and that gets back to the concept of a road map.

One of the things about engaging with senior decision makers is that they will only give you their time if they think it is important to do so. So, first of all, you need forums that are prestigious where they have peer pressure to attend or even pressure from their managers; secondly, they need to be around outputs and decisions that make a difference so that, if they are there, they feel that their time is being used in a valuable way. With that, I think we need to make sure that we engage not only with the big end of town—it is fine for the prime minister to do a deal with three large mining companies—but with the entire spectrum of the industry; and we do have groups that can represent different parts of the industry. If you start to get those people together around a road map like this and get genuine alignment so that everyone really understands the business proposition that is on the table, I really do not think industry funding would be an impediment. I think the potential untapped amount of industry funding for research in this country is very large. You can look at what has been put up as untied cash for the DET CRC—the best part of $30 million—and you can look at what CET in Western Australia has got from the industry over a relatively short life—$7 million to $8 million of direct cash contribution. So it is there, but it is all about them seeing the value of the proposition and seeing that it is important.

Zhaoshan Chang: Following on from your question about how to encourage academia to have more interaction with industry, I would say that we have lots of interaction with industry. One thing is that having lots of interaction with industry in helping with exploration obviously takes a lot of time and your publication rate drops, and currently the evaluation of the output from your researchers mostly depends on publications. I think that is one of the major things that prevent researchers from having more interaction with industry.

David Beck: This is a very different line of thinking from the last comment. I am a mining engineer and I would like to applaud the big picture thinking. There is a fantastic opportunity in forums like this to cover big picture issues. But I wonder whether we didn't need to start finding some of the large world-class mines—the ones that we are going to start after Cadia East—a few years ago and perhaps we need to start finding the next mines tomorrow. I wonder whether researchers with fantastic new tools that appear to have obvious applications are missing the mark with industry—and I am a part of that—in that it is being sold to us as, 'Here's a generic tool for mapping all of Australia'; whereas, if you went to the main landholder in a mineral province and said, 'Here's a fantastic new tool that can uncover new information in your province that you have the greatest interest in,' perhaps you would get more traction for obtaining immediate funding.

Chris Chambers: I am not sure whether this is the forum for this question: as a policy issue, if government is to provide an environment in which to explore and remove impediments, how does the proposed mineral resource rent tax do that, particularly in the context of competing with other countries for exploration and investment?

Peter Betts: I have two comments. The first is about what universities value, and it is definitely metrics on publications; we cannot escape that. We get valued and judged that way and our performance is completely managed that way. The other way we get judged is on income. You are seen as being equally important if you are bringing in large amounts of cash from either Australian Government funding bodies or external companies and, if you do that, you get put on a pedestal. But I think the biggest impediment is not that driver; it is the expectations of the university sector and the exploration sector and it is the time frames in which we can turn research around. For example, I have lots of conversations with companies and they want me to produce what could be research in a couple of weeks. To me, that is not research but consulting. That is how I treat it and I hand all my IP over to that company in that situation. The time frames for research usually require building a project and getting a student or a postdoc involved, and they take many months or years to do. Then the company has lost interest because they are focusing on a different problem by then. I am not talking about a big vision here; I am talking about project based research. So managing our expectations and what we can deliver, for example, as researchers versus what the companies require is, in my mind a big impediment.

Ian Graham: I would like to pick up very much on Peta Ashworth's comment, as it reflects on all of us in academia. Our departments are getting smaller and smaller, in terms of staff, and we do more and more teaching. Because of all that teaching we have less and less time to do research, and companies certainly do need that time line. I get companies coming to me all the time that want research done, but they want it done within a few months—and the time is just not there to do it in that time period.

Graham Begg: About eight or nine years ago, Jon Hronsky and I sat down and decided that, to understand giant ore deposits, we needed to map the subcontinental lithospheric mantle. In a somewhat audacious move, we embarked on mapping the whole world. Now, why did we do that from within a company? We have a partner, which is Macquarie University, in doing this. But why was it not already happening would be probably the most relevant question and the answer would be that it is the way that research is funded and researchers are rewarded in our country. The pie is diced up into very small pieces, although the creation of the CRCs has helped mitigate that to an extent. There is the opportunity for collaboration across bigger groups, and a new CRC, which is 'core to crust fluids', is operating on that scale. So there is an opportunity to tackle the really big scale. I think a lot of researchers are now becoming more aware of this big scale and there are networks available now for us to work across, together, perhaps informally, outside some of the CRCs to manage some of these bigger scale problems. When we embark on these, inevitably there are multidisciplinary issues and, in dealing with multidisciplinary issues, you need boundary spanners. So you need people who can talk to the geophysicists as well as the geochemists, the petrologists *et cetera*—the computational people—and help everyone to see the common thread and realise the most powerful outcome. I think that is something that is very much needed in our community.

Phil McFadden: I will just make the comment that I am hearing a shift in, you might say, the academic way of thinking. Now we are beginning to see a demand for mechanisms that facilitate and encourage greater collaboration and greater capability to take a strategic approach to things rather than a bitwise approach.

Steve Reddy: I want to pick up on comments that a couple of the speakers have made about publications in academia. One of the things that we are being told at university is that we need to focus our research efforts on publishing in A* Excellence in Research for Australia (ERA) journals. That directly links to our funding; we are told that we need to increase our publications or to write in areas that are receiving lots of citations. We all know that various subdisciplines of geosciences get more citations than others and one of the things that that is pushing us away from, in my opinion, research in mineral systems: they just do not get the right citations. There is another thing that we do not get in that ERA process: there is no assessment of the impact of that research. One thing that government should be doing to encourage research in all minerals systems is to look at the impact that research has on something and giving that some kind of metric. I know it's is a very difficult thing to do. If in your research you could incorporate a metric that takes account of impact on society or the economy, that would be a huge benefit and would push more people towards this kind of research.

Unidentified speaker: I think the most important thing in industry and academia working together is that we both get onto the right wavelength in our thinking. I think industry wants outputs, through our research outcomes, that they can use immediately in their practice. So, when you do a project with industry, to me, the most important thing

is the project management where you plan your project so that you have a sequence of intermediate outcomes that can be provided to industry.

I would like to comment a little on Campbell McCuaig's comment about subjectivity in data analysis. Our group in its discussion did cover a little of that. It is a very difficult problem, as you can imagine. It covers areas of psychology and it covers areas of how to enhance your data, how to extract your features and also, more importantly, how to visualise multidimensional datasets. So I think there is a multidisciplinary issue in that the transfer of knowledge between different disciplines is, I think, a really important key to solving a lot of problems, including that subjectivity issue.

Gideon Rosenbaum: I think that one of the problems in the current climate is that it is very difficult to work on mineral deposits from a purely scientific view as academics; we lack the wealth of data that exists in the industry. If we do get access to that data, we have problems with confidentiality and publications. Therefore, in an ideal world, we would have free access to this wealth of data and be able to look at that data in academia and publish our results in peer reviewed journals, and that could be a key to mineral discoveries.

Phil McFadden: This whole issue of access to data—data being an infrastructure and an asset—is a growing issue across the whole of the sciences and I think it is something that we really do have to solve.

John Miller: I have worked a lot in the past few years integrating projects between industry and our centre. In getting research projects with companies, researchers have to understand the structure of the companies, but one of the mismatches is that they do sometimes think differently. They are all solving problems, but a lot of the time when academics are working on a research project they are thinking, 'How do I get this published in a high-impact journal?' and a lot of industry is dominated by solving problems. Sometimes that highimpact research lines up with the problems that the industry needs solved—and, if you do that, you will get the money. If your project is something that is relevant to industry and it is also highimpact, then fantastic. The problem is: when you do not get that feedback from industry but understand the structure of the companies and still cannot get the thing funded, you have to really invest in blue-sky, highrisk research. I think that is our problem with this vision that we have of building an architectural model of Australia. We then have to engage to find a way of solving that in the way that industry solves a problem rather than lining up a series of Nature papers, Science papers or whatever. So I think that is one of the differences: industry solves problems, and we solve problems in research groups, but we also focus on things that will produce high impact science papers.

A good example for me is that I have a paper that has four citations; that is the paper that describes the discovery of the Golden Gift ore body, which is producing over 100,000 ounces of gold a year. For the company, that was the highest bit of impact from that research project. In terms of scientific impact and the way it is judged according to the way you would look at a peer reviewed journal, it has a very low impact. That is the sort of mismatch you can get in terms of how you judge the impact of a project. We need to think about that. We are trying to solve a problem and I would prefer to see our putting in place a series of mechanisms to solve that, rather than immediately thinking, 'How do we get this as highimpact research?' That is one of the mismatches that you see between industry and academia, and I have seen it quite often.

Phil McFadden: I think John is leaving us with a fairly strong message: as scientists, as people, we have to make a decision about what we value as impact, identify therefore the audience to whom we are really talking and speak to that audience in order to make certain that we get the maximum impact that satisfies our soul.

Maxim Lebedev: From my point of view, one of the problems with cooperation between researchers in academia and researchers in industry is lack of information. Maybe a national database of our research capabilities can solve such a problem—I do not know what the people who are sitting just behind me can do and industry does not know either.

Phil McFadden: I am trying to solve precisely that problem in a different community. The way we are trialling a solution is to build a dynamic, active database in which all the people on a weekly basis update their skills and what they are doing, and it is already having quite an impact. I think you are right: we need to think about those sorts of things. But we do need a better information flow and we do need to be smarter about the way we make use of the tools that already exist, and that comes back to making better use of what we already know. If we spread that knowledge around, we get a better outcome from it.

Summing up

Dr Neil Williams

My job now is to hold up a mirror to you all and reflect back some of the key messages you have delivered. In holding up that mirror, I am going to address three big questions: 'what?', 'who?' and 'how?' The 'who?' question is not one that I spoke about in my introductory talk, but it has clearly emerged as a huge issue. I think we have captured the 'what?' pretty well at a highly distilled level: a strong case has been made for more data in deep frontier areas. As we drill down into what has been said about the architecture of the subsurface lithospheric crust of Australia it is clear there is much more we can do in this arena to facilitate the discovery of new world-class mines. For example what can be done to delineate big subsurface plumbing systems; and what are the geochemical signatures of old erosional surfaces *et cetera?* These are good ideas, especially when coupled with some of the issues brought up in the open discussion—such as how can we better link geology, geophysics, geochemistry and mineralogy.

The 'who?' question is complex and I have identified five 'who' groups. Firstly, we have the minerals industry which, by and large, means the mineral exploration companies. They can be big, intermediate or junior companies. In the case of junior companies some operate mines in addition to exploring, but most are only involved in exploration. These companies tend to be the AMEC members, whereas the large companies tend to be the MCA members, and often ne'er the twain shall meet when it comes to exploration thinking and the positions their representational organisations put to governments. Next we have the academic communities within our universities where the priorities are research and teaching. In the research are we also have publicly funded research agencies, the main one as far as mineral exploration is concerned being CSIRO—who undertake a huge and important research programme in mineral exploration activity. Then we have the state, territory and Australian Government geological surveys whose prime function regarding mineral exploration is the provision of precompetitive data to promote investment mineral exploration and, additionally in the case of some of the state and territory surveys, there is the additional role of maintaining open and closed file systems for all previous exploration in their jurisdictions. Much of the work of the surveys is actually research work, but their research is complementary to that of CSIRO and the universities. Often the three research groupings work together even though they have distinctly different functions and roles to fulfil. Finally we have the service industry that supports the exploration industry and in this group the priority is the development and application of technologies to enable the explorers to do their job better. Often the service industries collaborate with the other 'who communities' particularly at the R&D stage of technology development. These five very different groups all have different stakeholders, funding mechanisms, roles and functions, and I am therefore not surprised that you have raised the issue of how geoscientists in these different groups have challenges when it comes to communication and collaboration.

Your cry for better collaboration between the groups is an important one to address, and your suggestions for forums to facilitate interactions between groups is one we need to support strongly in our final report. You also proposed a national research network to facilitate better communication between researchers amongst the different groups and that in my opinion is another initiative we need to support in our final report. My experience has been that such a network will work best at the pure research end of the spectrum, but can get more challenging at the applied end of the spectrum dominated by industry and the service sector. Difficulties we will need to work around include issues relating to confidentiality of information and the ownership of intellectual property. These difficulties can be overcome as any of you who have worked in CRC's will know. Related to the research network proposal you also suggested it would be great if there could be regular meetings like this. We would need to consider how such meetings would be funded but I think the idea of regular meetings of the members of all the groups would do much to facilitate greater communication.

A related point was put forward by the technology group, and this was important, of ensuring that the service industry becomes better connected the other research groups. The idea of embedding researchers from one group into another is excellent and the proposal revealed that the Academy of Science has also been thinking about this too. And that is something this workshop can build on and reinforce.

We also heard a few comments that are worrying. One such issue I have summarised as 'career instability'. We heard that some people are concerned that they have short-term appointments or are in a short-term funding situation,

such as for example, being attached to a CRC, that is likely to be wound up. This instability is not conducive to good long-term research in an area where, if you are going to unravel the 3D architecture of this country, you need a long-term effort. This is a problem and I don't know what the answer is. However, based on my experience of leading Geoscience Australia for the past 15 years, I think an issue like this has to be tackled one step at a time. Planning in an environment where funding is short-term requires skills to secure short-term funds, and to roll the funding over as the research evolves. Now, that is easy for me to say in the case of an Australian Government Survey but I don't know how you would best do this it in the university community, for example. Maybe we need an initiative to better develop good research proposal skills amongst our younger researchers, and skills to better plan long term research that progresses in short-term steps.

Turning now to the 'how?' question, we have a large amount of relevant material that is all recorded or has already been written down. In the technology and science areas, there seems to be strong agreement about building a research road map. For me, the question is: 'who does that and who is the audience?' Is it the presentation for PMSEIC that we hope will arise out of this Think Tank's recommendations, or should it be an industry driven issue?

We heard a lot about data management, standardisation, exchange and interoperability and my feeling is that a lot of that is happening already. I did not hear a strong view that there is not a lot of action in this area already. I heard and appreciate that the work is challenging and complex, and I also heard that those involved recognise the importance of strong support from their leaders for these activities. The fact that this is already an area of strong activity and collaboration suggests to me that the relevant leaders are indeed providing good support. We also heard some ask 'Do we need more data?' I think that this area is probably being looked after pretty well already through the NCRIS process and some of the other activities that are going on. On a related issue I did hear coming through loud and clear a concern about the issue of contamination bias in the data that we collect, and that is a serious issue. I heard a cry for national databases and information services whereby we can keep tabs on who is doing what and how data sets are being massaged. This, in fact, might be an issue that the proposed research network could have as a standing agenda item.

We also heard people ask how we go about doing the 'big' science research. A national deep-drilling program has been aired. I am attracted to that because it is visionary and it makes a lot of sense. There are great precedents in the world, such as the Integrated Ocean Drilling Program. If you do it in that way, it is competitive and this makes it attractive to research fund providers. But if we do go down this route I think it should be linked to parallel proposals for the deployment of new and more cost-effective and scientifically useful data acquisition systems. I like the idea of putting out arrays of magnetotellurics (MT) and passive seismic equipment in areas where deep drilling is proposed. Any activity like this that accelerates our ability to image the Australian crust using easily and cheaply acquired geophysical data should be encouraged.

Regarding MT, we heard a lot about the huge potential of this technique. However, we also heard that it is a cottage industry activity focused at a particular university and that there is much to be done to realise MT's full potential. If this is in fact the case then I think there are some recommendations that we need to make to grow the application of MT to the elucidation of the Australian crust. There may be other potentially useful geophysical data acquisition systems to which this comment could also be applied.

In the 'how?' question discussions we heard a lot about time frames and what needs to be done in the short term, and what should be done in the long term. In our report I think we need to stress that the challenge of deep exploration involves the unravelling of the 3D architecture of an entire continent – something that is certainly not a short-term issue. The challenge can be met via little short-term steps, but to succeed you have to maintain the expertise, the momentum and the intellectual property over the long term in the relevant areas. We must give the activity the time to achieve this big goal. That is not to say that people should not have to justify their existence from time to time, but we do need stakeholders to recognise that this is a long-term endeavour with long-term pay-offs.

So, just to summarise, I think we have in our grasp an exciting vision of what it is that we want. I think we have some exciting 'how we can do it' ideas about realising the vision of unravelling the 3D architecture of the Australian lithosphere; ideas about deep-drilling programs and new geophysical approaches, including new systematic ones; and we have some ideas for gingering-up related research in the university system. I think all of that is the stuff of an important new initiative that will come to fruition as a result of this Think Tank. You have all done a great job, and I thank you all for your contributions.

Early- and mid-career researchers

Dr Benjamin Ackerman

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Ben has spent ten years in minerals exploration as a geologist, both in industry and research roles. During this time he gained experience in gold and base-metal exploration in New South Wales, Victoria, Western Australia and Fiji, where he has managed exploration programs for porphyry copper-gold, epithermal gold deposits and industrial metals. He obtained his PhD in geology from the University of Wollongong for work on the geochemical exploration of the Girilambone region of New South Wales and continues to further his interest in mineral exploration in his current appointment as District Geologist with Newcrest Mining Limited in Fiji.

Ben will contribute to the theme of the Think Tank through experiences gained in mineral exploration in Australian and Fiji, which have included deep diamond drilling, exploration under more recent cover sequences and successful discovery and advancement of copper-gold deposits. He has designed and managed all aspects of mineral exploration in regions ranging from arid to tropical, and has stayed abreast of new technologies in mineral exploration and exploration drilling both in Australia and internationally. Having practiced mineral exploration in several physical, political and social settings, Ben has developed a broad understanding of the challenges in further resource discovery in Australia.

Dr Graham Baines

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Graham is a geophysicist whose research integrates geological observations with geophysical data, primarily magnetic and gravity surveys, in order to understand the geodynamic evolution of Earth's lithosphere. Having completed undergraduate studies in geology and geophysics at the University of Liverpool, he undertook PhD research in geophysics at the University of Wyoming. His PhD research used bathymetric, magnetic and gravity data, together with geochronologic dating and numerical models, to determine the tectonic evolution of $>130,000$ km^2 of oceanic lithosphere at the Southwest Indian Mid-Ocean Ridge. Since completing his PhD he has moved to Adelaide to take up a postdoctoral research position at the South Australian Centre for Mineral Exploration Under Cover (CMXUC), where his research integrates seismic, magnetic, gravity and sparsely distributed drillhole constraints to determine the basement architecture and evolution of the Archean-Mesoproterozoic Northern Gawler Craton, where it is buried beneath sediments of the Eastern Officer Basin.

Mineral exploration in Australia is increasingly focusing on exploration for deposits that are buried beneath or within layers of sedimentary cover. Locating such deposits requires the use of geophysical techniques to remotely sense and locate prospects. Graham's work at CMXUC has primarily focused on the integration of geophysical datasets with known geology to image the geology of basement in areas of significant cover. Integration of expertise and development of methodologies to accomplish this more efficiently have the potential to greatly assist in the next generation of minerals exploration in Australia.
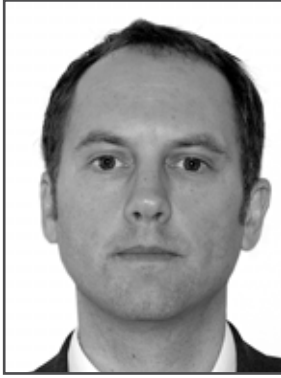
Dr Tim Baker

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Tim has been the Manager of the Geological Survey of South Australia since 2009. Prior to this he held positions as Exploration Manager for Sovereign Metals Ltd (2007-2009) and lecturer/senior lecturer in mineral deposit geology at James Cook University (1999-2007). He has published over 100 scientific articles in mineral deposit geology and presented at numerous national and international meetings. He has received international awards for this work, including the Lindgren Award from the Society of Economic Geologists. This prestigious cited international honour is presented to a researcher under the age of 37 who has made an outstanding contribution to the discipline. He received a BSc (Hons) degree from the University of Wales, College of Cardiff in 1992 and a PhD from James Cook University in 1996. He carried out postdoctoral research at the Mineral Deposit Research Unit, University of British Columbia between 1996 and 1999.

Tim has an international reputation in economic geology, developed through the past 14 years in academia, industry and government. He has carried out multidisciplinary research, exploration and consulting on a wide range of mineral deposit types in geographically diverse regions. His research activities have involved a wide range of partners including junior to major exploration and mining companies, universities, government surveys and competitive research funding agencies. His roles as an exploration and government survey manager have provided a cross-disciplinary perspective on industry and government. This includes experience in managing and executing exploration programs, interacting with diverse stakeholders, and developing a practical understanding of exploration, mining, infrastructure and environmental and social sustainability issues within the minerals sector.

Dr David Beck

Principal Engineer, Managing Director, Beck Arndt Engineering Pty Ltd
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David is a mining engineer working in the field of rock mechanics and mine design for complex and difficult geotechnical environments. Since forming Beck Arndt Engineering (BAE) in 2005, David has led and provided advice to geotechnical studies for some of the largest and deepest open pit and underground mines in Australia, South Africa, Indonesia, the USA and Canada. In many cases, BAE's work involves the conceptual development and optimisation of projects in deep or difficult geotechnical environments at the limits of current industry experience. BAE has developed tools and techniques for better integrating geophysical and geological data to better forecast risk in these uncertain environments and continues research in deep mine design, forecasting mine stability, and seismicity and hydromechanical simulation. Before forming BAE, David worked as a consultant and prior to that as a rock mechanics engineer for Mt Isa Mines, where he completed a PhD in the engineering management of induced seismicity in deep level hard rock mines.

Over the past decades the global mining industry has achieved continuous improvement in productivity through technical innovation. The most significant technical improvements have been in mechanisation and processing. In the fields of rock mechanics, deep orebody exploration and mass mining, innovation has struggled to keep pace with the needs of industry and society. Only pits and block caves have deepened or grown in size quickly and anecdotal evidence suggests current methods are nearing physical limits. Incremental improvements to old techniques will not keep pace with the challenges and problems of increasing heat, rock stress, seismicity, transport costs and difficulties in gaining orebody knowledge. These vulnerabilities will need to be addressed with step-change innovations. Current models for risk management applied during the design and operation of mines will also need to change. In the future, mines will need surer- and higher-resolution geological and geotechnical information and more robust designs. David's experiences in working on mines facing these challenges over the past 15 years will provide valuable input into discussions on resource policy, exploration, geophysical programs and mine planning.

Dr Graham Begg

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Graham has a BSc from Melbourne University and a PhD on epithermal gold systems and tectonics from Monash University. During 22 years with Western Mining Corporation and BHP Billiton he gained experience in exploration for a variety of commodities and from 2002-2007 was responsible for the global targeting framework for project generation. For the past eight years he has also been a principal investigator in a (WMC/BHP Billiton) collaborative research project with the ARC National Key Centre for Geochemical Evolution and Metallogeny of Continents (GEMOC) group at Macquarie University, Sydney. This project aims to create the first detailed map of the global continental mantle lithosphere, to facilitate a breakthrough in both understanding the controls on giant ore-forming systems and, by extension, greenfields mineral discovery. In 2007 he formed his own consulting company Minerals Targeting International Pty Ltd. He was the 2009 International Exchange Lecturer for the Society of Economic Geologists.

Graham will contribute to the Think Tank in several ways. Firstly, through his world-leading expertise in the 3D structure of continents, the relationship between crust, mantle lithosphere, tectonic setting and geodynamic processes. Secondly, through his understanding of how this provides the context for the spatial and temporal development of ore systems and giant ore deposits. Thirdly, through his broad understanding of the many scientific disciplines required to enable integration of the diverse information types. Finally, through his familiarity with the minerals industry; the exploration process; and the tools available to explorers, government bodies and research institutions.

Dr Elena Belousova

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Elena graduated with a BSc (Hons) degree in geology from Kiev University, Ukraine in 1988. She obtained her PhD degree from Macquarie University in 2000, studying the trace-element signatures of zircon and apatite in a wide range of rock types and mineral deposits. Research interests include the timing and nature of the growth of Earth's continental crust; essential knowledge for a robust framework for resource assessment and exploration. Her ARC-APD (2003-2006) work has shown a new approach to crustal evolution studies and contributed to the development of the TerraneChron® methodology, which is now a powerful technique for the Australian (and international) mineral exploration industry. The competitive Vice-Chancellor's Innovation Fellowship was awarded to Elena in 2006, and represented further recognition of the potential of TerraneChron®. This mixture of fundamental and applied research has resulted in her publications appearing both in high-impact journals and in those that reach the exploration-oriented end-users.

Elena's research, since her PhD, has been instrumental in developing leading-edge geochemical methodologies, based mainly on zircon geochemistry, in providing a tool for geochemical and tectonic remote sensing of inaccessible regions on the Earth's surface and in the deep crust. Her diverse research expertise in geochronology, geochemistry, analytical methodologies and field expertise, directed to understanding the evolution of the Earth's crust, provides the ideal background for further innovative ideas and developments that could be inspired through interaction with research from a broad range of relevant disciplines as well as professionals from industry attending this Think Tank.

Dr Stephen Beresford

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Steve's career is a mix of academia and industry, including tenured faculty at Monash University; professor at University of Western Australia; principal exploration geologist in nickel at Western Mining Corporation; manager of project generation (ASA) at BHP Billiton; and commodity specialist. His current positions include Chief Geologist of Minerals and Metals Group and Adjunct Professor at the University of Western Australia and Monash University. Steve continues to supervise students, publish papers and give over 10 workshops per year on exploration. In academia he has published over 50 papers, supervised over ten postgraduate students and five postdocs, and received competitive ARC grants and industry funding worth more than $4 million. In industry he has been involved in, and led, exploration groups in 32 countries, on all continents except Antarctica.

Steve's speciality is at the earliest stage of exploration – that is, area selection or project generation. His career has been uncommon, holding senior positions in research and exploration while still mid-career. He believes that the unique perspective gained through his various positions and his speciality in one portion of the exploration value chain will be his main contribution to the Think Tank.

Dr Peter Betts

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Peter is a senior lecturer in the School of Geosciences at Monash University and a senior partner in a small consulting firm, PGN Geosciences, which specialises in geophysical interpretation and modelling for the resource sector. His primary research interest is the integration of structural geology, aeromagnetic and gravity interpretations to understand geological structures and their signatures in large-scale magnetic and gravity datasets, with an emphasis on continental evolution and controls of mineral systems. Peter has an international reputation for developing plate tectonic models for the evolution of the Australian lithosphere during the Proterozoic era and has published 55 peer-reviewed papers in international journals. He is the chair of the Geological Society of Australia Specialist Group in Tectonics and Structural Geology. He also consults widely to international exploration and mining companies; including geophysical interpretation and modelling for terrane analysis, mineral targeting, and construction of 3D models.

Peter's research skills are in direct alignment with the theme of the Think Tank. His current research activities include mapping deep Earth structures in the Australian continent using the Earth's magnetic and gravity fields and he is one of Australia's leading geoscientists in constraining the tectonic evolution of the Australian plate, so he can provide geological context for the discussions. Furthermore, he has undertaken research in understanding Proterozoic mineral systems in north and south Australian terrains and regularly consults for Australia's mineral explorers, so has an understanding of the applied difficulties associated with mineral exploration.

Laurie Callaghan

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Laurie has worked for over ten years as a software developer at various large and small enterprises, in both the public and private sector. He has been with Intrepid Geophysics, a leading company in geophysical processing software development, for the past five years. He is interested in processes for improving software development practices, enhancing the usability of complex software systems, and extracting better performance from recent and future computer hardware advances. Laurie holds a BSc in computer science from the University of Queensland.

Effective use of information technology is a critical part of our resources industry. Future developments such as the proposed National Broadband Network will increase its capacity. We must devise strategies to use this increased capacity to increase our capabilities. Laurie combines a broad interest in many areas of science with a strong focus in IT as a practical tool to help solve real problems.

Chris Chambers

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Chris holds a BSc (Hons) from Flinders University of South Australia and has 15 years of continuous industry experience as a mine geologist, exploration geologist and property-generation geologist, in four countries. He has had exposure to eight styles of gold and base-metal mineralisation but specialises in low-sulfidation epithermal gold mineralisation. During his career, Chris has worked closely with Earth science students and researchers from the ARC Centre of Excellence in Ore Deposits (CODES) at the University of Tasmania, the Economic Geology Research Unit at James Cook University, the WH Bryan Mining Geology Research Centre at the University of Queensland, and a variety of industry consultants and experts.

In his role as an explorer, Chris has two main research areas:

- *the zonation and gradation of host structure characteristics, vein textures and multi-element geochemistry in relation to gold enrichment; and*
- *the role of far-field and near-field stresses on the enrichment of gold.*

Much of Australia has been tested for mineral deposits but only to relatively shallow depths. Chris sees the recognition of zones that are peripheral to mineralisation as a key driver of future ore discovery at depth.

Dr Zhaoshan Chang

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Zhaoshan obtained his first PhD from Peking University, one of the best universities in China, in 1997, and worked there as an assistant professor for three years. In 2000, he entered another PhD program at Washington State University and obtained his second PhD degree in 2003. Both degrees were on mineral deposits. In early 2004, he worked as a postdoctoral research associate at WSU. From June 2004, he started working at CODES as a Research Fellow in economic geology. In 2008 he was promoted to Senior Research Fellow. Zhaoshan has studied a wide range of deposits, including skarns, porphyry deposits, epithermal deposits and sediment-hosted gold deposits, in 12 countries (Australia, Indonesia, Philippines, Mongolia, USA, Mexico, Peru, Chile, Canada, Russia, Serbia, Bulgaria and China). He has undertaken research on diverse topics, from exploration tools to state-of-the-art laboratory techniques (eg, U-Pb dating using LA-ICP-MS methods) and fundamental ore-forming processes.

Zhaoshan can contribute to the Think Tank by presenting research results on new exploration tools for undercover mineral deposits and new ideas on the future direction of mineral exploration, and by participating in such discussions. He has published research results in leading international journals and presented at international meetings in each of the past 10 years (including several presentations that won awards). Exploration tools that Zhaoshan and his colleagues devised have been applied in exploration for porphyry and high-sulfidation epithermal deposits. Some of the targets he generated have been or will be drill-tested. His research has been recognised by colleagues and the mineral industry; he has been invited to deliver speeches, to chair at international meetings, to teach in international workshops and to provide training to exploration staff of international companies. Zhaoshan has served as a reviewer for international journals and national science foundations and in 2009 was awarded a Guest Professorship by China University of Geosciences, Beijing.

Dr James Cleverley

Stream Leader, Mineral Systems and Targeting, CSIRO Minerals Down Under Research Flagship
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James is a senior geochemist and leader of the Mineral Systems and Targeting research stream at CSIRO in Perth, Western Australia. After completing his BSc at Plymouth University, MSc at Leicester University and a PhD at the University of Leeds in 2002, he moved to Australia to take up a postdoctoral position in the Economic Geology Research Unit at James Cook University. James moved to CSIRO in Perth in 2006, where he has been helping to develop the understanding and application of hydrothermal geochemistry, simulation science and micro-chemical characterisation to the understanding of fluids and dynamics in ore systems. He has worked closely with industry on several ore deposit types, including Fe-oxide copper-gold, copper, Archean gold, uranium and sediment-hosted base-metal systems, and firmly believes they have common ingredients that will revolutionise the way we explore for new ore deposits.

In his current role leading research in the CSIRO Minerals Down Under Flagship, James has interfaced between academic technique and knowledge development and application of minerals exploration science in industry. This gives him good insight into the current and future trends in Earth science research and practical application to the resource and energy industry. He takes a science leadership role in CSIRO and the research community in hydrothermal geochemistry, and is involved in developing world-leading micro-analytical techniques including through the Australian Synchrotron. He has been involved in setting strategic directions for research and for communication with stakeholders in the government and private sectors. This ability to bring together science strategy with sector knowledge sets him in good stead for this Think Tank.

Dean Collett

Group Manager Minerals Projects, Newcrest Mining Ltd
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Dean has worked as a geologist and senior geoscience manager in Australia and the Asia Pacific region for 25 years. He has the uncommon combination of experience in open-pit and underground mining, feasibility studies and exploration, as well as research and development portfolio management. He has worked for BHP Minerals, Sons of Gwalia, Placer Pacific, Mt Isa Mines Ltd and is currently Group Manager (Minerals) for Newcrest Mining. He holds appointments on the Science Steering Committees for the Deep Exploration Technologies CRC, AMIRA P843a Geometallurgy project, and the CODES Centre of Excellence at the University of Tasmania. Dean has held positions in the recent past on various other industry professional groups and mining industry community consultation committees. Dean holds a BSc and an MSc from James Cook University and has published and presented his work at local and international conferences on a variety of exploration-deposit models, mining geology, geostatistics, mining management, mining environmental and exploration method topics.

The four key challenges for the Australian mining industry are: an increasingly disguised footprint of mineral deposits; an increasingly longer time between discovery and development; decreasing economics; and community acceptance. All of these challenges are linked by the solutions presented by superior ore-deposit knowledge and improved cross-functional collaboration along the value chain from exploration through to operation and mine closure. Dean will contribute to the Think Tank on the research gaps contributing to all of these challenges.

Dr Robert Dart

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Robert is presently employed as a postdoctoral research fellow at the University of Adelaide, and is soon to commence as a postdoctoral research fellow with the Deep Exploration Technologies Cooperative Research Centre (DET CRC). His research interests are in the fields of regolith geology and landscape processes and their implications for mineral exploration. More specifically he is presently investigating landscape controls on the dispersion of mineralisation indicators within the regolith and the improvement of geochemical data interpretation by considering the impact of landscape processes. Following a successful career in computing, Robert completed a BAppSc (Hons) in geology at the University of South Australia in 2004. He then completed a PhD at the University of Adelaide in 2009. His PhD research investigated the relationship of regolith carbonates with gold and associated elements, and the landscape and pedological processes controlling this relationship.

A key impediment for Australian mineral exploration is that most of the continent is blanketed by regolith. Geochemical sampling of the regolith can identify anomalous zones and buried mineralisation. Robert's PhD research of Au-in-calcrete was about minimising exploration risk through innovative interpretation of the landscape. He will contribute to the Think Tank as one of the country's researchers fluent in the importance of regolith and landscape processes on the expression of buried mineralisation. Outcomes of the Think Tank will contribute to his postdoctoral research with DET CRC where regolith research will translate to cost-effective mineral exploration in areas of deep cover.

Dr Raj Das

Senior Research Scientist, Computational Modelling Group, CSIRO Division of Mathematics, Informatics and Statistics
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Raj is a senior research scientist in CSIRO's division of Mathematics, Informatics and Statistics. He completed his PhD at Monash University in the field of structural failure analysis and optimisation. During his PhD he developed a range of durability-based optimisation tools for structural design of aircraft and rail components, which have been adopted by aerospace and rail industries. He was then appointed as a research associate at the University of Manchester in 2005 and worked on the structural response and collapse of joints in steel-framed structures in fire. Raj's current research interests involve the application of mesh-free numerical methods to modelling deformation and failure in large-scale geomechanical applications. He has established strong linkages with mining and material processing industries and academic institutes and has active research collaboration with Monash University, the University of Quebec and Pennsylvania State University.

Raj has extensive knowledge and expertise in the computational modelling and structural analysis in geomechanical applications. In the Think Tank he would like to emphasise the significance of computational geomechanics in mineral exploration in Australia. The primary focus of his input will be how computational modelling can be effectively combined with experiments and field data to devise efficient and cost-effective mineral exploration strategies. Raj will highlight the areas where lack of understanding of the behaviour of rock mass leads to ineffective mineral exploration and extraction plans, often resulting in lower productivity and/or quality of ores than those expected during mapping the regions. The role of accurate geological field data as input to the numerical models and its sensitivity on the reliability of computational simulations as a predictive tool will be highlighted. His overall contribution will be to identify the key directions of research in the area of computational geomechanics necessary to develop cost-effective and efficient mineral exploration technologies.

Dr Miles Davies

PACE Manager (Plan for Accelerating Exploration), Geological Survey Branch, Minerals and Energy Resources, Primary Industries and Resources, South Australia
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Miles's research interests focus on palaeoenvironmental interpretations of geological terranes. More broadly, his academic research work integrates with practical applications encountered within the geological survey of South Australia, such as the search for and description of heavy mineral sand and sedimentary uranium systems. His PhD research at Adelaide University included consulting work with Western Mining on the identification of palaeochannels for alluvial diamond exploration – a project developed to utilise low-cost sampling and analysis for the delineation of possible target zones for further exploration. As an exploration geologist in the minerals industry his work focused on the search for a range of mineral commodities such as gold, copper, base-metals and iron in both South Australia and Queensland. Miles's current position PACE Manager with the Minerals and Energy Resources Division (MER) demands a high level of collaboration with the exploration industry and an understanding of the issues faced when moving through the prospect to mine pipeline. Programs currently in development include the up-scaling of the PACE initiative and the implementation of projects such as the streamlining of government processes for the granting of mineral leases, the development of best practice guidelines for community consultation and the expansion of functionality of MER's online systems.

Miles has spent several years as a researcher in geoscience, as an exploration geologist within the minerals industry and as a member of the South Australian state government focused on developing strategies to improve exploration within the state. His contributions to the Think Tank would be sourced from his range of experience gained from all of these arenas, namely academic, industry and government. Miles's current role in particular requires a strong focus on collaboration with the minerals industry as well as within government and academia. This unique position allows comment on the strengths (and weaknesses) of each, as well as potential avenues of opportunity.

Tania Dhu

Geophysicist, Minerals and Energy Resources, Primary Industries and Resources, South Australia (PIRSA)
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Tania attended the University of Adelaide majoring in geology and geophysics and graduated with an Honours degree in geophysics in 2002. She currently works with the Mineral and Resources Group, PIRSA, as a geophysicist. Her work involves the integration of different geophysical datasets from potential fields to electrical methods as an aid to exploration within a state whose resources are predominantly under cover. She is also undertaking a PhD at the University of Adelaide, investigating the spatial variation of the Earth's electrical response and attempting to link this with geological variation.

Tania's work covers areas such as the synthesis of geophysical depth estimates with geological knowledge to accurately map basement and the development of inputs to predictive modelling. She also has experience with scaling issues in electrical data through her PhD studies. An understanding of how these techniques are applied within South Australia, where cover is a major obstacle to resource discovery, will effectively contribute to the Think Tank.
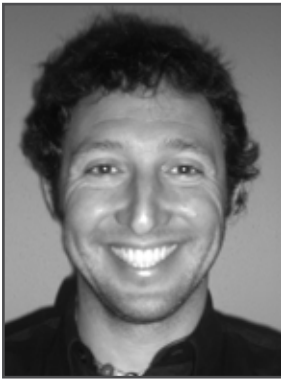
Assistant Professor Marco Fiorentini

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Marco received his PhD from the University of Western Australia in 2005. He has subsequently become a world-recognised authority on the genesis of Ni-Cu-PGE deposits. The implications of his studies for understanding the evolution of the early Earth's mantle, lithosphere, and hydrosphere-atmosphere, have been recognised and published in prestigious international journals, such as Nature and Science. Since 2005, he has had an enviable record in terms of integrated research activity within and across groups in academia and industry, successfully attracting external funding from state and federal governments. In 2008 he was awarded an APDI fellowship and was instrumental in designing and implementing the largest nickel project initiative ever undertaken in Australia. Marco balances high-calibre pure science with applied research, as evidenced by his multiple industry-sponsored projects and his selection in 2009 as Nickel Theme Leader in the Centre for Exploration Targeting.

Marco ranks as one of Australia's brightest young Earth scientists. The keys to his research success are his infectious enthusiasm and his capacity to collaborate with the best national and international researchers in several fields, creating the necessary synergy to achieve ambitious research goals. He is internationally recognised in both industry and academia as a researcher who can think holistically and work efficiently. In his research, a non-conventional 'out of the box' approach is successfully coupled with cutting-edge analytical techniques to generate new working hypotheses in highly controversial fields of both fundamental and applied research.

Dr Ryan Fraser

Project Leader, AuScope Grid, Spatial Information Services Stack, and Australian Spatial Research Data Commons
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Ryan is a project leader within CSIRO's Minerals Down Under Flagship. He leads three large projects dealing with the exchange and delivery of geoscientific information. These projects focus on enabling the delivery of data in an interoperable manner to the various communities – in particular the geoscience community. He has a software engineering background with particular expertise in high-performance data and computational technologies. He has primarily been involved in the design and execution of systems to deliver geoscientific information and the provision of data and computing services to the research community and industry. Ryan leads a large team to deliver technologies to enable data exchange and orchestrate change within the community.

To achieve better understanding of the Earth and address the challenges of future requirements of deep exploration, easy access to streamlined and standardised data is essential. This will aid informed and timely decisions to make exploration more accessible. Through Ryan's experience on various data delivery and interoperability projects he can bring relevant expertise and knowledge to this Think Tank on what is required to provide data information systems to the geoscience community, to have impact and assist in decision-making processes.

Associate Professor Klaus Gessner

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Klaus graduated with a Diplom from the University of Frankfurt and then a PhD from Johannes Gutenberg Mainz in 2000. He joined CSIRO in 2001, before moving to the University of Western Australia. His research interests lie in structural geology with an emphasis on the processes that produce giant ore deposits. He has recently completed a major study of the structure of the Mt Isa copper deposits and linked that to numerical modelling of the control of deformation on the fluid pathways responsible for mineralisation. His interests extend to large-scale deformation of the crust and much of his work is centred on crustal deformation in Turkey. His strong international reputation is built on understanding the development of 'core complexes' in the Turkish part of the Alpine tectonic chain. Klaus is presently working on gold mineralisation in the Yilgarn of Western Australia, and on links between faults, ore deposits and geothermal systems in Australia, Turkey and New Zealand. He has 22 highly cited fully refereed papers.

Klaus is an internationally acclaimed structural geologist with a strong interest in mineralising systems. He has worked with industry to apply his observations and numerical modelling expertise to exploration for new mineralisation in the Mt Isa region and the Yilgarn of Western Australia. He brings this practical hands-on experience to the Think Tank, which will benefit from his wide field experience on the mineral targeting problem. In particular, he has experience in communicating and transferring his results to industry. He is enthusiastic and anxious to develop a new approach to mineral exploration.

Professor David Giles

State of South Australia Chair of Mineral Exploration
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After four years in the minerals industry (1992-1996: Billiton, Great Central Mines) David returned to postgraduate study at Monash University. His PhD project (1996-2000) was based at the Cannington deposit and involved intimate collaboration with BHP Billiton. This was followed by a series of postdoctoral appointments, including an APDI (2003-2006) as part of an ARC Linkage Grant addressing exploration for Proterozoic base metal deposits, again in collaboration with BHP Billiton. In 2006 he was appointed the inaugural State of South Australia Chair of Mineral Exploration and Director of the Centre for Mineral Exploration Under Cover (CMXUC) at the University of Adelaide. David's roles are to facilitate mineral exploration beneath the veneer of recent sediments and weathered rock that covers much of South Australia, and to address the skills shortage in the minerals sector by training the next generation of minerals industry professionals. He teaches undergraduate programs in geology and mineral exploration at the University of Adelaide and manages a group of researchers and students with projects (including two current ARC Linkage projects) embedded in the mineral exploration industry. In 2009 he was part of a team of researchers and industry collaborators responsible for the successful proposal 'Deep Exploration Technologies CRC', in which his continuing role will be as Program Leader – Deep Targeting.

David has a mix of industry and academic experience particularly relevant to this Think Tank. Indeed, in many ways the subject of the Think Tank is a summary of his roles as a researcher and educator at the University of Adelaide.

Dr Weronika Gorczyk

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Weronika graduated with a PhD from the Geological Institute, ETH-Zurich, Switzerland in December 2007 after completing an MSc in geology at Jagiellonian University, Krakow, Poland in 2003. She joined CSIRO in 2008. Her research interest is the numerical modelling of processes that produce giant ore deposits. The computer codes she uses model the interaction of metamorphism, melting and fluid flow with deformation behaviour within the entire lithosphere. The computer codes are fully coupled in the sense that changes in physical properties arising from the above processes and the associated feedback effects are updated continuously during the computer calculations. Weronika's strong international reputation is built on the modelling of subduction processes and her emphasis has moved to considering the formation of giant orebodies arising from instabilities at old cratonic margins due to metasomatic processes. She is presently extending the codes to operate in 3D. She has six highly cited fully refereed papers.

Weronika is continuously developing new concepts that enable mineralisation in the Earth's crust to be modelled in a quantitative manner. Her goal is to develop criteria that enable targeting of mineralisation during exploration to be better focused. She brings this quantitative modelling expertise to the Think Tank, which will benefit from integrating her approach with different approaches to the targeting problem. Everyone will benefit from her understanding of lithospheric processes and their influence on localising mineralisation. Weronika brings an air of enthusiasm and enquiry that will drive active discussion and her influence on the outcomes of the workshop will be substantial.

Dr Wojtek Goscinski

Coordinator, Multimodal Australian ScienceS and Visualisation Environment
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Wojtek is the coordinator of the Multimodal Australian ScienceS Imaging and Visualisation Environment (MASSIVE), a specialised Australian high-performance computing facility for imaging and visualisation. Since late 2008 he has been the Advanced Technology Analyst at the Monash e-Research Centre, a role in which he promotes effective and creative applications of technology in research. He has completed a Bachelor of Computing at Deakin University (2001), a PhD in high-performance computing at Monash University (2006), and most recently a Bachelor of Architectural Design at RMIT (2009). Wojtek is also a part-time Research Fellow at the Spatial Information Architecture Laboratory in the School or Architecture and Design at RMIT and was formerly a lecturer in the Faculty of Information Technology at Monash University. His research interests include high-performance computing, scientific visualisation and advanced architectural design techniques.

Wojtek has strong technical expertise in parallel computing and its application to large-scale simulation and modelling. He has a multidisciplinary background that helps him to engage across a wide range of scientific domains. He assisted with the development of the 3D-Alive facility in the Geoscience Department at Monash University – a facility that helps geoscientists to better view their 3D data. His position as coordinator of MASSIVE provides him with an appreciation of the importance of computational infrastructure to underpin Australian science and he can provide insight into the technical requirements of current- and next-generation simulation, modelling and visualisation, in the geosciences, resource discovery and resource management.

Dr Ian Graham

School of Biological, Earth and Environmental Sciences, University of New South Wales
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Ian graduated from the University of Technology, Sydney with a PhD in geology in 2000 ('Tectonic significance of chromitite-bearing serpentinite belts, Tumut Serpentinite Province, southern NSW, Australia') then took up a postdoctoral fellowship at the University of Pretoria, South Africa, working on the sub-Rustenburg layered suite dioritic sills of the Bushveld Complex. He was then a research scientist within the geology section of the Australian Museum in Sydney, before taking up his current position as a senior lecturer in geology at the University of New South Wales in 2007. He is currently the first vice-president of the International Association on the Genesis of Ore Deposits (IAGOD), associate editor of Ore Geology Reviews, *chair of the NSW Division and committee member of the specialist group in geochemistry, mineralogy and petrology of the Geological Society of Australia, and an ARC Reader. His research interests include the genesis of magmatic-related ore deposits, epithermal gold deposits, gem deposits, and applied mineralogy.*

Ian can contribute to the Think Tank's theme because of his strong background in economic geology, including four current industry-sponsored honours projects in Western Australia (Archaean VMS), Papua New Guinea (epithermal gold) and Indonesia (epithermal gold) and last year had two other industry-sponsored honours projects in Papua New Guinea (epithermal gold) and Indonesia (placer gold and platinum). Earlier this year he was secretary of the local organising committee and chair of the scientific committee for the 13th Quadrennial IAGOD Symposium in Adelaide. Ian has strong contacts throughout the university sector, government agencies (such as the various state geological surveys and Geoscience Australia), professional societies and industry.

Dr Anthony Harris

ARC Centre of Excellence in Ore Deposits (CODES), University of Tasmania
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Anthony is a Senior Research Fellow at CODES, investigating aspects of porphyry ore deposits. After graduating from the University of Queensland he worked briefly for Rio Tinto Exploration. He returned to the University of Queensland to undertake his PhD, which sought to further constrain the evolution of porphyry ore systems. Since starting at CODES in October 2002, Anthony has been involved with basic and applied studies of porphyry ore deposits throughout Australasia, China, North and South America. Using advanced microbeam techniques (including laser ablation, PIXE and synchrotron radiation) he has studied micron-sized fluid inclusions that help elucidate fundamental ore-forming processes. His work is published in leading international journals, including Science. He currently manages a 100 per cent industry-funded research project that seeks to better describe the chemical and physical environments of porphyry ore deposits. Anthony received the Society of Economic Geologists Waldemar Lindgren Award for 2004. This award is offered annually to a young scientist whose published research represents an outstanding contribution to economic geology.

Anthony works closely with exploration and mining professionals to undertake strategic science that provides new exploration opportunities through advancing an understanding of ore systems and exploration models. His research investigating aspects of porphyry ore deposits (some of the largest bulk minable Cu and Au resources known) sees him embedded in Newcrest Mining Ltd. This opportunity has afforded him new insight into the requirements of industry. Anthony's role is to enhance the skills of industry professionals via a training program underpinned by targeted research activities designed to advance conceptual models and exploration techniques.

Dr Jane Hodgkinson

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Jane is a geologist in the Mining and Exploration Division of the CSIRO. She gained her BSc (Hons) in geology at Birkbeck College, University of London in 2003 and her PhD in 2009 at the Queensland University of Technology. Her research at CSIRO has involved analysis of vast and complex minerals-exploration datasets using self-organising map (SOM) analysis for improved mineral targeting, reduction of sulfur in coal for environmental protection, 3D coal-mine modelling, geosequestration targeting for international clients investing in Australia and the adaptation requirements for the mining industry in the face of climate change. Jane has published and co-authored work in international journals and conferences and is additionally interested in geological hazards including earthquakes and landslips.

Since joining CSIRO in 2007, Jane's experience in the mining industry has been broad and she has developed and performed new projects and liaised with industry. She has been involved in future strategic planning meetings where knowledge gaps and industry requirements are identified. Working for gold, iron ore, diamond and coal mining companies for example, Jane has worked on mineral targeting techniques and 3D modelling of ore and deposit bodies. She is presently engaged with industry and social scientists to assess climate change implications in the mining industry to ensure the future of mining in Australia under new climatic conditions.

Associate Professor Eun-Jung Holden

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Eun-Jung gained a BSc, an MSc and a PhD in computer science from the University of Western Australia, and is currently a Research Associate Professor at the Centre for Exploration Targeting (CET) within UWA. Her research expertise is in image analysis and pattern recognition with 15 years experience. Previously working on human motion analysis and visualisation, she started working at CET in 2006 with a specific aim to bring in advanced image analysis technology to geoscientific data processing. By working closely with the mineral exploration industry, she has been developing cross-disciplinary projects to address the data-processing challenges facing the industry. Eun-Jung's achievements include the development of award-winning human motion visualisation software and commercial geophysics data-processing software that provides efficient and effective data discontinuity detection, namely the CET Grid Analysis Extension for Geosoft Oasis montaj, which was released and marketed by Geosoft in April 2010.

Eun-Jung's contribution to the Think Tank will be her expertise in extending geoscientists' capacity to extract and integrate information from existing data by utilising effective visualisation and automatic processing tools. Discovering resources from deep Earth will require better ability to understand patterns in remote sensing data. Her research focus has been on addressing this issue by applying advanced image enhancement, automatic feature detection and pattern recognition techniques to provide effective, fast and non-subjective processing with reproducible outcomes. In addition she will be bringing extensive hands-on experience in designing and developing multidisciplinary research crossing the areas of computer science and geoscience.

Dr Margarete Jadamec

Postdoctoral Research Fellow, Facility Manager, 3D-ALIVE, Monash University
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Margarete received her BSc (Hons) in geology and geophysics from the University of Connecticut in 1999, an MSc in structural geology from the University of Alaska in 2003, and a PhD in geophysics from the University of California, Davis in 2008. In 2008 she joined the computational geodynamics group at Monash University as a postdoctoral research fellow. She is Project Leader (2008-present) of 3D-ALIVE (3D-Applied Laboratory for Immersive Visualisation Environments) at Monash University and designed the facility in collaboration with Monash Schools of Geosciences and Mathematical Sciences, Monash e-Research Centre, AuScope, and CSIRO Advanced Scientific Computing. Her research interests include continental deformation, subduction dynamics, 3D visualisation, and numerical modelling. An important scientific contribution from her PhD work is the prediction of fast, localised mantle velocities (80 cm/yr) in models also satisfying surface plate motions and seismic anisotropy observations (Jadamec and Billen, 2010, Nature).

Margarete will contribute to the Think Tank in three ways. First, she is familiar with both geological and geophysical datasets and in incorporating those observations into 3D numerical simulations of geodynamic processes. Second, she has experience in using new technology such as 3D immersive visualisation and massive passive parallel computing in the analysis of complex 3D geologic structures, and is now manager of a visualisation facility in Australia. Thirdly, through her research she has demonstrated the ability to work collaboratively to deliver practical, innovative, and paradigm shifting results.

Aleksandra Kalinowski

Geoscience Australia
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Aleks is a geologist currently working on geological storage of carbon dioxide at Geoscience Australia (GA), where she is also undertaking postgraduate study with the University of New South Wales in this dynamic and topical field. After completing her undergraduate degree at the Australian National University in 2002, she worked in the minerals exploration area at GA before participating in GA's graduate recruitment program in 2004. She then moved into the carbon capture and storage (CCS) team in 2005, where she worked on assessing the potential of some of Australia's sedimentary basins for CO_2 storage. In 2006 Aleks and her husband moved to Boston where she was fortunate to work on CCS at the Laboratory for Energy and the Environment at MIT as well as energy policy-related issues at the Kennedy School of Government at Harvard University. She is currently leading the international CCS project at GA.

Working at GA in both minerals exploration and carbon capture and storage has given Aleks a broad perspective about the technical, economic, skills gaps, social and other issues facing these industries. Throughout her career she has had experience working on technical, policy, capacity building and public outreach activities in CCS. Finding new geological resources and attempting to fill knowledge gaps as well as building technical capacity and public confidence in these areas, locally and internationally, is exciting and challenging. Aleks warmly welcomes the opportunity to contribute to this Think Tank and to engage with other researchers on these issues.

Dr Lawrence Leader

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Lawrence is a research assistant in the School of Earth Sciences at the University of Melbourne. His interests include structural geology, tectonics, mineralisation and numerical modelling of deformation and fluid flow. Since the completion of his PhD degree at the University of Melbourne in 2008, Lawrence has been working on regional- and mine-scale studies that focus on the structural control of gold mineralisation in western and central Victoria.

Through his research, Lawrence has worked closely with academic, government and industry groups associated with the gold exploration and mining industry in Victoria, and thus has significant knowledge of how applied research can be used by the industry for effective minerals exploration.

Dr Maxim Lebedev

Senior Research Fellow, Department of Exploration Geophysics, Curtin University of Technology
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Maxim gained a Masters in physics and engineering from the Moscow Institute of Physics and Technology in 1986 and his PhD in physics from the same university in 1990. He worked for a decade as a physicist at the High Energy Research Centre in Russia, and for approximately eight years as a material scientist at the Japanese National Institute of Advanced Industrial Science and Technology. In 2007, he joined Curtin University and became the leader of an experimental group in rock physics. His research is focused on the properties of subsurface reservoir rocks and minerals. He is author and co-author of over 100 scientific papers, and has been granted five international patents. He holds a current ARC Discovery grant and is recognised widely as a national and international leader in the field.

Maxim will contribute to the Think Tank through his experience in a broad range of disciplines, including geophysics, physics, material science and engineering. He will add to discussions about the challenges and opportunities in the Australian resources sector associated with developing new technologies for the exploration of resources. Networking with national research leaders will allow Maxim to share his knowledge and enable him to contribute to strategies for developing deep Earth resources as a national priority. In all, he will benefit greatly, both personally and professionally, through his involvement in this exciting Think Tank.

Professor T Campbell McCuaig

Director, Centre for Exploration Targeting, University of Western Australia
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Campbell received his PhD in geology from the University of Saskatchewan in 1996. Subsequently with SRK Consulting, he rose to the position of director, garnering 10 years experience in providing solutions to the mineral exploration industry. His experience spans six continents and numerous commodities in geological terranes ranging from Archaean to Eocene in age, including gold, nickel, iron, copper, uranium and zinc, amongst others. Since August 2005, Campbell has been Director of the Centre for Exploration Targeting (CET), a joint venture between the University of Western Australia, Curtin University, and the minerals industry that is focused on advancing the science of exploration targeting. His leadership has resulted in a world-recognised sustainable research centre with more than 25 staff, 30 research PhD/MSc students, a turnover of more than $4 million a year and research outcomes that are impacting on exploration industry practice, yet also being recognised at the highest academic levels by publications in journals such as Nature and Science.

Campbell is internationally recognised in both industry and academia as a visionary in exploration geoscience. He has a remarkable track record of engaging industry and academia to identify challenges hampering mineral discovery and then designing and implementing research programs to overcome those challenges. The success of CET attests to this ability, where in five years he has personally attracted more than $10 million in research funding and built a sustainable research centre with over 70 corporate members. Campbell is also recognised as a talented communicator, constantly in demand to speak and provide courses on exploration geoscience and industry–academia collaborative research.

Professor John McLeod Miller

Research Professor, Centre for Exploration Targeting, University of Western Australia
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John is a Research Professor at the Centre for Exploration Targeting at the University of Western Australia. He received his PhD in 1999 and his expertise is in the fields of structural geology, tectonics and mineralisation. He has done extensive research programs in gold, nickel, uranium, copper, lead and zinc mineral systems in Australia and internationally. He has over 30 international publications and is currently a chief investigator on four active ARC Linkage Grants. He was awarded the prestigious Joe Harms medal in 2004 by the Geological Society of Australia for excellence in mineral exploration and ore deposit research. This was awarded for research that led to a gold discovery that extended the Stawell gold mine's life by at least five years; it is one of the largest employers in the rural Stawell community and provides community stability.

John has expertise relevant to the Think Tank theme, having done numerous applied research studies at both mine- and regional-scales resulting in the development of new geological models to generate exploration targets and to aid resource extraction at existing deposits. A core focus has been integrating field observations with 3D software to rapidly model, visualise and interpret data. His research was used as a case study of technological innovation in the geosciences in a 2005 submission to an Australian Federal Government House of Representatives Standing Committee by the Australian Geoscience Council.

Dr Steven Micklethwaite

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Steve completed his PhD in 2002 at Leeds University. From 2002-2008 he was a research fellow at the Australian National University. While at ANU he developed, with Professor Stephen Cox, a novel software technology for blind, deep-Earth minerals exploration, based on the mechanics of earthquakes and how they influence fluid flow and mineralisation within the crust. In 2009 he was awarded the UTAS Business Commercialisation Prize, worth $25,000, for an idea centred on the commercialisation of this application. Steve is currently researching the development and predictability of mineralised epithermal structures, working on the Gosowong epithermal goldfield in Indonesia. Over the past seven years he has built extensive links with the minerals exploration industry, working with nine different companies and carrying out research with industry exploration teams on eleven different mining sites from four different nations. He also has a growing international recognition, with invitations as keynote speaker to scientific meetings in the USA and UK. He has international and national collaborative links with the Australian National University, Sydney University, CSIRO, Glasgow University and the University of British Columbia, which have led to the publication of a number of journal articles. Steve investigates processes of deformation and fluid flow and their application to mineral deposit formation. This research is cross-disciplinary, uniquely combining the disciplines of earthquake mechanics, structural geology and economic geology to generate creative and new outcomes for the exploration industry. He is particularly interested in the impact of pore-fluid pressure, and earthquake-related stress changes on the enhancement of permeability in the crust, plus the application of fractal concepts to develop new tools useful for predicting the spacing and location of mineralised structures.

Steve is concerned about developing new field-based and numerical techniques, to create tools that enable greater predictability in exploration. He is in the process of commercialising an application that has been successful at this in mesothermal and Carlin-type gold deposits. He also has several research projects currently under development, which participants of the Think Tank may be able to collaborate on.

Dr Kieren Moffat

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Kieren is a social scientist at CSIRO. He completed a PhD in social and organisational psychology at the University of Queensland in 2008. He leads a team of social scientists in the Earth Sciences and Resource Engineering Division, and is responsible for social science research delivery into several minerals-related portfolios in CSIRO, including the Mineral Futures initiative. His research interests include analysis of the drivers of future development in the Australian minerals industry and their implications for sustainability, particularly with respect to the role of societal expectations. He is also leading research to explore the future conditions under which the minerals industry will need to operate to hold a social licence to operate in both onshore and offshore resource sectors. Prior to joining CSIRO, Kieren worked as a management consultant in the mining and health sectors. His PhD research explored diversity management issues in the Australian Defence Force.

Kieren's social science training and research interests provide him with different and critical perspectives on deep Earth exploration and utilisation of Australian resource commodities. His knowledge of global and domestic foresighting activities exploring the future drivers of the industry and in particular the role that societal expectations will play, may offer valuable contributions to the Think Tank. Similarly, his research into the nature of trade-offs that society is willing to make with respect to the industry in the future, and the intersection between technology development and the social risk inherent in its deployment, may also provide useful inputs for discussions about future deep Earth mining activities.

Dr Joshu Mountjoy

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Joshu is an early-career scientist in the field of marine geology and geophysics. Experience in terrestrial geology, including as a consultant in ground engineering and mining, in combination with science research in the offshore environment, has enabled him to develop a well-rounded skill set with a strong ability to visualise 3D problems and to see the global picture while understanding the necessity for detailed analysis. Offshore research involvement has included active tectonic processes, canyon development, submarine landslide processes, submarine hazards, habitat mapping, seafloor gas hydrates, and seafloor mineral deposits. Joshu has experience with the collection and analysis of marine geophysical and geological datasets, including high-resolution multibeam bathymetry, multi-channel seismic data, sediment cores and rock samples. His current research topics and principal interests are submarine landslide hazards, canyon development on active tectonic margins, and characterisation of active faults in high-resolution seismic reflection data.

A broad background in Earth science, including exposure to onshore mining and environmental impact assessment, offshore petroleum exploration, and undeveloped offshore resources such as gas hydrates and massive sulfide deposits, puts Joshu in a strong position to critically analyse issues that are key to the mineral industry's future. A reductionist approach to problem analysis, in a framework of holistic understanding of the Earth system, knowledge of environmental impacts, and broad understanding of social and cultural issues will be critical to streamlining the challenges that Australia faces to maintain its success as an economic power in the developed world.

Dr Craig J O'Neill

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Craig is a young geodynamicist working on simulation of tectonic processes and integrating numerical simulations with geological and geochemical constraints on the evolution of the Australian continent. He graduated from the University of Sydney in 2004 with a PhD in geophysics and has had postdoctoral appointments in Australia and the USA. Currently an ARC-funded Australian Postdoctoral Fellow and lecturer based at Macquarie University, his current research interests include the earliest evolution of the Earth from its primordial state to one capable of supporting life, and the origin and conditions for plate tectonics.

Craig's research delves into the mechanics of plate-boundary processes, the same processes that are ultimately responsible for Australia's mineral wealth. He also collaborates extensively with the minerals and petroleum industries, bringing sophisticated numerical modelling techniques to bear on resource-related science problems. He brings to the Think Tank a detailed knowledge of Australia's mineral wealth, a working knowledge of cutting-edge resource-related technologies, a cross-disciplinary research ethos and an appreciation of the integration of knowledge and technology to an exploration framework.

Thomas Poulet

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Thomas graduated in 2000 from the Ecole Polytechnique, the top level multidisciplinary engineering school in France. He also undertook an application curriculum in signal processing at the National School of Telecommunications until 2002. Since joining CSIRO in 2003, Thomas has been working on various projects aimed at transforming our understanding of the formation of mineral deposits from a qualitative to a quantitative and predictive science. His areas of expertise include numerical modelling, signal processing, mathematical optimisation and visualisation of high-dimensional model parameters, software engineering, e-Research, grid services and high-performance computing. Thomas's current research activities centre on reactive transport in porous media and the thermodynamics of dissipative processes. It is part of a wider effort to provide a common multi-scale framework to couple all processes involved in ore-deposit formation, including mechanical deformation, heat and mass transport, as well as reactive fluid flow in porous media.

Thomas can bring to the Think Tank a wide expertise in numerical modelling and applied mathematics, with seven years experience developing numerical tools targeted at helping the minerals exploration industry. He can also bring a multidisciplinary background and team-playing interest, which have already made him a catalyst in many research projects and equipped him with competences at all levels of the numerical workflow. He believes that more realistic numerical models require a tight coupling of all processes involved at all scales and is excited by the opportunities that the Think Tank provides in this respect.

Dr Tim Rawling

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Tim is a structural geologist with research interests in 3D geological modelling, numerical simulation of Earth systems and structural geophysics. He currently works for GeoScience Victoria, managing the 3D Victoria modelling program. Prior to this he was the MCA Lecturer at the University of Melbourne and project leader for the predictive mineral discovery CRC (pmd*CRC) Tasmanides Project. He has also worked as a consultant geologist to both the minerals and energy exploration industries, both in Australia and overseas. Specifically, Tim's research is focused on the application of new technologies to geological analysis, exploration and resource development-related problems. This includes the integration of structural geology, geophysics, 3D modelling and numerical simulation to investigate the geodynamic evolution of complex systems and the nature and influence of geometrical and mechanical controls on fluid flow in basins and hard rock environments. He is also interested in the development of exploration techniques and workflows incorporating these new technologies.

Tim can contribute to the theme of the Think Tank in several ways. The research that he has been involved in for 10 years is directly applicable to exploration of the deep crust. In addition he has a very good understanding of industry, the current and developing technologies, and also brings experience in state government and science leadership to the table. He is passionate about the application of new technologies to solving difficult exploration problems and believes in the predictive capability of many techniques currently in development.

Dr Nicholas Rawlinson

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After completing his PhD at Monash University in 2001, Nicholas began his academic career at the Research School of Earth Sciences at the Australian National University as a postdoctoral fellow in seismology. In the past 10 years, he has carried out research into seismic wave propagation in the solid Earth, geophysical inversion techniques, and observational seismology using seismic array data. He has also been responsible for the development of the WOMBAT seismic array project, which uses a transportable array to progressively cover southeast Australia with passive seismic stations at spacings of no more than 50 kilometres. To date, over 550 stations have been deployed, making it one of the largest programs of its type in the world.

Much of Nicholas's research involves imaging crustal structure using a variety of seismic techniques. He has done collaborative work with Mineral Resources Tasmania on the generation of a high-resolution 3D crustal model of Tasmania, and currently has a project with the NSW Geological Survey on imaging deep structure beneath the Macquarie Arc, a highly mineralised porphyry copper-gold province. He has another current project on using seismic tomography to identify favourable locations for hot rock geothermal energy production. With this background, he can bring new ideas on how to contribute to predictive frameworks for mineral exploration to the Think Tank.

Dr Anya Reading

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Following undergraduate study at the University of Edinburgh (BSc in geophysics) and postgraduate research at the University of Leeds (PhD in seismology), Anya began her career in Earth sciences with the British Antarctic Survey. She participated in major geophysical data collection expeditions on land and at sea. After time as a lecturer back at the University of Edinburgh, Anya moved to Australia to take up a research fellowship with the Australian National University in the Research School of Earth Sciences, where she continued to carry out challenging observational geophysics in Antarctica and also in the Australian outback. In 2007, she took up her current position as a senior lecturer in geophysics at the University of Tasmania, which she holds jointly with a research role in the ARC Centre of Excellence for Ore Deposits (CODES). She now divides her time between teaching and research into innovative and computational geophysics.

Anya is a research seismologist of international standing with experience of working in challenging environments and use of innovative techniques. She combines this background with a practical perspective and has current applied research interests in deep crustal investigations for geothermal and ore deposit exploration. Her teaching expertise spans other geophysical techniques including innovations in electrical methods in minerals and environmental applications. This area of expertise is well-suited to the theme of the Think Tank. Anya brings a thoughtful, lively and constructive approach to committee and community roles and will contribute significantly to the Think Tank.

Professor Steven Reddy

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Having completed his PhD in 1990, Steven has gone on to become a geologist with research interests ranging from sub-micron scale deformation of minerals to global-scale plate tectonics. Over the past five years his research has concentrated on the development and application of quantitative microstructural analysis to Earth sciences, including the characterisation of microstructure in minerals used for geochronology; the deformation of mantle rocks and subducted tectonic plates and implications for geodynamics; and the formation and evolution of ore minerals and deposits. In 2009 he published a comprehensive review of secular variations in the Earth, from the core to the atmosphere, from 3.0 to 1.2 billion years ago. He currently leads a project to provide a geological assessment of the geothermal potential of the Perth Basin.

Steven has a broad expertise in 'Deep Earth' research and the practical problems associated with such studies. He has experience of technical issues related to the geological assessment of ore deposits, and a working knowledge of the state-of-the-art analytical techniques that will lead to greater understanding of the processes controlling their formation. He is currently the deputy Dean of Research for Science and Engineering at Curtin University and has a broad appreciation for other disciplines and their potential application to the Australian resources sector. Steven considers himself to have a strategic approach to research and development issues and believes these skills will allow him to make a significant contribution to the theme of the Think Tank.

Dr Frank Reith

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Frank holds an ARC Research Fellowship in geomicrobiology, shared between the University of Adelaide and CSIRO Land and Water. His research is aimed at investigating the fundamental processes underlying the geomicrobial cycling of noble metals in Earth surface environments with respect to the potential of utilising microorganisms for geochemical exploration and ore-processing applications. He combines the use of state-of-the-art molecular microbial methods (eg, transcriptomics and eco-(meta)-genomics) and micro-analysis techniques (eg, Synchrotron-XAFS, FIB-SEM-EDS/EBSD, EPMA and HR-TEM), with field-based exploration approaches to understand the environmental cycling of gold and platinum and find novel microbially-based approaches for exploration and processing. After his MSc (Diplom) at the University of Bayreuth, Germany, he moved to Australia in 2002, where he received his PhD from the Australian National University in 2006. Since then he has held postdoctoral appointments at CSIRO Exploration and Mining and the University of Adelaide.

With multidisciplinary skills encompassing (bio)-geochemistry, synchrotron spectroscopy, electron microscopy, soil science, regolith geoscience and geology as well as classical and molecular biology, Frank is a leading expert on the geomicrobiology of noble metals. His excellent public-speaking skills will add to his exciting contribution on the development of bioindicators and biosensors for gold exploration. A highlight of his research is the discovery of a gold-specific genetic operon in the bacterium Cupriavidus metallidurans. This knowledge, for which a patent application has been submitted, can now be used to construct the first biosensor for gold exploration.

Dr Simon Richards

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Key to finding new mineral deposits and advancing mineral exploration is understanding when, where and why deposits form. Simon's current research is unique because it combines established micro-analytical chemical analysis of mineralised and non-mineralised intrusives with newly developed 3D geological maps of the Earth's interior. These detailed 3D maps are being combined with lithosphere- and asthenosphere-scale plate tectonic reconstructions and mineral deposit information (eg, age, location and chemical fingerprint) to build unprecedented interactive 4D models of how Earth's mineral forming systems are linked to mantle-scale structures and processes. Simon believes that developing new methods to compile, visualise and interpret geological data, using cutting-edge technologies, is key to advancing the science of mineral exploration. Current research is focused in the highly prospective south-west Pacific, where the plate tectonic controls on mineralisation are being revealed. Simon also has major projects with industry partners in the south-west Pacific.

Simon will make a significant and invaluable addition to the Think Tank, especially given the themes to be discussed. His fields of research, involving high-volume, geospatial data analysis and unique forms of visualisation, and his relationship with industry place him in an ideal position to contribute. He will undoubtedly provide a positive contribution on topics ranging from data compilation, analysis and presentation to expected future developments in the way in which geoscientists present geological models (ie, information transfer) to industry and the general public and how industry can work with academia to achieve useful techniques and technologies.

Dr David Robinson

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David has 10 years experience providing advice and conducting research from within Geoscience Australia. As a graduate recruit he worked in diverse fields, ranging from geomagnetism research through to policy development in the petroleum resource exploration area of the Department of Industry, Tourism and Resources. In 2002 he joined the Natural Hazard Impacts Project, where he has led the development of Australia's earthquake hazard and risk-modelling capability, designing and building tools that are used widely within Australia and south-east Asia for emergency management planning and forecasting earthquake hazard and risk. David has a university medal and BSc (Hons) with majors in geophysics and mathematics from Flinders University of South Australia. He recently submitted a PhD thesis entitled 'Studies on earthquake location and source determination using coda waves' and in 2007 was awarded the Robert Hill Memorial Prize for scientific communication by the Australian National University's Research School of Earth Sciences.

David's background spans marine and exploration geophysics, seismology and mathematics. He has served on the ACT branch of the Australian Society for Exploration Geophysicists, both as president and treasurer, and is aware of issues facing the exploration and geoscience industries. In particular, he is interested in securing an educated geoscience workforce to face future challenges as well as ensuring a strong, vibrant, growing Australian economy that utilises our natural resources in a socially and environmentally responsible manner. David has extensive experience working with multidisciplinary teams and is committed to engaging the expertise of economists, engineers, business leaders and policy makers.

Dr Gideon Rosenbaum

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Gideon is a graduate of the Hebrew University (Jerusalem) and Monash University. Prior to his appointment as senior lecturer with the University of Queensland's School of Earth Sciences, he was a research fellow at the Johannes Gutenberg Universitat (Mainz). Gideon's research history includes collaboration with Australian, New Zealand, French, Italian, Swiss and Israeli geoscientists. He has authored a significant number of peer-reviewed papers, has received two active ARC Discovery grants and is associate editor of the Journal of Geophysical Research. *He is an active member of the academic life of the School of Earth Sciences and displays a strong and cooperative interest in the research projects of his colleagues.*

Geodynamics and the reconstruction of Earth dynamics through time are Gideon's particular areas of expertise. His skills will contribute to the theme of the Think Tank by providing a necessary focus upon the tectonic history of the Australian continent and its relationship to the occurrence of mineral deposits. Presently, mineral exploration benefits from a 3D visualisation of mineralisation zones. However, the key to future mineral discoveries is that refinement of insight to be provided by a full 4D understanding of the tectonic jigsaw puzzle, that is, of the evolution of physical mineral location across a geologic time span.

Dr Alanna Simpson

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Since joining Geoscience Australia in 2007, Alanna has undertaken research into natural hazards in the Asia-Pacific region, particularly the risks to communities from volcanic eruptions. This research is a key part of AusAID's efforts to reduce disaster risks. In this time, Alanna has also supported the Australian government to improve linkages between science development and policy delivery, specifically in the field of disaster risk reduction but more broadly across climate change and water resource issues. Alanna currently leads Geoscience Australia's Regional Risk program, which aims to build the capacity of scientists in the Asia-Pacific region to independently develop and deliver natural hazard risk information. As a graduate recruit at Geoscience Australia, Alanna worked on carbon capture and storage research, risk analysis, and policy development in AusAID. She has a PhD in geology from the University of Queensland (2007), with her research utilising mineralogy, geochemistry and geochronology to understand magmatic processes.

Alanna's research covers fields directly related to mineral exploration, with skills and knowledge developed during her PhD and MSc theses just as applicable to mineral exploration as they are to crustal magmatism. She currently plays an active role in Australian government policy development and has a clear understanding of the influence of policy on scientific research. Alanna has significant experience working with people from diverse professional and cultural backgrounds. She is also passionate about the sustainable use of resources to ensure that while we grow the economy now, we also secure resource wealth and a healthy environment for future generations.

Dr Carl Spandler

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Carl is an academic geologist with a strong track record of research into geological processes, including plate tectonics, crustal genesis, magma generation and ore-deposit formation. He has been at the forefront of development of new experimental and micro-scale geochemical techniques and has applied these techniques to achieve innovative results in several Earth science research fields. Since completing his PhD at the Australian National University in 2005, he has held an Australian Postdoctoral Fellowship at the ANU (2005-2006) and a postdoctoral fellowship at the University of Bern, Switzerland (2006-2008). He is currently a lecturer at James Cook University, Townsville. Carl has published over 20 papers (most as first author) in high-ranking international journals, including Nature and Geology; with many of these papers subsequently achieving a high number of citations. He has presented research results at more than a dozen international conferences and workshops, including numerous keynote presentations.

Throughout his academic career, Carl has invested in the development of geochemical methods to advance our understanding of geological systems, including ore deposits. His research has led to the discovery of platinum mineralisation in New Zealand and a new model for the genesis of chromium ore deposits. He is currently supervising student research projects on gold and molybdenum mineralisation in northern Queensland. Carl sees great potential in applying advanced geochemical techniques and ore deposit petrology to improving our understanding of how and where ore deposits form (and hence, exploration models) and how best to process ores once extracted from the ground.

Dr Mark Symmons

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Mark is a senior lecturer in psychology at Monash University. He received his PhD in 2005 and has since co-authored 34 peer-reviewed publications and won over $1.2 million in grants, competitive tenders and industry research contracts. He pursues research in two fields: road safety and haptics (haptics relates to the sense of touch, including sensations that arise from contact between the skin and surfaces, and perception of movement). Of particular relevance to the mining field, Mark's team is currently undertaking contract research developing and testing new interfaces to enable touch interaction in virtual reality to remotely control mining machinery. The intention of the project is to reduce the need for fly-in/fly-out and to improve productivity and safety. The work is also relevant to operator training.

With a psychology background and a research interest in human factors, safety and behaviour, Mark's work spans multiple disciplines. He can thus contribute to discussions that are highly technical in engineering-focused areas such as automation, remote control, machinery safety and workplace environment, as well as to fields that are more social and focused on the individual, including teams, motivation, leadership, the environment and communities. Mark teaches and publishes in a range of these areas. Accordingly he can provide a bridge between what can be very disparate areas.

Dr Stephan Thiel

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Stephan is a research associate at the Centre of Tectonics, Resources and Exploration (TraX) at the University of Adelaide. He completed his Masters at the Freiberg University of Mining and Technology, Germany and was an IPRS scholarship recipient for his PhD dissertation ('Modelling and inversion of magnetotelluric data for 2-D and 3-D lithospheric structure, with application to obducted and subducted terranes') at the University of Adelaide from 2004-2008. His specialty is the analysis, modelling and interpretation of electromagnetic data to define large-scale lithospheric structures, mineral systems and geothermal areas. His current research interests involve imaging the electric signature of continental lithosphere and mantle from the perspective of mineral exploration potential. Recently, he obtained an IMER grant to monitor fluid injection into enhanced geothermal systems using time-lapse magnetotellurics (MT).

Deep-sounding electromagnetic methods, such as MT, are a relatively low-cost alternative to conventional exploration tools and are susceptible to the bulk electrical conductivity of the host rocks, minerals and aqueous phases of the subsurface. The MT method is able to image features from the near-surface to mantle depths. It can delineate a mineral system with highly conducting orebodies and establish a potential connection to deeper parts of the crust and mantle, to aid in understanding its genesis. Hot fluids in conventional and enhanced geothermal systems are also a primary target for MT, providing an imaging tool in the renewable energy sector.

Dr Mark Tingay

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Mark is a senior lecturer and Australian Postdoctoral Fellow at the Australian School of Petroleum, where he examines the tectonic evolution of sedimentary basins in south-east Asia and Australia. His primary field of research is in petroleum and geothermal geology and geophysics, particularly the development of delta systems and formation of basins. He also specialises in drilling technologies and the mechanics of fluid flow in high-pressure systems, such as in geothermal energy production, oil-field blowouts and mud volcanoes. Mark has undertaken collaborative projects with over 20 petroleum companies in more than a dozen countries, including Azerbaijan, Egypt, Oman, Thailand and Malaysia. He has 40 refereed publications, consulted on numerous petroleum geomechanics projects and has provided over 40 media interviews on geoscience and resources issues.

Mark will contribute his broad and extensive knowledge of the challenges facing the petroleum and geothermal industries in Australia. Furthermore, he is strongly engaged in raising awareness and understanding of geosciences within the general public and thus will be able to contribute his experiences with the social and environment aspects of exploration and production. In particular, Mark can contribute his knowledge of man-made geological disasters such as oil-field blowouts and induced seismicity, and approaches for avoiding such environmentally and socially destructive accidents in Australia.

Dr Hrvoje Tkalcic

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Hrvoje is a Fellow in Seismology at the Research School of Earth Sciences, Australian National University. He received his Diploma in physics from the University of Zagreb, Croatia, and a PhD in geophysics from the University of California, Berkeley. He was a postdoctoral fellow at the University of California, San Diego (SCRIPPS) and Lawrence Livermore National Laboratory, prior to accepting an academic position in observational seismology at the ANU in 2007. His research interests include global observational seismology, Earth's structure and seismic sources. His publications include work on the Earth's core and the lowermost mantle, lithospheric structure, strong-motion prediction in populated areas, and physics of seismic sources in volcanic environment. He is responsible for the operation of the Warramunga seismic and infrasonic array in the Northern Territory, which is designated as a primary monitoring station for the Comprehensive Nuclear Test Ban Treaty.

As a geophysicist, Hrvoje looks at earthquake waveforms and uses various seismological techniques (and develops his own) to infer Earth's properties based on observations. The focus of his research is on answering fundamental questions about the dynamics and properties of Earth's inner and outer core, the lowermost mantle and lithosphere (including the Earth's crust). Hrvoje has an understanding of how surface observations could be linked to structures and processes within the Earth's interior. He could readily contribute to the general discussion on novel applications and identify important issues that this Think Tank aims to address.

Dr Nick Williams

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With a background in ore deposit geology and geochemistry, Nick completed a PhD in geophysics at the University of British Columbia in 2008. Working with UBC's Geophysical Inversion Facility and Mineral Deposit Research Unit he investigated ways to recover predictive maps of the subsurface by integrating geology, physical property data and geophysical modelling techniques. He completed Honours in geology at the University of Tasmania in 2000, and a BSc in Earth science at Monash University in 1999, after undertaking most of the coursework at the University of California, Santa Cruz. Since 2001 he has worked at Geoscience Australia on the challenge of promoting exploration in Australia despite the continuing decline in discovery of new ore deposits due to the dwindling number of unexplored outcropping rocks. Future exploration success demands novel subsurface exploration techniques. With experience in geology, geochemistry and exploration geophysics, he understands that no single technique will improve exploration effectiveness. Instead, he specialises in ensuring that all available geological and geophysical information is interpreted together in a holistic way. The process of geophysical inversion provides a rigorous numerical framework for achieving this. Inversion facilitates recovery of 3D models of subsurface rocks or properties required to explain remotely measured geophysical data, while also satisfying available geological observations. For seven years his primary work role has been investigating and testing ways of using inversion methods to derive predictive 3D maps, at regional to deposit scales, using gravity, magnetic, and electromagnetic datasets together with available mapping and drilling observations.

Nick is particularly excited to be involved in this Think Tank as it is so closely aligned with his primary research activities. With a background in both geology and geophysics he brings a unique insight into how multiple geological and geophysical datasets can be combined to support deep exploration. He has developed several new techniques to support this approach and generate more predictive exploration targeting models. These efforts were recognised with an award for best presentation at the 2009 Australian Society of Exploration Geophysicists Conference, and invitations to give talks and a keynote address at several major conferences.

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