



ASEG-PESA 2015

Geophysics and Geology together for Discovery

24th International Geophysical Conference and Exhibition
15 - 18 February 2015 Perth, Western Australia

Workshop

Geophysical signatures of mineral systems; more than bumps

RioTinto



Condor Consulting, Inc.

Thursday, February 19, 2015

**Chairs - Ken Witherly, Condor Consulting, Inc.
John Hart, Rio Tinto Exploration**

Geophysical signatures of mineral systems; more than bumps

It is generally accepted that the shallow, easy to define ore bodies were recognized first and developed. In the past 20 years, the discovery performance across virtually all mineral sectors has fallen, resulting in growing concern that if unchecked, there could be shortfalls in a number of commodities within the next 20 years.

The collective sense is that the geological column hosts more deposits than have been found to date but these are expected to be at greater depths than have typically been explored before. To be able to operate in this environment, new approaches to the identification of deposits is required and the concept of a mineral systems approach, first suggested 20 years ago, has emerged as a powerful means to build strategies and capabilities going forward. In terms of geophysical exploration, the major change that will be required is a shift from a focus almost entirely on direct targeting of deposits with geophysical surveys to a staged process where geophysical approaches are used initially to help define the pathways in the Earth which carried the mineralizing solutions which formed the target deposit.

These pathways would provide a much larger target to explore for and if detected and mapped, should allow explorers to follow the pathway to the location of potential deposits. This task is different from most geophysical studies undertaken, where the focus has been typically on improving the direct targeting capabilities and not the larger scale mapping problem that a mineral systems approach will require. In the current assessment, a review is undertaken of what is seen as the current state-of-play for a number of major deposit styles and how geophysical data is being used at present to explore for these. The assessment overall is encouraging but major challenges remain outside of the technical issues of defining a mineral systems strategy that relate primarily to human resources and the commercial environment.

This forum will examine the current state of understanding of geophysical signatures of mineral systems; current examples, on-going research and areas which require further assessment. A major tenant that is already apparent is that the successful development of undercover exploration strategies will require a degree of integration of geophysical outcomes with other geoscience data not typically achieved historically.

PROGRAM SCHEDULE

- 8:00-8:15 Registration
- 8:15-8:30 1. INTRODUCTION; **John Hart**
- 8:30-9:05 2. An economic perspective on deep and under cover exploration: what are we looking for and how do we get there?
Allan Trench
- 9:05-9:40 3. The Implications of the Mineral Systems Concept for Geophysical Exploration: A Perspective: **Mike Dentith**
- 9:40-10:15 4. Undercover exploration in 2030: An UNCOVER Vision:
Steve Beresford
- 10:15-10:30 **COFFEE**
- 10:30-11:05 6. Mineral Systems Approach to Porphyry Copper Exploration - A Magnetic Perspective in Southwest Alaska: **Eric Anderson**
- 11:05-11:40 7. Pathways to porphyries - mapping alteration and related mineralization: **Terry Hoschke**
- 11:40-12:15 8. Real time data and geologically meaningful bumps:
James Cleverly
- 12:15-12:30 9. DISCUSSION: **John Hart**
- 12:30-13:30 **LUNCH**
- 13:30-14:05 10. From 3D geology to 3D Geophysics, what next?: **Mark Jessell**
- 14:05-14:40 11. Petrophysical insights into targeting ore systems:
James Austin (presented by **Dave Clark**)

- 14:40-15:15 12. Finding the right bumps under glacial till in the Central Lapland Greenstone Belt: **Janne Kaukolinna**
- 15:15-15:30 **COFFEE**
- 15:30-16:05 13. Following the mineral system and tracking it under cover – using every tool at our disposal: **Gavin Selfe**
- 16:05-16:40 14. Signatures of Mineral Systems; A Perspective from the Financially Challenged: **Graham Ascough**
- 16:40-17:30 15. PANEL DISCUSSION
- 17:30-18:00 16. WRAP UP: **Ken Witherly**
- 18:00 **CLOSE OF WORKSHOP**

SPEAKER/CHAIR CONTACT DETAILS

Ken Witherly

President, Condor Consulting, Inc.
St. 150 2201 Kipling St.
Lakewood CO USA 80215
T: 303-423-8475
C: 303-520-5732
Skype: ken.witherly1
ken@condorconsult.com
www.condorconsult.com

John Hart

Principal Geophysicist - Africa Eurasia
Rio Tinto
37 Belmont Ave, Perth,
Western Australia, Australia, 6014.
T: +61 (0)8 6213 0573
C: +61 (0)427 457 440
F: +61 (0)8 9270 9223
John.Hart@riotinto.com
www.riotinto.com

Short Biographical Notes

Eric Anderson

Eric Anderson works for the US Geological Survey in Denver, Colorado. He spent much of 2014 as a visiting researcher at University of Western Australia working with Mike Dentith on the geophysical signature of gold deposits. His research interests are in potential field geophysics and economic geology. He received a BS degree in geology from Augustana College (1996) and then worked in oil and gas exploration. He completed a MS degree in geology and geochemistry at the University of Colorado, Boulder (2003) where he researched fluid evolution in the epithermal and porphyry environment. He received a PhD from Colorado School of Mines (2013) that was focused on understanding the magnetic signature of mineral deposits and associated geology.

Graham Ascough

Graham Ascough is a senior resources executive with more than 25 years of industry experience evaluating mineral projects and resources in Australia and overseas. He is currently non-executive Chairman of ASX listed companies: Mithril Resources Limited, Musgrave Minerals Limited, Phoenix Copper Limited and Avalon Minerals Limited. Mr Ascough, a geophysicist by training, has had broad industry involvement playing a leading role in setting the strategic direction for companies, completing financing and in implementing successful exploration programmes. He is a member of the Australasian Institute of Mining and Metallurgy and is a Professional Geoscientist of Ontario, Canada. Mr Ascough was the Managing Director of Mithril Resources Ltd from October 2006 until June 2012. Prior to joining Mithril in 2006, he was the Australian Manager of Nickel and PGM Exploration at the major Canadian resources house, Falconbridge Limited, which was acquired by Xstrata Plc in 2006.

James Austin

Jim Austin is a structural geologist and geophysicist whose main interest is in the application of magnetics to mineral exploration. Prior to joining CSIRO he worked with the Predictive Mineral Discovery CRC, for the Encom-Mapinfo Geoscience Consulting Group and also as an exploration geologist in Broken Hill, the Mount Isa Inlier, Papua New Guinea and the Thomson Orogen. In his current role at CSIRO he is focussed on understanding the geophysical properties of Iron Oxide Copper-Gold (IOCG) and Magmatic Nickel Sulphide systems, partnering with numerous exploration companies around Australia, including MIM-Glencore, MMG, Minotaur, Musgrave Minerals, etc. He has published papers on applied geophysics, structural geology and mineral exploration and is currently a member of the SEG, ASEG and the Society of Economic Geologists.

Steve Beresford

Steve Beresford is the Chief Geologist of First Quantum Minerals, an Adjunct Professor at Centre for Exploration Targeting (UWA) and Chair of the Geoscience committee for UNCOVER.

Steve has over 20 years experience across the academia-industry divide which includes Professor at University of Western Australia, Chief Geologist at MMG and currently First

Quantum Minerals. Prior to that he was with WMC Resources and BHPBilliton. Steve has been a director of public and private listed junior Nickel exploration companies.

Dave Clark

Dave Clark is a Principal Research Scientist with the CSIRO Manufacturing and Mineral Resources Flagships. He has a B.Sc (Hons) degree in physics and an M.Sc. in geophysics from the University of Sydney, and a Ph.D. in geophysics from Macquarie University. Dave's main research interests are applications of rock magnetism to exploration; potential field interpretation; processing and interpretation of magnetic gradient tensor data for resource exploration and for detection, localisation and classification of magnetic targets; and predictive geophysical exploration models.

James Cleverly

James Cleverley is currently Principal Geochemist at REFLEX (Perth, Australia) following a move from CSIRO in 2014. James has been involved in two industry-led research cooperatives dating back to his second post-doc at James Cook University with the predictive mineral discovery*CRC and more recently heading up the hydrothermal geochemistry projects in the Deep Exploration Technologies CRC. James was the project lead for the DET CRC Lab-at-Rig project that is a collaboration between REFLEX, Olympus and CSIRO which is currently being commercialised. He is passionate about the use of geochemical data, data analytics and the understanding of hydrothermal systems for exploration targeting and mine optimisation, but has been lucky enough to work on everything from large gold deposits to chondritic meteorites.

Mike Dentith

Mike Dentith is Professor of Geophysics at the Univ of WA and a co- research theme leader (Geophysics and Data Analysis), in the CET. His research interests are in various aspects of mineral exploration geophysics, especially geophysical signatures of mineral deposits and the use of geophysics in assessing prospectivity at the terrain scale. He is co-author of the textbook 'mineral exploration geophysics for geoscientists' and has edited two volumes of geophysical case study compilations, on WA and SA.

John Hart

John Hart graduated from the University of Western Australia in 1992. Initially employed by BHP Minerals, he worked on primarily base metal projects in Eastern Australia, India, Southern African and Botswana before joining Minotaur Resources in 2001. After involvement in copper exploration projects in South Australia and Queensland, he joined Rio Tinto in 2010. John Hart is currently Principal Geophysicist Africa-Eurasia for Rio Tinto Exploration.

Terry Hoschke

Terry Hoschke graduated in geophysics from the University of New England in Australia in 1980. He worked as a geophysicist for Geopeko in the 1980s exploring for a number of commodities including gold, uranium and base metals. He managed the Darwin exploration office for North Limited for 3 years from 1992 and subsequently worked on porphyry exploration for North in Indonesia. He worked for Normandy/Newmont from 2001 to 2013 during which time he

completed an MSc thesis on the geophysics of porphyry and epithermal systems. This was subsequently published by CODES. He is currently a geophysical consultant, based in Perth

Mark Jessell

Mark Jessell is a Winthrop Professor and Western Australian Fellow at the CET UWA having arrived from Toulouse, France where he was a Director de Recherche with the Institute de Recherche pour le Development, and where he started the West African Exploration Initiative (WAXI). His scientific interests revolve around microstructure studies (the Elle platform), integration of geology and geophysics in 2 and 3D (the Noddy project), and the tectonics and metallogenesis of the West African Craton (WAXI). His current Western Australian Fellowship is focused on improving the links between geological and geophysical data analysis in 3D via analysis of the geological and topological uncertainty.

Matthew Kanakis

Matthew Kanakis is an Honours graduate of UWA with a double degree in geoscience and commerce. He is currently a consultant with KPMg in Perth specialising in research and development eligibility, compliance and reporting. His honours research focused on the geological economics of gold mining in Australia, specifically the geological factors that drive production cost performance across both open pit and underground operations.

Janne Kaukolinna

Janne Kaukolinna started geophysical career in 2002 working mainly on environmental, geotechnical and rock mechanical studies for the first few years, after which focused on exploration geophysics moving from data acquisition and field operations more into interpretation and consulting. 2008 was hired by Anglo American to work as geophysicist for Europe with main responsibility on Lapland Ni-Cu-PGE project. After leaving Anglo in 2012 and short period in consulting joined First Quantum as Regional Geophysicist for Europe.

Gavin Selfe

Gavin Selfe has 25 years' experience in the minerals exploration industry and currently consults to many varied exploration companies in Africa. Much of his work is dedicated to deep-seeing geophysical techniques for geological mapping under cover. He specialises in interpreting geology from airborne datasets as well as ground-based gravity, EM and AMT. He graduated in 1987 with a dual major in geology and geophysics. He subsequently worked as a geophysicist for De Beers and Anglo American for 15 years and was based in an exploration office in West Africa for 5 years. His experience includes diamonds, gold, nickel, copper, platinum, iron ore and zinc exploration. He has given papers at numerous conferences, and is ex-president of the South African Geophysical Association (SAGA).

John Sykes

John Sykes is a PhD Candidate at the Department for Mineral & Energy Economics, Curtin University, and Adjunct Research Fellow at the Centre for Exploration Targeting, University of Western Australia. His research focuses on the long term future of copper mining. John also

runs his own consultancy, Greenfields Research, specialising in long term mineral economics, and previously was a Consultant in Copper Mining & Smelting for CRU Group.

Allan Trench

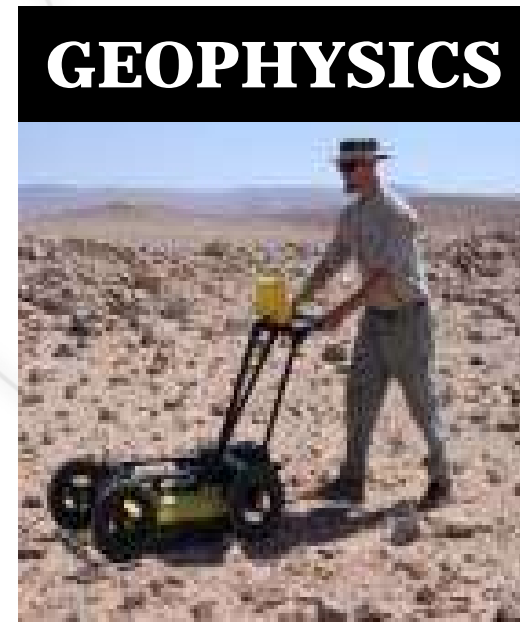
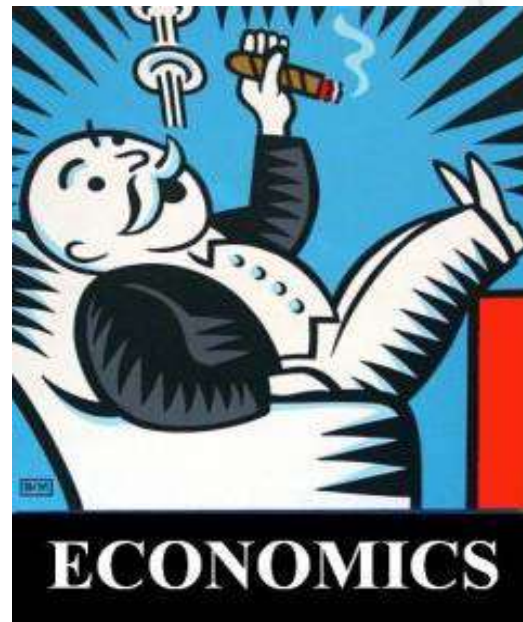
Allan Trench is Professor (Risk & Value) at the Centre for Exploration Targeting, University of Western Australia and Curtin University Graduate School of Business, a Non-Executive Director of several resources sector companies - and the Perth representative for CRU Strategies, a division of independent metals & mining advisory CRU group.

Allan has over 20 years' experience within the mining/metals and oil/gas sectors including senior management positions with WMC and Woodside Energy. Allan has held academic positions at Oxford University (Geophysics) and Curtin University of Technology (Mineral Economics) and worked as a management consultant with McKinsey & Company engaged in both strategy and operations-focused engagements. His current focus is the analysis of corporate and asset-level mineral exploration strategies, value accretion through effective exploration and the analysis of mineral markets. Allan is the author of nine books and 50 journal and technical publications in geology/geophysics and mineral finance/management.

Ken Witherly

Ken Witherly graduated from UBC (Vancouver Canada) with a BSc in geophysics and physics in 1971. He spent 27 years with Utah/BHP Mineral Company during which time as Chief Geophysicist, he championed BHP's programs in airborne geophysics, which resulted in the development of the MegaTEM and Falcon technologies. In 1999, Ken helped form a technology-focused service company that specializes in the application of innovative processing and data analysis to help drive the discovery of new mineral deposits.

AN ECONOMIC PERSPECTIVE ON DEEP AND UNDER COVER EXPLORATION: What are we looking for and how do we get there?



Allan Trench¹², John P. Sykes¹² & Matthew Kanakis²³

1. Department of Mineral & Energy Economics, Curtin University
2. Centre for Exploration Targeting, Curtin University & University of Western Australia
3. Consultant, KPMG, Perth WA 6000

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Geophysical signature of mineral systems; more than bumps
Perth, Australia: 19th Feb 2015

Centre for **EXPLORATION**
TARGETING



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We all bring biases to looking at industry issues.... including this one*

- Geophysicist then Mineral Economist
 - Nickel/Gold bias – Kambalda, St Ives, Leinster/Mt Keith, Super Pit
 - Underground EM mine/exploration 'revolution'
 - Gold/nickel division contrasting performances
 - McKinsey – management perspective
 - Woodside – petroleum perspective
 - CRU Group – initial focus on managing copper – cost analyses of operations and projects
 - Academic – 'What do we really know' perspective
- So an Australian bias – nickel & gold underground bias - and more recently Chile/copper bias**

*Trench

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Slide 2 of 43

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19 Feb 2015



Personal perspectives (bias) on the deep exploration and development challenge....

- It is possible to make any project look simple on a spreadsheet
- Reality is far more complex
- Most spreadsheet cost models have an underlying and linear 'sanctity of grade' built in
- Ore geometry and scale effects are as important – especially between mines
- Cost modelling gets underground 'wrong' more often than for pits
- Economics suffers some similar ambiguity challenges to geophysics – i.e. multiple solutions are possible using different costs and shapes
- Mine economics can suffer the same 'black box' challenges as for geophysics – e.g. understanding what is really being measured in a model, and the multiple definitional issues of reported costs
- **Bias towards real data and factual analogues over model-only solutions: Model simplicity can be good (being wary of the 'sanctity of grade' trap)**

*Trench

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Slide 3 of 43

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An economic perspective on deep and under cover exploration

WHAT ARE WE LOOKING FOR? QUALITY NEW DISCOVERIES

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Slide 4 of 43 ASEG-PESA 2015 Workshops: Geophysical signatures of mineral systems, more than bumps 19 Feb 2015

What can mineral economics contribute?

- What are we looking for? Quality new discoveries
 - Future precious and base metals discovery at depth more so than bulks
 - What 'quality' really means (or otherwise) in Copper, Nickel & Gold as examples
 - Sometimes quality will be deep and high-grade, but not always
 - Quality may be deep, low-grade, but scalable for example
- How do we get there? Better Understanding
 - Through a clearer understanding of the impact of grade, scale, mineralisation-style and geometrical effects on mine economics
 - The excellent case study of Australian Gold Mine 'geological economics' (Kanakis (2014))
- Where to next? We need to get to first base yet
 - Where mineral economists will likely mislead you (and fool ourselves too)
 - Some high-level project economics from in-ground discovery to out-of-ground value creation
 - So much more fact-based and modelling work ahead

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Slide 5 of 43 ASEG-PESA 2015 Workshops: Geophysical signatures of mineral systems, more than bumps 19 Feb 2015

We don't yet understand grade effects on economics – in pits or u/g – although it looks simple

GEOLOGY

Grade Enhancement Near Surface Mined First

MINING

Preferential 'Bring-Forward' of High Grade

ECONOMICS

High Prices 'Creates' Low Grade Ore

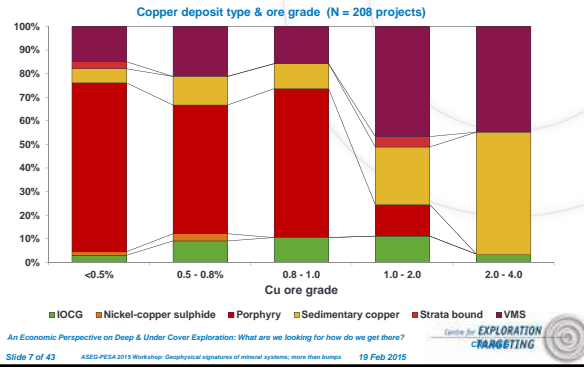
So Grade Must Fall Over Time...and costs rise?

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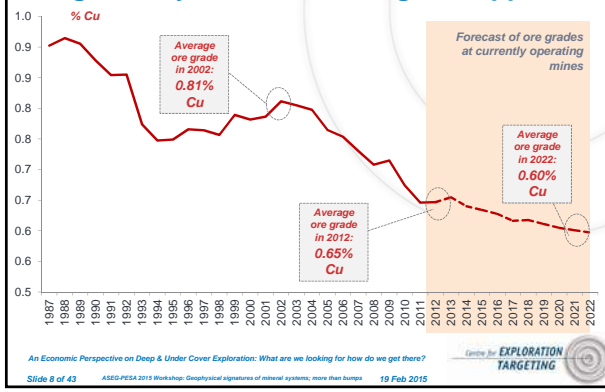
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Slide 6 of 43 ASEG-PESA 2015 Workshops: Geophysical signatures of mineral systems, more than bumps 19 Feb 2015

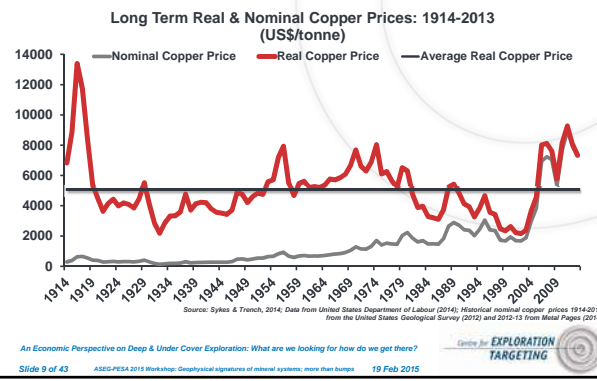
...and if we don't fully understand grade-economics then we have a major problem: Grades vary a lot...



...what we do know however is that grades generally fall over time e.g. in copper

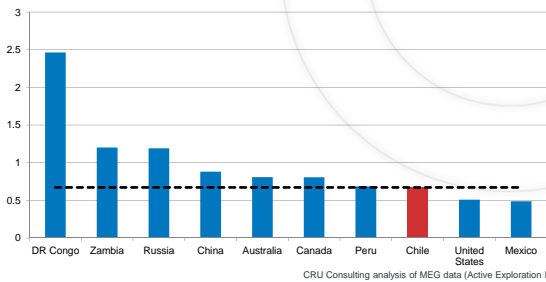


And we also know that falling grades of themselves do not drive higher prices in real terms...



Declining grades are likely – so the economics of mining of lower grades matters..

Grade of exploration projects in top 10 copper producers (%Cu)



CRU Consulting analysis of MEG data (Active Exploration Projects)

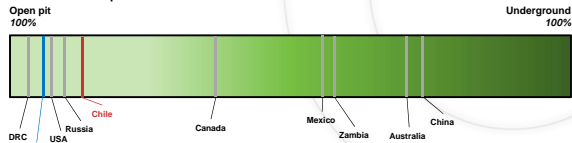
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Slide 10 of 43 ASEG-PESA 2015 Workshops: Geophysical signatures of mineral systems, more than bumps 19 Feb 2015

... despite the 'future is underground' not being universal – e.g. pits still dominate Cu pipeline

Production & Pre-production



Feasibility



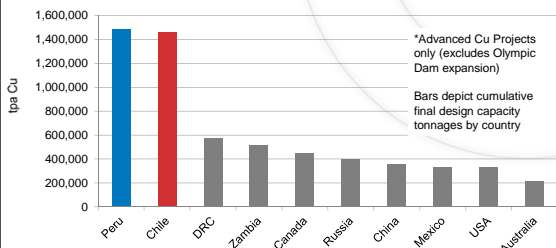
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Slide 11 of 43 ASEG-PESA 2015 Workshops: Geophysical signatures of mineral systems, more than bumps 19 Feb 2015 Source: CRU, MEG

...that said, Australia must focus on deep exploration and development – or risk being left behind..

New Cu Project Annualised Production Capacity Potential*



*Advanced Cu Projects only (excludes Olympic Dam expansion)
Bars depict cumulative final design capacity tonnages by country

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Slide 12 of 43 ASEG-PESA 2015 Workshops: Geophysical signatures of mineral systems, more than bumps 19 Feb 2015 Data: MEG, CRU

So what drives relative costs if not grade? Deposit-type tells us little

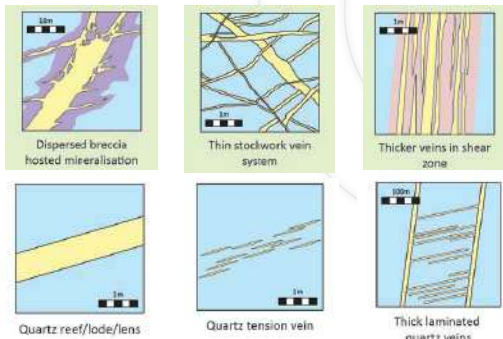
- Orogenic Gold and Epithermal Au-Ag deposits gave variable results on the cost curves
- Porphyry deposits were very low cost except for Boddington
- Of the IOCG deposits the only figure available was a December Half Year Total Cash Cost for Prominent Hill, which was around the mean of the dataset
- *There is not much to go with here.....*

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Slide 22 of 43 ASEG-PESA 2015 Workshops: Geophysical signatures of mineral systems, more than bumps 19 Feb 2015



What about mineralisation-style then?



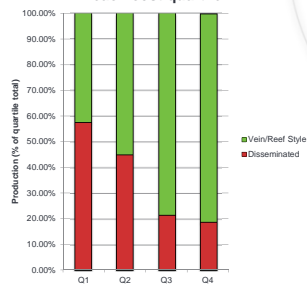
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Slide 23 of 43 ASEG-PESA 2015 Workshops: Geophysical signatures of mineral systems, more than bumps 19 Feb 2015



Disseminated mineralisation appears important

Percentage of deposits with different mineralisation style in each cost quartile



- Deposits with more disseminated style mineralisation displayed lower costs than those with vein/reef style mineralisation
- Relationship especially evident in the cash cost datasets.

Source: Kanakis (2014)

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Slide 24 of 43 ASEG-PESA 2015 Workshops: Geophysical signatures of mineral systems, more than bumps 19 Feb 2015



An economic perspective on deep and under cover exploration WHERE TO NEXT?

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Slide 28 of 43 ASEG-PESA 2015 Workshops: Geophysical signatures of mineral systems, more than bumps 19 Feb 2015



So is a new underground target better economically than a typical new pit?

Typical Australian medium sized OPEN PIT gold mine

- Resource contained Au: **4.0Moz**
- Reserve contained Au: **2.8Moz**
- Mining Losses: **95%**
- Mine Life: **15 years**
- Throughput: **3.5Mt/y**
- Grade: **1.5g/t**
- Processing Recovery: **85%**
- Production: **150,000oz/y**
- Opex: **\$750/oz**
- Capex: **\$150 million**
- Construction: **2 years**

Typical Australian medium sized UNDERGROUND gold mine

- Resource contained Au: **13.3Moz**
- Reserve contained Au: **6.7Moz**
- Mining Losses: **75%**
- Mine Life: **30 years**
- Throughput: **1.0Mt/y**
- Grade: **5.0g/t**
- Processing Recovery: **90%**
- Production: **150,000oz/y**
- Opex: **\$850/oz**
- Capex: **\$65 million**
- Construction: **4 years**

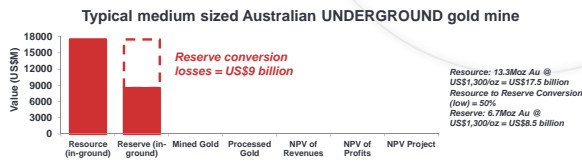
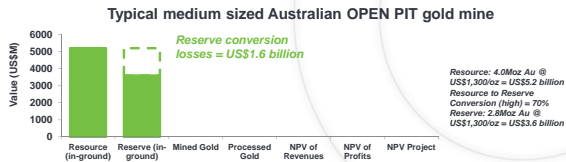
Based on data collated by Matthew Kanakis (and some tacit assumptions by Syles & Trench)

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Slide 29 of 43 ASEG-PESA 2015 Workshops: Geophysical signatures of mineral systems, more than bumps 19 Feb 2015



First convert resource to reserve...



NB: Calculations have undergone rounding so may not be fully accurate

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Slide 30 of 43 ASEG-PESA 2015 Workshops: Geophysical signatures of mineral systems, more than bumps 19 Feb 2015



Where mineral economists will likely mislead you (and ourselves too)

- Over-simplistic economic models of underground targets – all economic assumptions, limited geology & mining inputs
- Hard-wiring of a simple 'grade drives economics' modelling assumption (to the exclusion of complexity & scale effects; orebody shape, mineralisation style)
- Limited factual analysis of existing underground deposits and their economics versus pit developments
- Lack of 'modifying factors' within analyses

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Slide 37 of 43 ASEG-PESA 2014 Workshops: Geophysical signatures of mineral systems, more than bumps 19 Feb 2015

A final word on the road ahead....

“What we are dealing with are complex mineral systems. As analysts we are still in the 1800’s stuffing birds and classifying them. We want to map the genome”

- Professor Cam McCuaig, CET Director 2014



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Slide 38 of 43 ASEG-PESA 2014 Workshops: Geophysical signatures of mineral systems, more than bumps 19 Feb 2015

THANK YOU

Contact information:

John P. Sykes: johnpaul.sykes@postgrad.curtin.edu.au

Allan Trench: allan.trench@curtin.edu.au

Matthew Kanakis: mkanakis@kpmg.com.au

For more information:

Centre for Exploration Targeting: www.cet.edu.au



Curtin University



FURTHER READING

- Kanakis, M.D., 2014. Grade Expectations – Australian Gold Mines defy the 'Grade is King' Cost Hypothesis, *Australian Institute of Geologists News*, 188, November, 6-10.
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- Sykes, J.P., & Trench, A., 2014. Finding the Copper mine of the 21st century: Conceptual Exploration Targeting for Hypothetical Copper Reserves, *Society of Economic Geologists Special Publication* 16, 273-300.
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- Trench, A., Packey, D., & Sykes, J.P., 2014. Non-Technical Risks and Their Impact on the Mining Industry. *AusIMM Monograph 30: Mineral Resource and Ore Reserve Estimation, Chapter 7: Risk in Resource and Reserve Estimation*, 605-617.

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An economic perspective on deep and under cover exploration

BACKUP – BROADER RISK DISCUSSION

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Slide 41 of 43 ASEG-PESA 2015 Workshops: Geophysical signatures of mineral systems, more than bumps 19 Feb 2015

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What does economic mean nowadays? You can choose either technical vs political risk?

Size, Grade & Political Risk for Top 10 Largest Nickel Projects showing that the highest grade projects are in the riskiest political environments

Project	Location	Quartile	Contained Nickel (Mt)	Nickel Grade (%)
Weda Bay	Indonesia	1st	~7.0	~1.75
Dumont	Canada (QC)	1st	~6.0	~0.5
Kalgoorlie	Australia (WA)	1st	~5.5	~0.75
Zebediela	South Africa	1st	~4.5	~0.75
Jacaré	Brazil	2nd	~4.0	~1.0
Gag Island	Indonesia	2nd	~3.5	~1.5
Mount Margaret	Australia (WA)	2nd	~3.0	~0.75
Maturi	USA (MN)	3rd	~2.5	~0.25
Turnagain	Canada (BC)	3rd	~2.0	~0.25
Sulawesi	Indonesia	4th	~1.5	~1.75

Data: Schodde; Fraser Institute

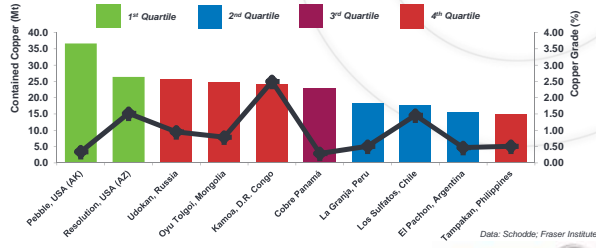
An Economic Perspective on Deep & Under Cover Exploration: What are we looking for how do we get there?

Slide 42 of 43 ASEG-PESA 2015 Workshops: Geophysical signatures of mineral systems, more than bumps 19 Feb 2015

Centre for EXPLORATION TARGETING

Actually... it's quantity and a more subtle notion of 'quality'

Size, Grade & Political Risk for Top 10 Largest Copper Projects demonstrating that there is no clear relationship between grade and political risk. Mine type, by-products etc coalesce to form a more subtle concept of 'quality'



An Economic Perspective on Deep & Under Cover Exploration: What are we looking for how do we get there?
 Slide 43 of 43 ASEG/PESA 2015 Workshops: Geophysical signatures of mineral systems, more than bumps 19 Feb 2015



Exploring With Geophysical Methods in a Mineral System Context: A Perspective

Mike Dentith

Centre for Exploration Targeting



THE UNIVERSITY OF
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Mineral Systems Workshop, Feb 2015

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TARGETING



Exploring With Geophysical Methods in a Mineral System Context: A Perspective

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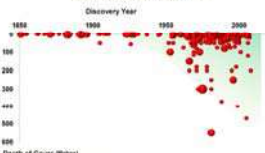
Mineral Systems Workshop, Feb 2015



Mineral Systems & Geophysics

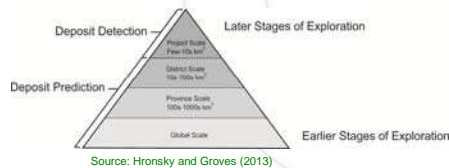
- Mineral systems
 - Consider everything it takes for a deposit to be present
 - Petroleum: Source-pathway-trap
 - Minerals: Source-pathway-physical throttle-chemical scrubber-preservation

Depth of cover for major mineral discoveries in Australia: 1850-2010

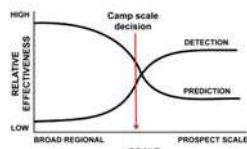


Mineral Exploration

- Exploration targeting



Source: Hronsky and Groves (2013)

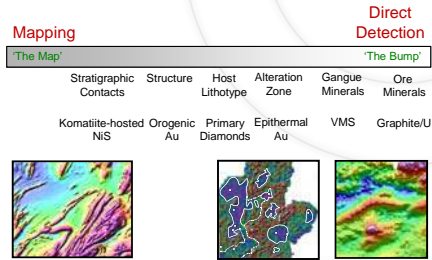


Source: McCusig et al., (2010)



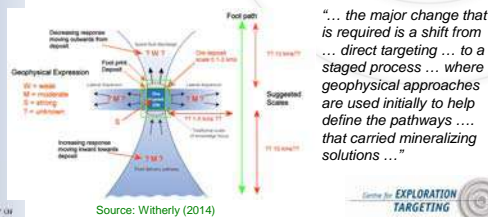
Mineral Exploration Geophysics

- Geophysical exploration strategy at the prospect scale



Mineral Systems & Geophysics

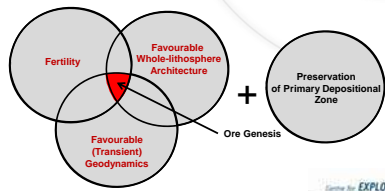
- The role of geophysics in a mineral system-based exploration strategy?
 - Petroleum: Source-pathway-trap
 - Minerals: Source-pathway-physical throttle-chemical scrubber



Source: Witherly (2014)

Mineral Systems & Geophysics

- The role of geophysics in a mineral system-based exploration strategy?
 - Critical elements of a mineral system
 - Minerals: Source-pathway-physical throttle-chemical scrubber



Source: McCuaig and Hronsky (2014)

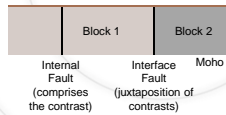
Pathway/Favourable Lithospheric Architecture

- **Major discontinuities in the basement**
 - Reactivated faults
 - Boundaries between crustal blocks
 - Often have a cryptic surface expression
- **Depth extent important**
 - Mantle tapping?
 - Relationship with other significant structures
- **Deep geophysics**
 - Increased activity in research organisations
 - Contrasts with the industry (shallow and deposit scale)

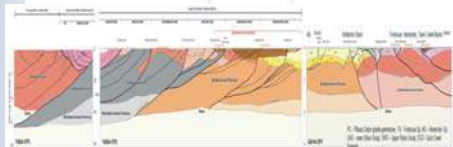


Pathway/Favourable Lithospheric Architecture

- **The usual suspects**
 - Gravity and magnetics
 - Active seismic methods
 - Passive seismic methods
 - Magnetotellurics
- **Fundamental limitations**
 - All geophysical methods lose resolution with depth
 - The response is controlled by a combination of physical property contrast and the volume of the material representing the contrast (most cases)
 - ‘Internal’ fault zones hard, ‘interface’ faults less so



Pathway/Favourable Lithospheric Architecture



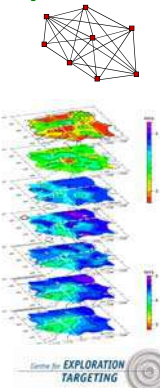
- **Reflection seismic**
 - Responds to flattish contrasts in acoustic impedance ($\rho \cdot v$)
 - Highest resolution, but also most expensive
- **Pros and cons**
 - Excellent for mapping both ‘internal’ and ‘interface’ faults
 - Can be hard to interpret in detail (side swipe, velocity effects)
 - Poor indicator of bulk properties
- **At least one transect is required in a prospective terrain – “calibration point”**



Pathway/Favourable Lithospheric Architecture

- **Ambient noise tomography**

- Simultaneously recording 'noise' with an array of recorders
- Comparison between any two recordings allows for velocity structure of the intervening area to be derived
- Wavelength based analysis allows a pseudosection to be derived
- Tomographic comparison of each receiver pair allows a data pseudovolume to be created



Pathway/Favourable Lithospheric Architecture

- **Body wave tomography**

- Record arrival times of teleseismic events (distant earthquakes)

- **Pros and cons (both types of tomography)**

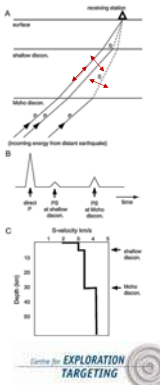
- Cheap (national equipment pool)
- Recording times of months are sufficient for ambient noise
- Body wave tomography depends on seismicity
- Only very largest velocity variations are mapped ('interface' faults)
- Poor resolution of boundary dip and depth extent



Pathway/Favourable Lithospheric Architecture

- **Receiver functions**

- Based on the modification of teleseismic wavefield as it passes through the crust (conversions, multiple reflections)
- Receiver function is the velocity structure beneath the recording station
- Produces 1D velocity-depth function

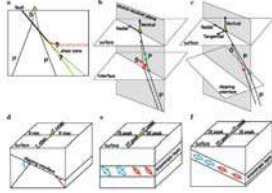


Source: Reading et al. (2014)

Pathway/Favourable Lithospheric Architecture

- **Pros and cons**

- Deployment time depends on seismicity
- Only very largest velocity variations are mapped ('interface' faults)
- Poor resolution of boundary dip and depth extent
- Recent developments: higher resolution, imaging faults (both types)



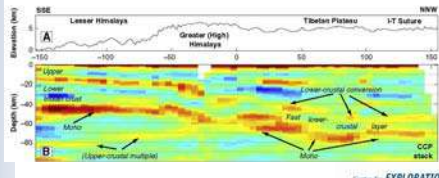
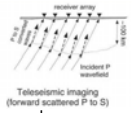
Source: Schulte-Pelkum & Mahan (2014)



Pathway/Favourable Lithospheric Architecture

- **Receiver functions – common conversion point (CCP) processing**

- Array of closely spaced recorders with processed as a beam
- Produces a 'low resolution' seismic reflection-like section plus major velocity variations



Source: Schulte-Pelkum et al. (2005)



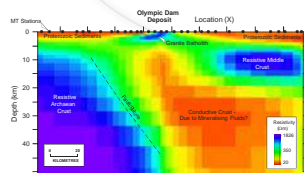
Pathway/Favourable Lithospheric Architecture

- **Magnetotellurics**

- Passive (natural source), frequency domain, electromagnetic method
- Deployment times of days

- **Pros and cons**

- Cheap (natural sources, access to equipment pools)
- Do not understand causes conductivity variations
- Empirical evidence of significant responses

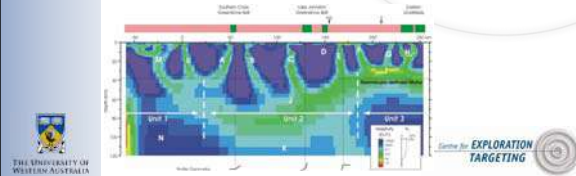


Source: G Heinson, pers comm



Pathway/Favourable Lithospheric Architecture

- **Pros and cons**
 - Responds to conductance (S.x)
 - Conductivity variations in the natural environment are extreme (so can potentially map thin features)
 - A 'textural' property (hard to predict)
 - Expect conductivity variations associated with fluids (past and present)
 - Can map both 'interface' and 'internal' faults



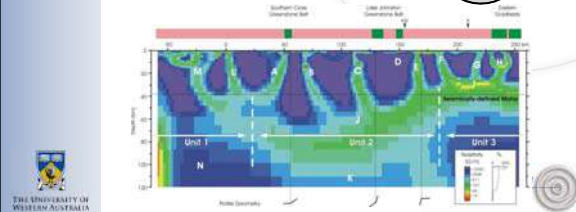
Pathway/Favourable Lithospheric Architecture

- **Summary**
 - There are plenty of useful and established deep geophysical tools in the shed
 - There are potentially some exciting new ones over the horizon
 - We need to combine 'interface' and 'internal' fault imaging methods
 - Need deep reflection data as a calibration point
 - Lithospheric architecture/pathways is manageable with a caveat about the resolution we can achieve
 - Would like to better understand what is being mapped - petrophysics



Source and Pathway

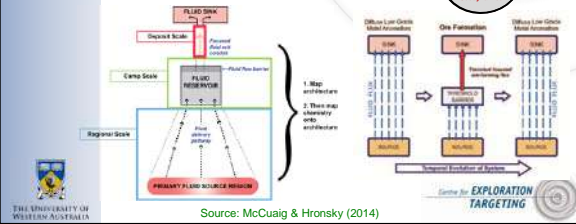
- **The role of geophysics in a mineral system-based exploration strategy?**
 - Petroleum: Source-pathway-trap
 - Minerals: Source-pathway-physical throttle-chemical scrubber



Source and Pathway

- The role of geophysics in a mineral system-based exploration strategy?

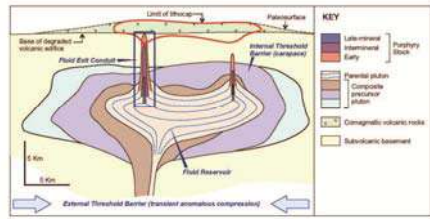
- Petroleum: Source-pathway-trap
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Source and Pathway

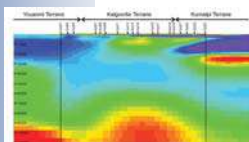
- Favourable (transient) geodynamics

- Fluid conduit ☺, but fluid reservoir ☹
- Barrier ☹

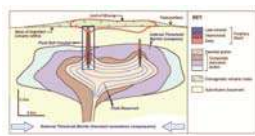


Mineral Systems & Geophysics

- Imaging the source and/or reservoir?



Source: Blewitt et al. (2011)

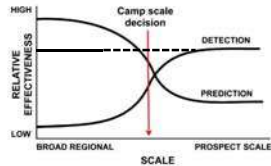


Source: G Heinson, pers comm



Source and Pathway

- Does the reservoir represent the elusive 'camp-scale' target
 - Are the fluids or the generation of the fluids creating detectable physical property contrasts?
 - Petrophysics of source, pathways and reservoirs – effects of alteration/differentiation/metasomatism etc



Source: McCuaig et al., (2010)



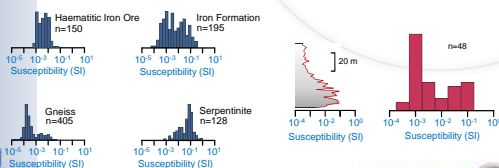
Petrophysics

- Why has this been on the wish list for so long?
 - Petrological problem with a geophysical consequence
 - Key mineralogical components are often minor constituents by volume
 - It's a difficult problem and there are few incentives to be in this space
- What's going on?
 - Databases are appearing
 - 'Core scan' facilities are appearing
 - Work on geochemical prediction (portable XRF)
 - Portable NRM meters



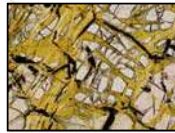
Petrophysics

- Is our approach the right one?
 - Databases = rock collections?
- Is there too much emphasis on accuracy and not enough on data volume?
 - Need analyse populations



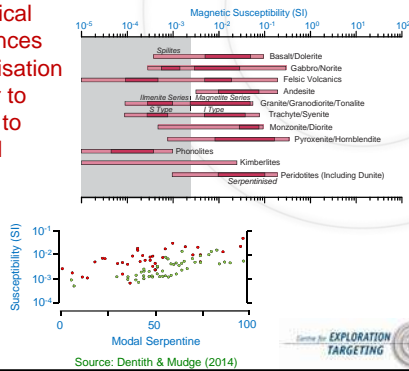
Petrophysics

- Are we collecting stamps
 - Need to understand processes
- Need to understand alteration more than build databases of 'fresh' data
 - Too much emphasis on compilations of 'fresh' data?
 - Petrophysical consequences of common types of alteration are very poorly documented
 - Serpentinisation is an exception



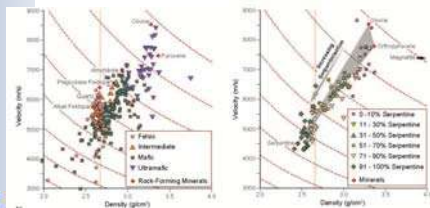
Serpentinisation

- Petrophysical consequences of serpentinisation are similar to those due to lithological variation



Serpentinisation

- Petrophysical consequences of serpentinisation are at least equal to those due to lithological variations
 - Density, velocity, magnetism, electrical properties?

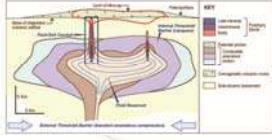


Source: Dentith & Mudge (2014)



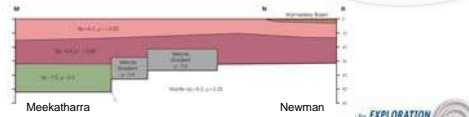
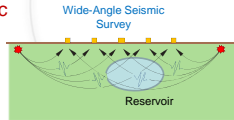
Targeting Reservoirs

- Alteration has significant petrophysical consequences – we should be able to see them
 - Gravity – may be?
 - MT – promising
 - Seismic?
- Seismic methods?
 - Cheap
 - Response to velocity variations (bulk mineralogy)
 - Receiver functions and/or wide-angle methods



Targeting Reservoirs

- Refraction (wide-angle) seismic
 - Responds to variations in velocity
 - Active type but significantly cheaper than reflection surveys
- Pros
 - Gives reliable velocity information – reservoir?
 - Map major interfaces (Moho)
 - Use mine blasts as sources, place charges in old pits



Source: Drummond (1996)



My Perspective

- Detecting 'reservoirs' and 'sources' using geophysics?
 - Potentially a means of targeting at the 'camp-scale'
 - We need to better understand the petrophysical consequences of fluid flow/ponding and also "sourcing"
 - Evidence suggests the petrophysical consequences of alteration are significant and hence potentially detectable
 - Wide-angle seismic and MT may be the methods that (together) can do this

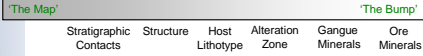


My Perspective

- We have the geophysical tools we need for deep-crustal terrane-scale exploration and we may get some better ones soon
 - Better MT inversions
 - Receiver function-based seismic methods
- Governments need to collect these kinds of data
 - To 'map' and 'detect' at the district and larger scale

Mapping

Direct
Detection



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TARGETING



Undercover exploration in 2030


Steve Beresford


Chair of Geoscience - UNCOVER

Chief Geologist - First Quantum Minerals




FIRST QUANTUM
MINERALS LTD.


UNCOVER
SUSTAINABLE EXPANSION
SECURITY RESILIENCE



Undercover exploration in 2030

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UNCOVER
SUSTAINABLE EXPANSION
SECURITY RESILIENCE





World Class belts of tomorrow will not look so inviting



Ndola airport, Zambia



FIRST QUANTUM


UNCOVER
SUSTAINABLE EXPANSION
SECURITY RESILIENCE



Introduction

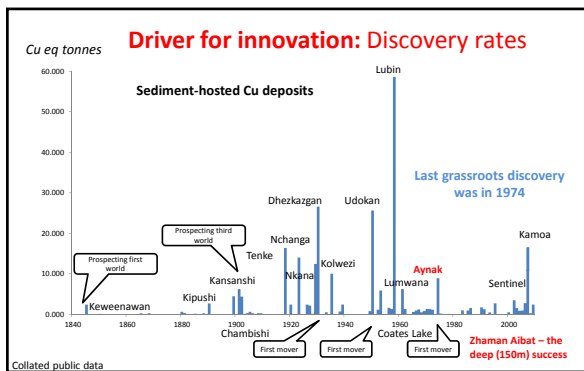
1. Undercover exploration today
2. What is UNCOVER?
3. Vision for undercover exploration in 15-30 years
4. Changing role of geophysics in undercover exploration – beyond bump hunting




We all know this:

1. Recycling the surface search space **will not** lead to a reversal in **Australia's** declining mineral deposit discovery rates
2. We have the technology to lead this change already

So what's the problem?






Hypothesis

Under cover exploration demands a **different** exploration workflow than explorers have used to date.....

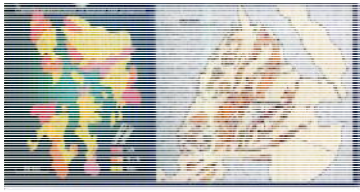
1. Undercover exploration today – what is good practice for 2015?
2. What do we already know how to do? (But aren't doing across the industry) **EASY WINS**
3. What does undercover exploration look like in 2030? What are the steps (trial and errors) we need to get there?



Discovery - Lets not forget others have successfully done this before!

Cannington This is what every company says they are trying to do


Case study in development of mineral systems, innovation at the scale that impacts, teamwork, new datasets, persistence, understanding search space and Bayesian understanding.




Walters et al 2001

UNCOVER

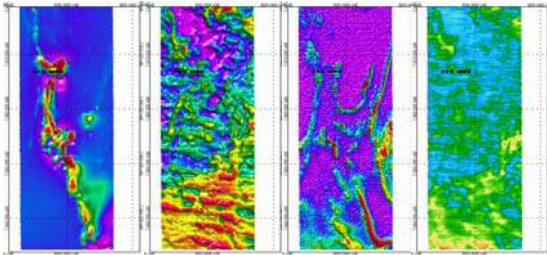
A typical undercover program in 2015



Tsodilo, Botswana



A balance of direct detection, stratigraphic drilling and imaging the mineral system



Mag Shallow EM Deep EM Kalahari depth

UNCOVER
SCIENTIFIC RESEARCH
 RESOURCES RESEARCH

What's different to surface exploration?

- We have to start from the **outside and move in** i.e. the opposite of prospecting
- We find the far field footprint before we find the mineralization! What does this look like?
- Upfront expenditure is higher (datasets, strat drilling vs target testing drilling)
- Results are often slower to arrive
- Under cover exploration is a bit like exploring a donut and the jam/middle is missing (along with all the characteristics of our ore deposit). Geologists like jam.

FIRST QUANTUM

UNCOVER
SCIENTIFIC RESEARCH
 RESOURCES RESEARCH

What is UNCOVER?

Established in 2010 by the Australian Academy of Science

- A **national** scientific research strategy
- A **collaborative** partnership
- Reveal and unlock Australia concealed mineral wealth
- To achieve this we need to be as **effective exploring undercover** as we are today at the surface
- That statement should be met with **incredulity**. This requires a step change (real meaning of the word)

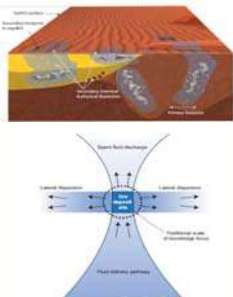


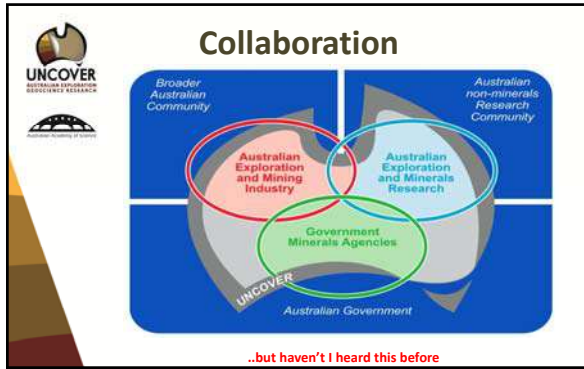
UNCOVER
SCIENTIFIC RESEARCH
 RESOURCES RESEARCH

UNCOVER - Themes

Four broad themes emerged using a **Mineral Systems** approach:

1. Characterising the cover
2. Lithospheric Structure
3. 4D Metallogenesis
4. Distal footprints





We have other industries that are driving this sort of step change with new forms of collaboration

Roadmap for New Opportunities in Melanoma Research

Society for Melanoma Research (SMR) and Melanoma Research Foundation (MRF)

Human Genome


Exoplanet Missions

Where is UNCOVER today?

- AMIRA Road map pulling together the collective industry's view, needs and wants (Commenced September 2014)
- Governments are leading the charge already eg depth of cover, new approaches to stratigraphic drilling


AMIRA INTERNATIONAL


UNCOVER: Cover-thickness mapping technical workshop summary and outcomes



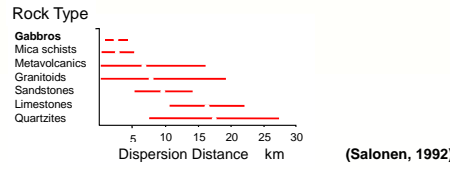
1. Characterising the cover

- We need to know more than depth to basement
- Cover is the key to expanding the secondary deposit footprint. We need to be 'cover lovers' as Steve Hill puts it.
- Defining the geometry of unconformity surfaces has become a critical starting point






Deposit preservation under cover

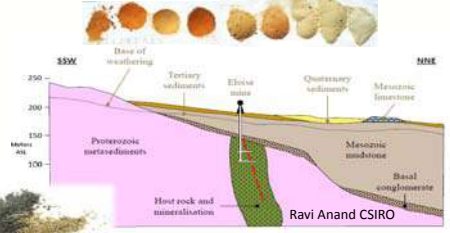


(Salonen, 1992)

Ultramafic rocks recessively weather in glacial terrains. Our deposit type is preferentially covered!




Interface sampling to detect, map rock types and understand belt fertility




Mapping this unconformity geometry has become the key because so many techniques hang off the geometry and nature of this contact

Mineralogy applied to unconformity sampling

Gemscan



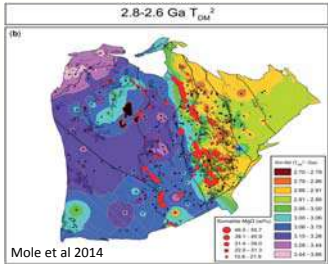
Rapid fieldscan mode picks up the sulfide globules within pyroxene



We can map target rock types and their S saturation history in paleo stream sediment samples

FIRST QUANTUM

2. Lithospheric architecture



2.8-2.6 Ga T_{ca}^2

Mole et al 2014

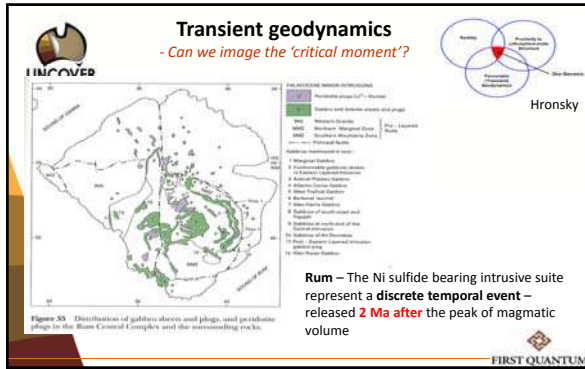
These technologies have been in active application for a decade. We need more data and more integration

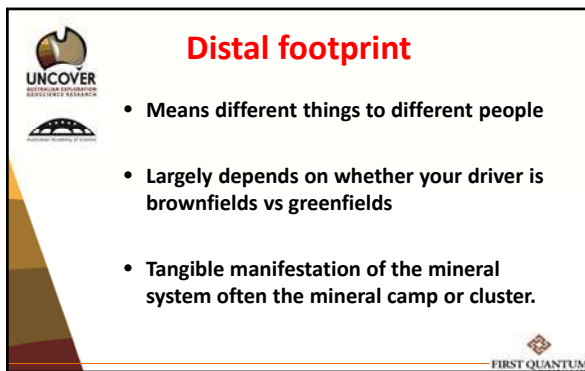
3. 4D metallogenesis

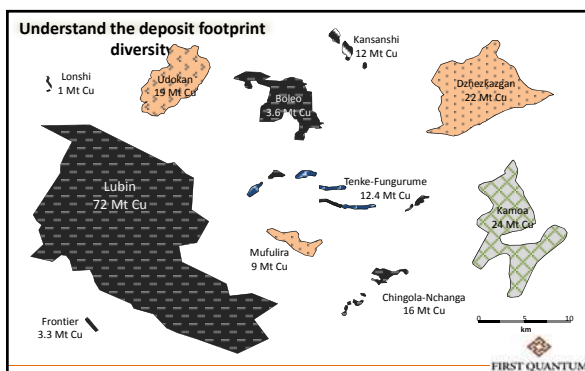
- More than dating ore deposits

1. Establishing *casuality* in targeting elements
2. Delineation of transient events and their geological proxies
3. Belt assembly history and fertility

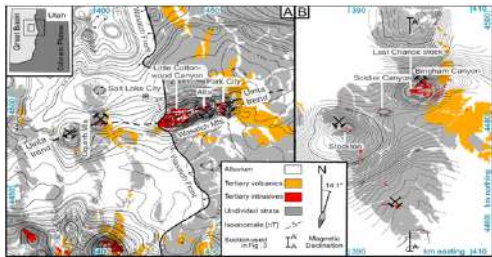
FIRST QUANTUM







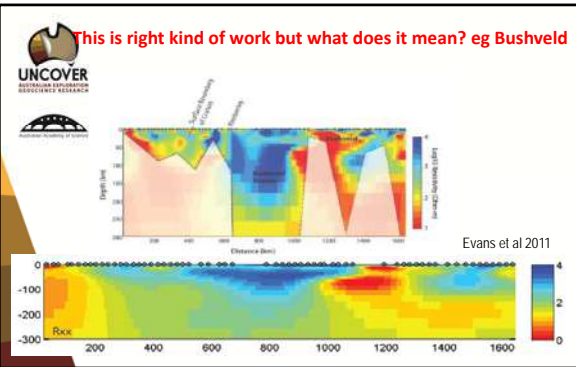
Imagery of staging systems in magmatic systems



Magnetics upward continued to 3300 m

Steinberger ETH

This is right kind of work but what does it mean? eg Bushveld



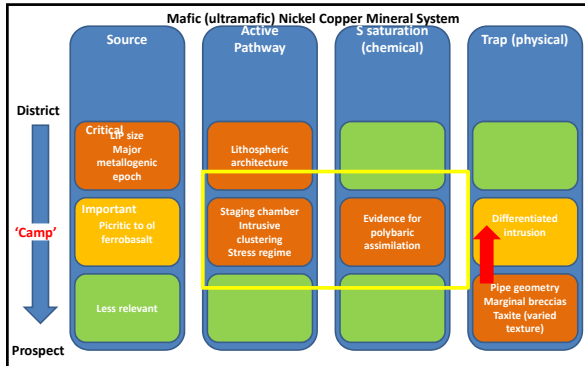
Stay focused on size

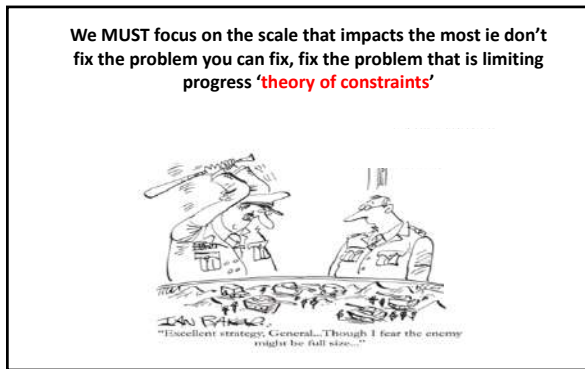


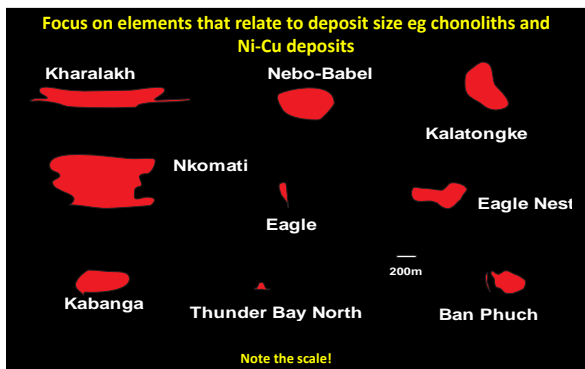
Q: So, when you finally came to Escondida, what made you think that it might be something special?

DL: First of all, the zone of hydrothermal alteration around the deposit was gigantic. It probably had a long dimension of fifty kilometers.

David Lowell – Discovery of Escondida







How early can I map those critical elements?

In precompetitive magnetic data?

Can we identify chonoliths in potential field data?

Dan Core
Fathom Geophysics

Atlas of synthetic models addressing permutations eg petrophysical, data density, remanence

Buckingham 2013

We are trying to image geometry using poorer quality data as a predictive tool. We will accept trade offs.

FIRST QUANTUM



How do we provide constraints when we have more data?

New inversion methodologies and new visualization tools for geologists


Kaukolinna

Show geologists uncertainty in modelling



Exploration in 2030

- **Short term** – The science we know what to do and how to do. We need a level of collaboration we haven't seen before in OUR industry.
- **Mid term** - The second phase will be science we know what to do but not how to do. Getting the questions/problems right
- **Long term** - The third phase will be science we only think we know what to do and we need to learn how to do (We have to start the building blocks of these now)




The mineral systems scale problem will not solve itself





The issue: Almost by definition it's the scale we have the poorest data density


Conclusions: 'Teaching birds on how to fly'




- **Imaging the tangible manifestation of mineral systems** eg staging, exhausts, metal reservoirs, and threshold barriers
- **Visualization of uncertainty**
- **Imagery of unconformity surfaces** – role in the geological map of tomorrow
- **Integration with geologists** (easier said)





...and lets get beyond IOCG



 **Conclusion 1:** The techniques of the deeper search space will be different. So might the exploration workflow.....



 **Conclusion 2: We need to do**



Innovation doesn't have to be rocket science - CRAESTAR





Mineral Systems Approach to Porphyry Copper Exploration – A Magnetic Perspective in Southwest Alaska

Eric D. Anderson

ASEG 2015 workshop

Geophysical signatures of mineral
systems: More than bumps

February 19, 2015




USGS
science for a changing world

**Mineral Systems Approach to Porphyry Copper Exploration –
A Magnetic Perspective in Southwest Alaska**

Eric D. Anderson

ASEG 2015 workshop
Geophysical signatures of mineral
systems: More than bumps

February 19, 2015



A map of Alaska with the Pebble district highlighted in green and marked with a yellow star. Anchorage is also marked with a red dot. The map shows the border with Canada to the north and the US-Canada border to the east.

Outline of Presentation

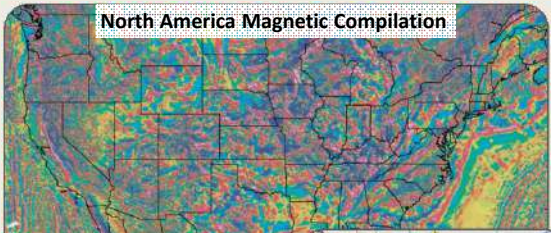
*Goal: Show you ways to think about aeromagnetic
data and porphyry copper systems*

- **Background**
- Geologic setting and aeromagnetic signature of
Pebble district
- Pebble – Pike Creek comparison
- Magnetic signature of other intrusion-related
resources
- Implications for exploration

USGS
science for a changing world

Aeromagnetic Data

North America Magnetic Compilation



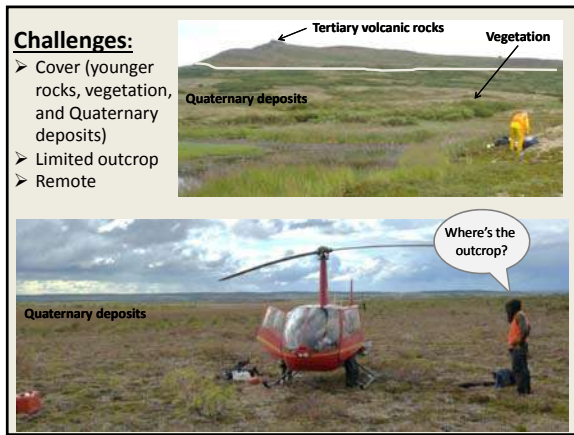
Advantages/Disadvantages

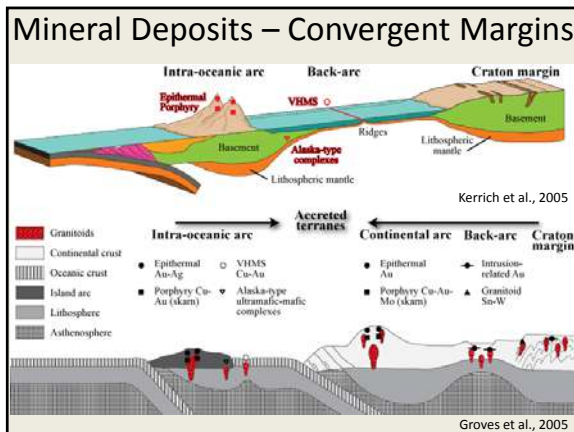
Data available: <http://mrddata.usgs.gov/>

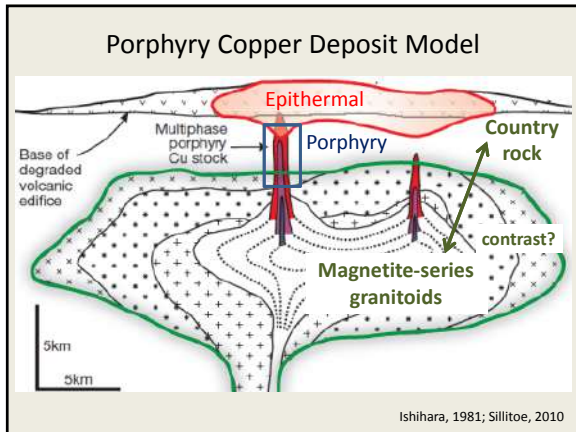
>1500 Individual Surveys

A colorful aeromagnetic map of North America showing magnetic intensity variations. An inset map shows the survey coverage across the continent.





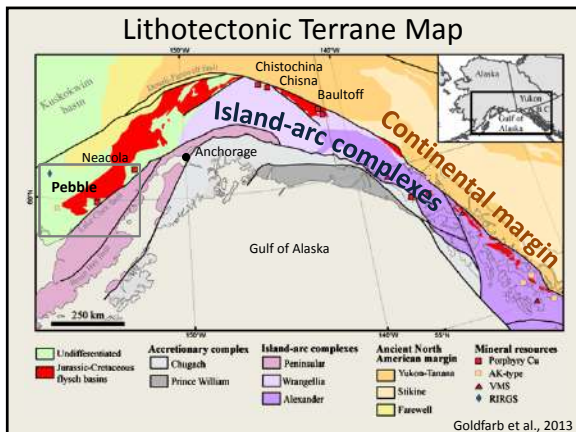


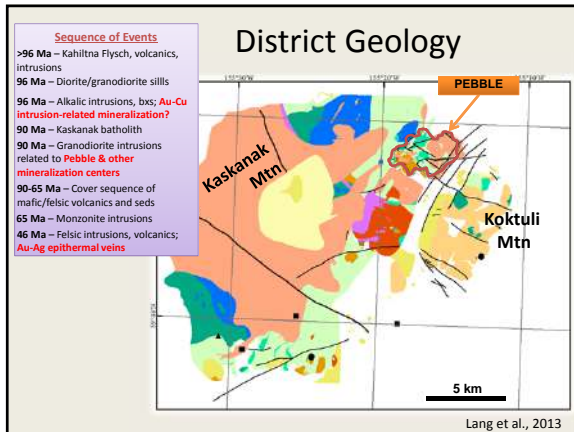


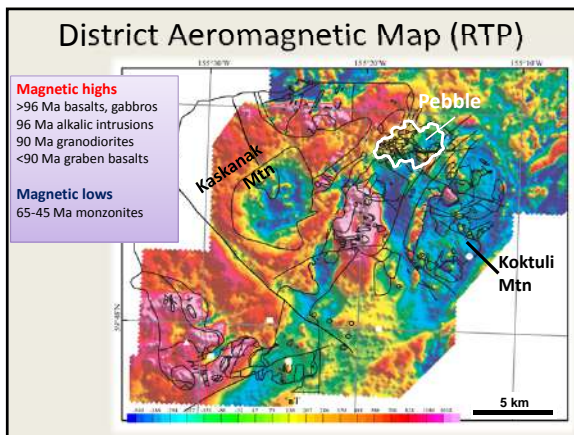
Outline of Presentation

Goal: Show you ways to think about aeromagnetic data and porphyry copper systems

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Outline of Presentation

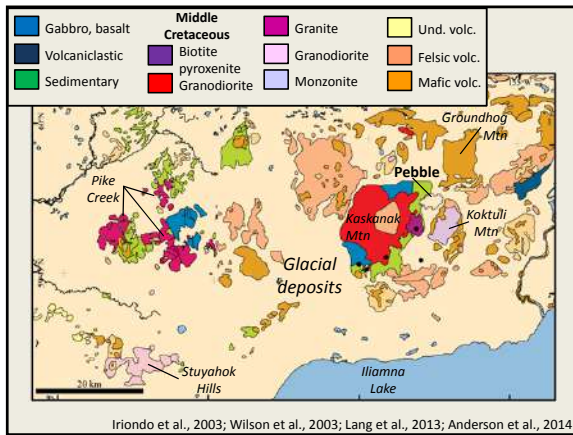
Goal: Show you ways to think about aeromagnetic data and porphyry copper systems

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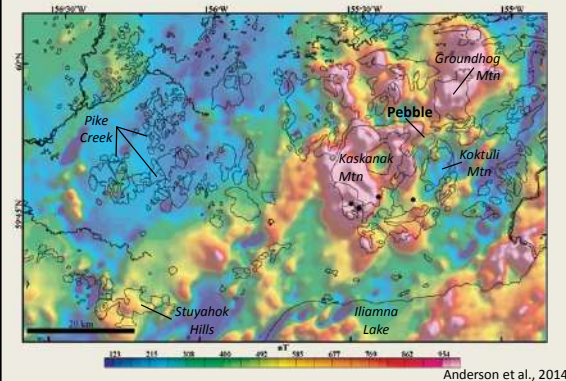
Pebble – Pike Creek Comparison



- Recently mapped areas
- Recent age dating indicate Pike Creek intrusions similar to Shotgun deposit
- Available magnetic susceptibility measurements
- Continuous aeromagnetic data coverage



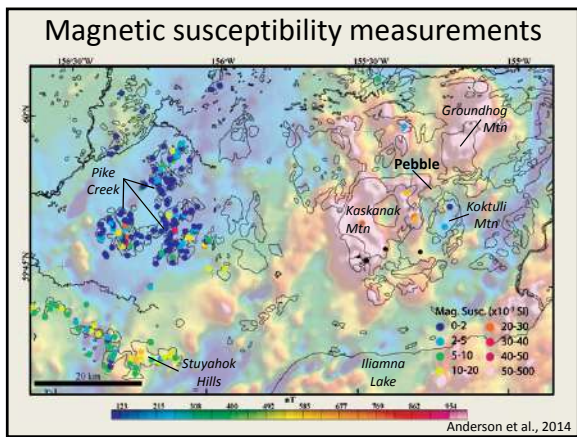
RTP Aeromagnetic Anomaly Map

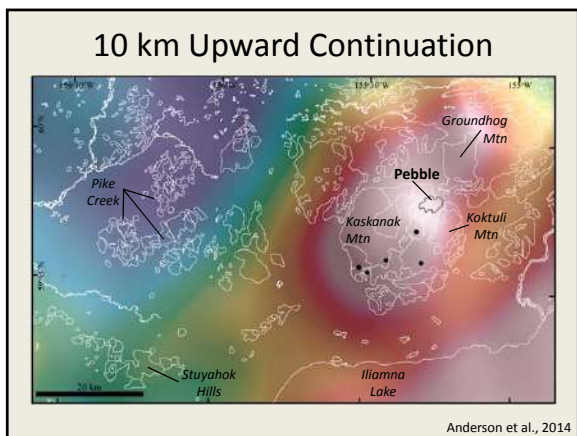


Magnetic susceptibility measurements

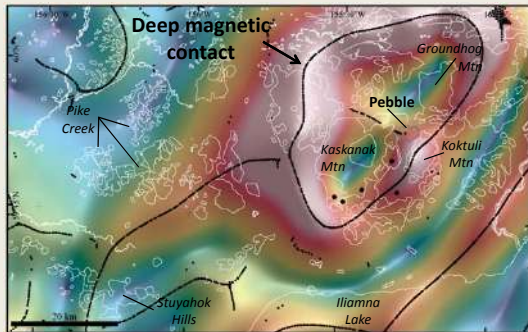
Lithology	Range (10 ⁻³ SI)	Mean (10 ⁻³ SI)	Median (10 ⁻³ SI)	N
Rhyolite, dacite	0.01-11.4	2.86	1.89	19
Basalt, andesite	0.04-40.2	12.6	10.2	19
Igimbrite	5.01-10.3	7.53	7.45	9
Pike Creek Area Intrusions				
Monzonite, granodiorite, quartz monzonite, quartz monzodiorite (Stuyahok Hills)	2.27-33.6	12.8	10.4	25
Alkali-feldspar granite, syenogranite, monzogranite, quartz monzonite, quartz diorite, monzonite (Pike Creek)	0.03-12.8	1.80	0.45	74
Pebble Area Intrusions				
Monzonite (Koktuli Mtn)	1.22-2.98	1.90	1.50	5
Granodiorite, quartz monzonite (Kaskanak Mtn)	4.50-50.4	28.8	30.1	25
Biotite pyroxenite	0.34-600	291	301	118

Anderson et al., 2014



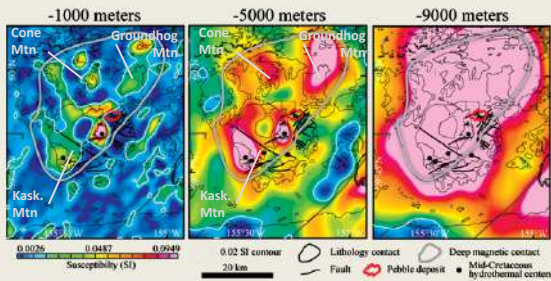


Total Horizontal Gradient



Anderson et al., 2014

3-D Inverse Modeling

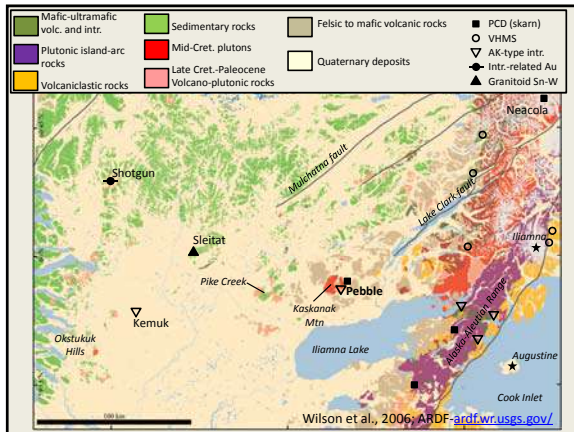


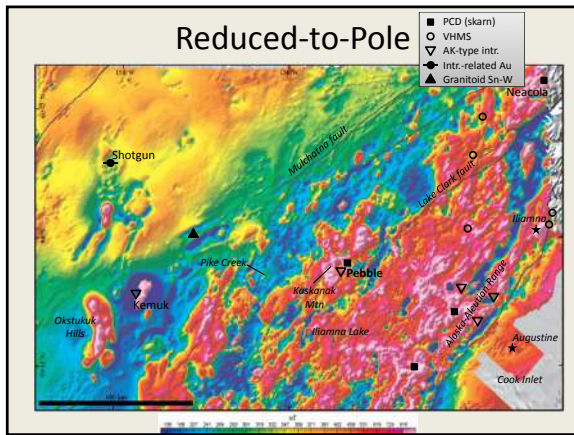
Anderson et al., 2014

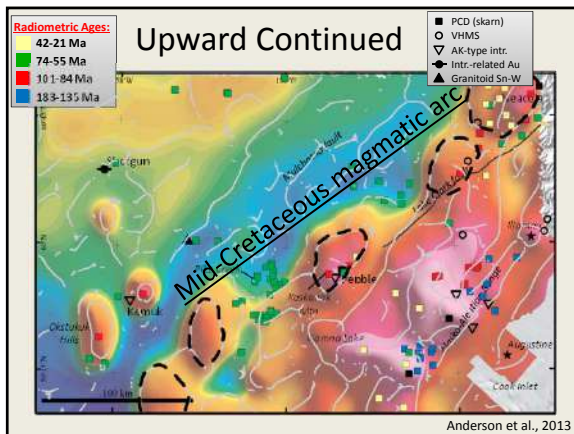
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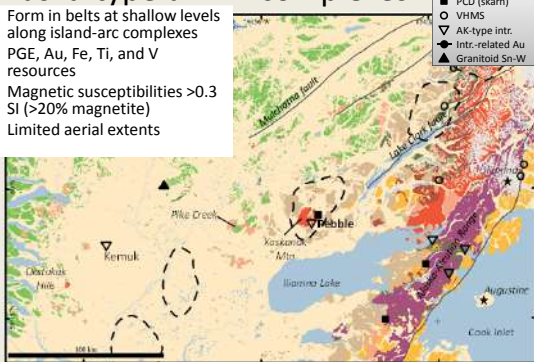






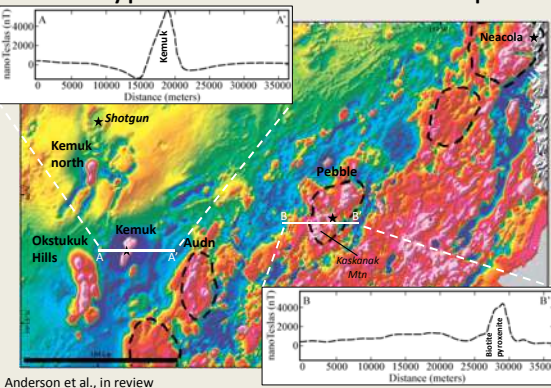
Alaska-type um-m complexes

- Form in belts at shallow levels along island-arc complexes
- PGE, Au, Fe, Ti, and V resources
- Magnetic susceptibilities >0.3 SI (>20% magnetite)
- Limited aerial extents



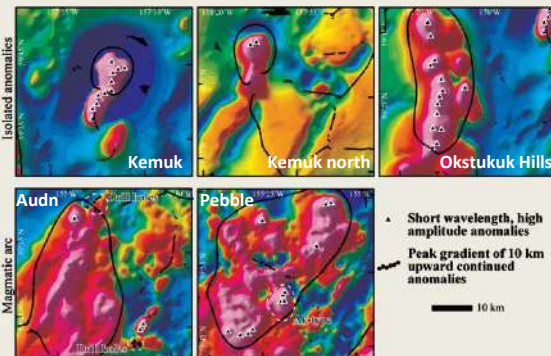
Alaska Resource Database File: <http://ardf.wr.usgs.gov/>

Alaska-type Ultramafic-mafic Complexes

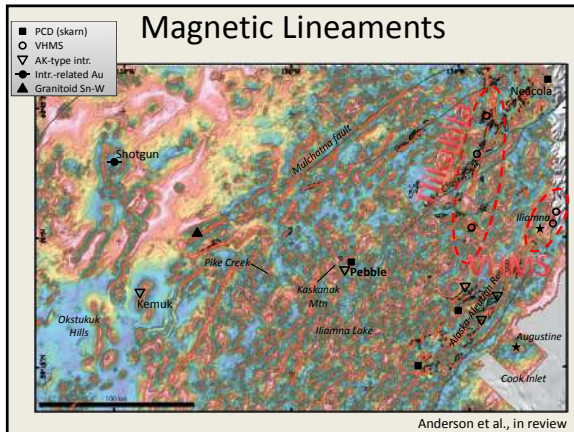


Anderson et al., in review

Alaska-type Ultramafic-mafic Complexes



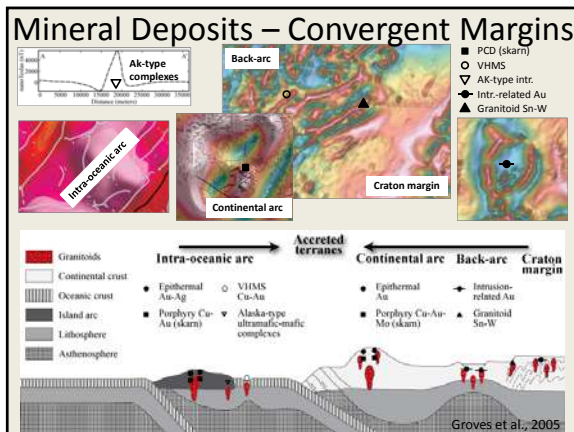
Anderson et al., in review



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Concluding remarks...

Goal: Show you ways to think about aeromagnetic data and porphyry copper systems

- Filtered and modeled aeromagnetic data provide a framework for exploration in an accreted island-arc setting
- Porphyry copper systems can be imaged at broad scales
- Aeromagnetic data differentiate granitoids with similar compositions, but differing mineral deposit styles
- Modeling suggest a large volume of highly magnetic material underlies the Pebble district
- Alaska-type ultramafic-mafic complexes produce characteristic short wavelength, high amplitude anomalies
- Lineaments may reflect extension in back-arc

Thank you!

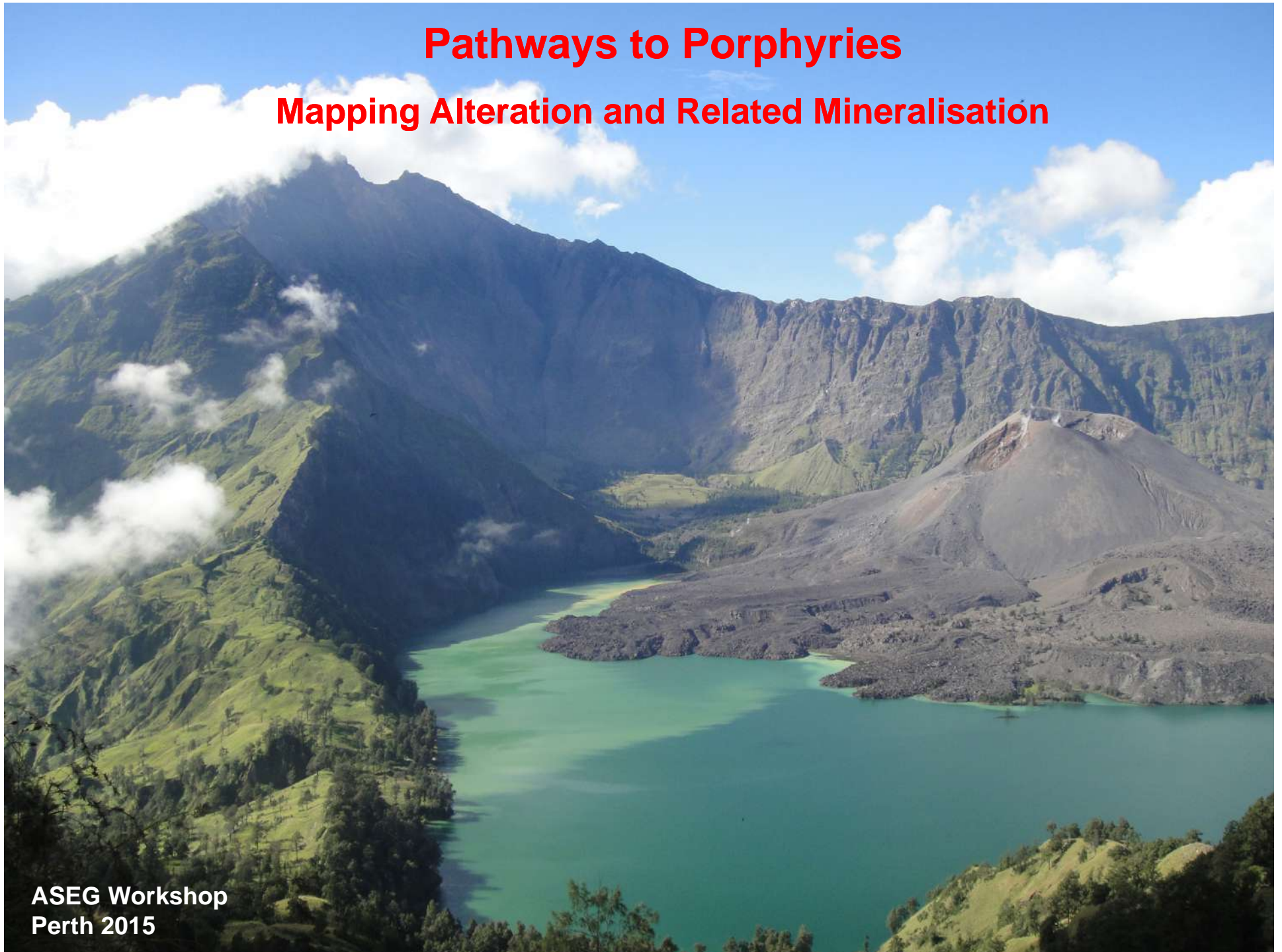
ericanderson@usgs.gov

This work was largely funded by the Concealed Deposits project within the Mineral Resource Program at the USGS. A special thanks to Karen Kelley, Bob Eppinger, Paul Bedrosian, and Rich Goldfarb for both their encouragement and thoughtful discussions.

The Pebble Limited Partnership provided data and logistical support.

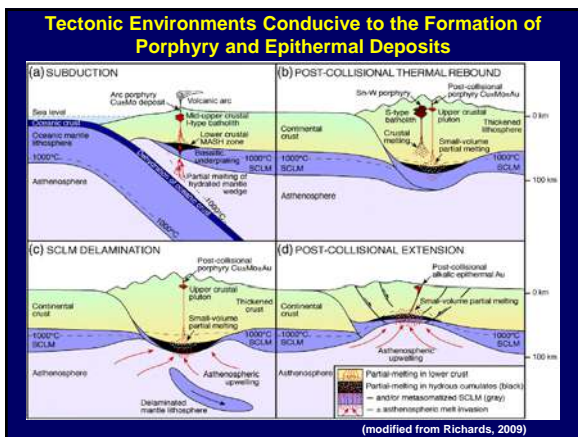
Pathways to Porphyries

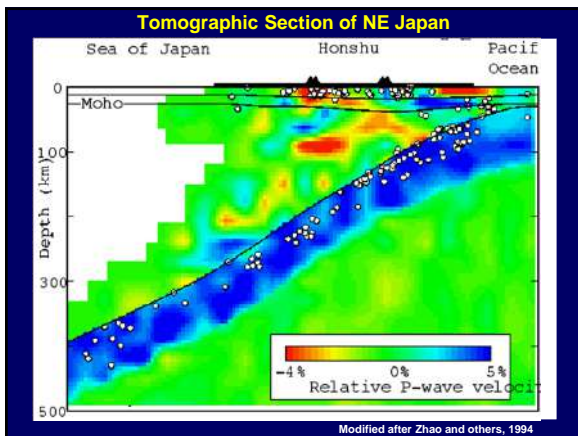
Mapping Alteration and Related Mineralisation

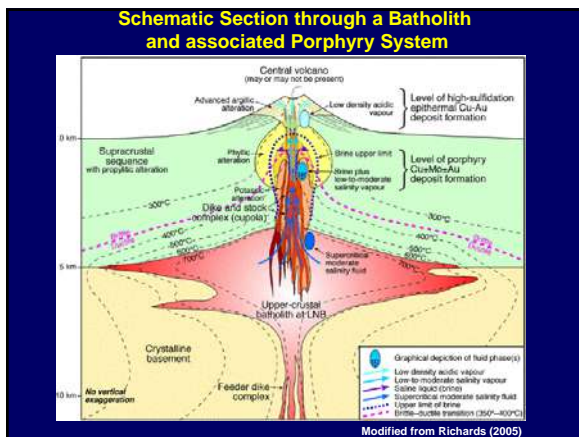


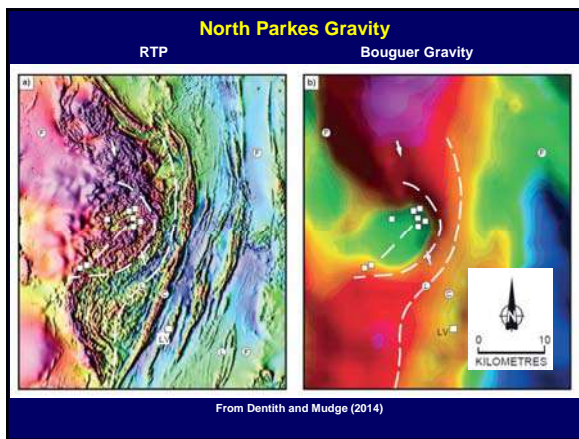
ASEG Workshop
Perth 2015

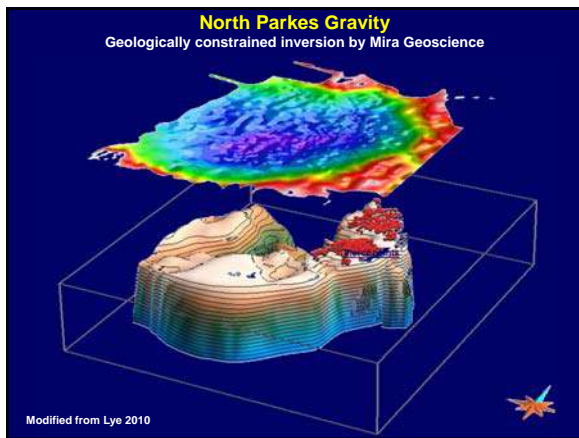


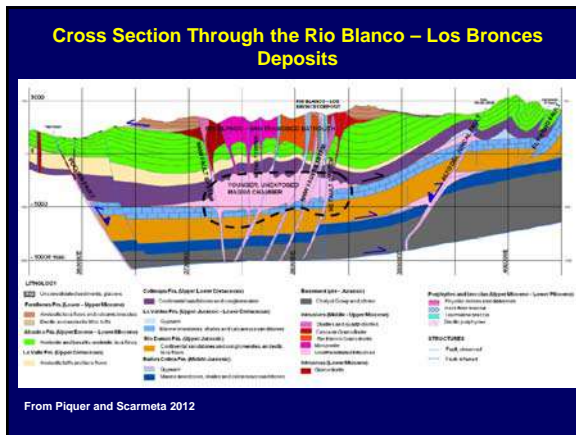


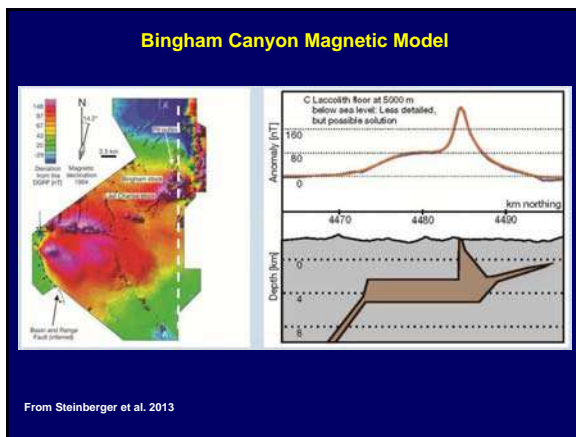


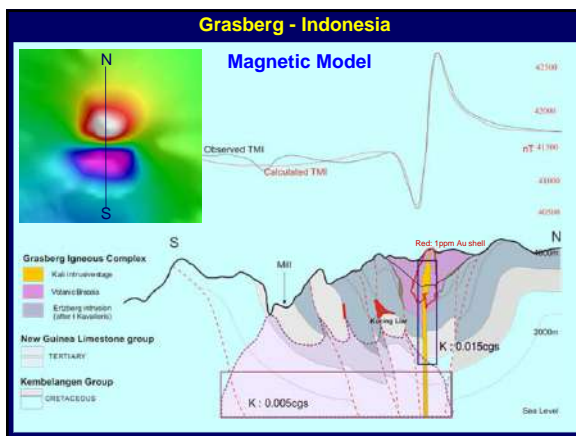


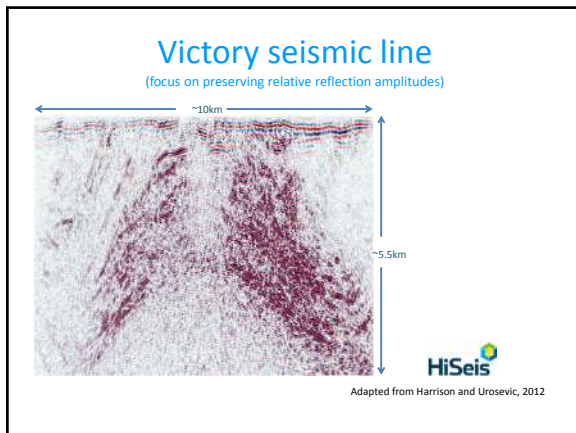


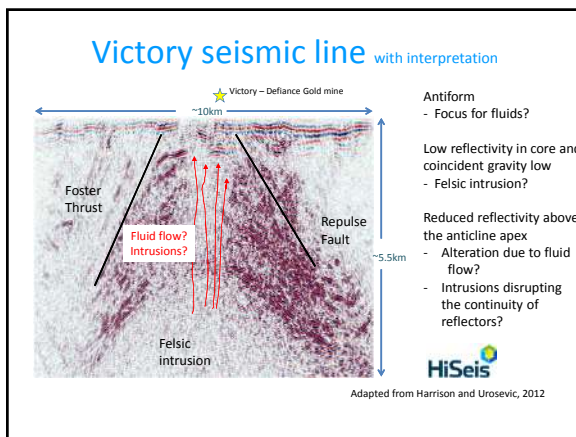


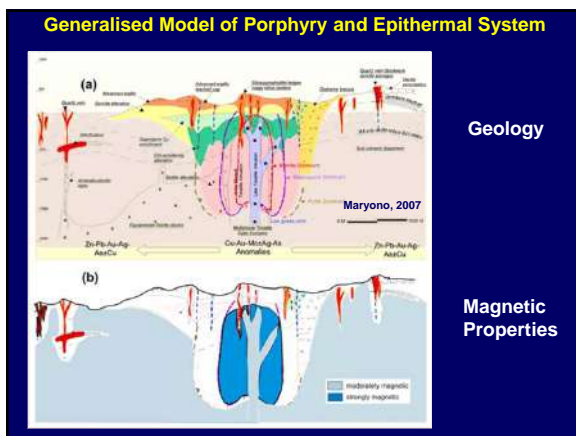


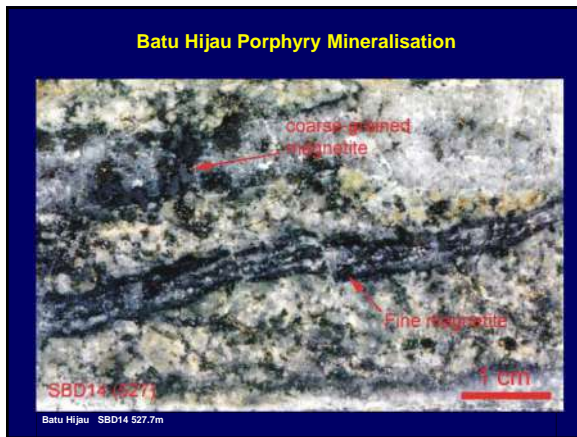


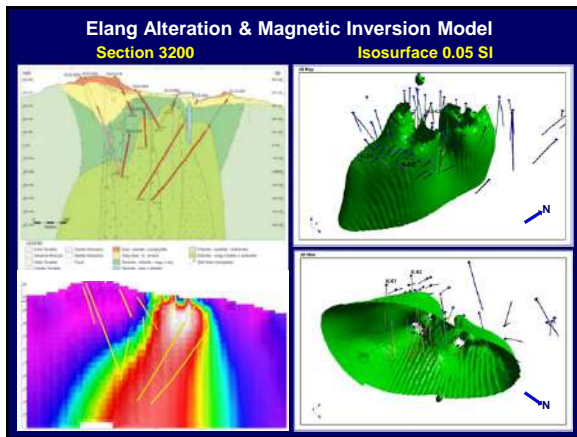


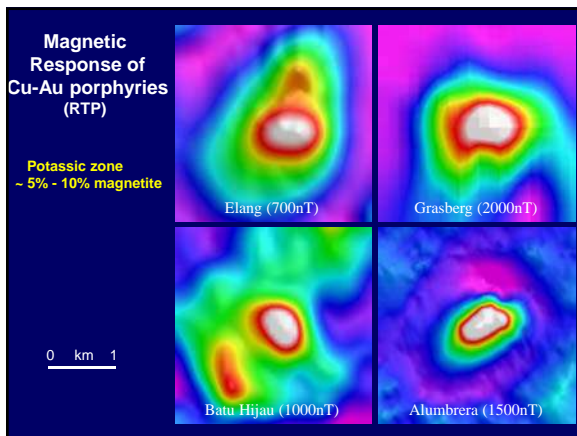


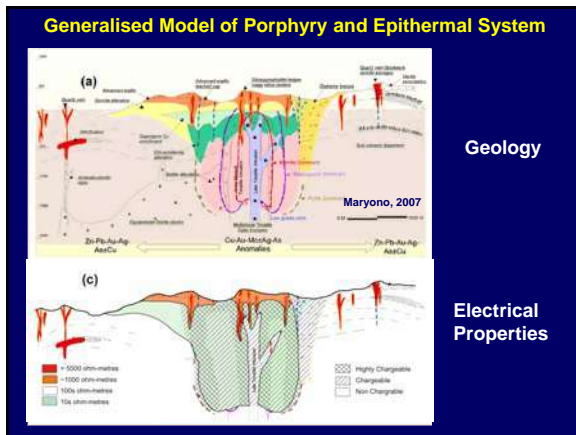


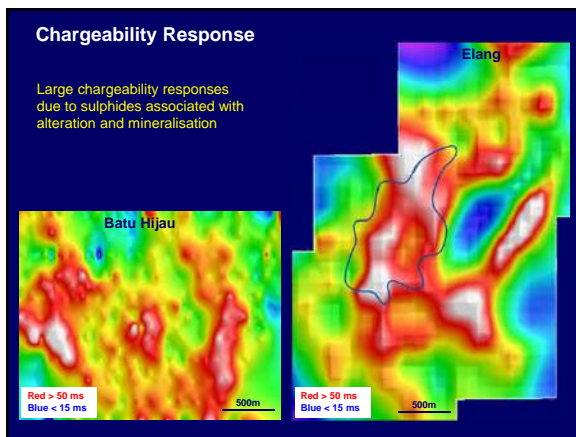


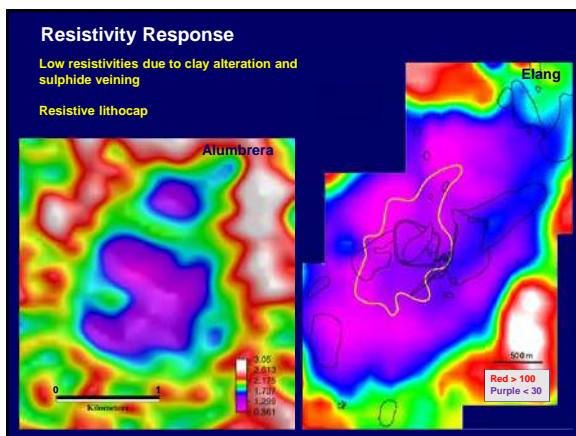


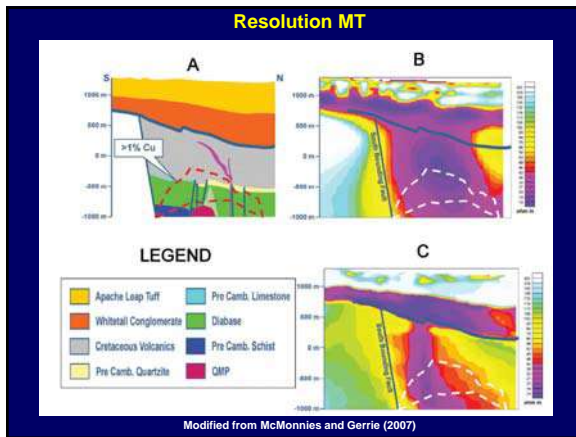




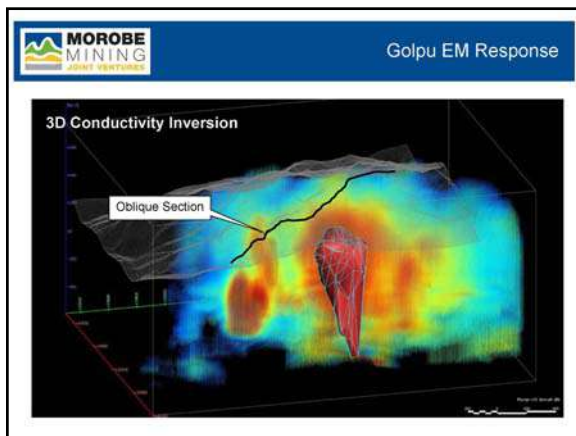












CONCLUSION

Mapping Magma Chambers and Stocks

- Gravity Contrast
- May be magnetic
- Resistivity Contrast (MT)
- Seismic Tomography
- Reflection Seismic

Mapping Porphyry Alteration at Depth

- Mineralisation associated with magnetite
- Magnetite destructive alteration
- Conductive sulphide veins & clay alteration
- High chargeability due to sulphides

Real-time data and geologically meaningful bumps

James S Cleverley
Principal Geochemist, REFLEX



KNOW MORE

Downhole Surveying
Core Orientation
Directional Control
Onsite Geoanalysis
Rig Monitoring




SHARE FASTER

Data collection and storage
Data integration
Data distribution and sharing
Data analytics






MINE SMARTER


Geochemical Consulting
Geochemical Data Analysis
Geometallurgy
Training
Software



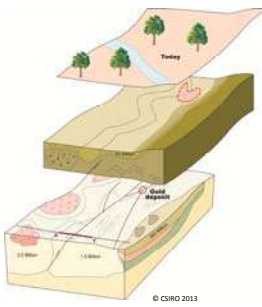
Real-time data and geologically meaningful bumps

James S Cleverley
Principal Geochemist, REFLEX

 KNOW MORE Downhole Burntesting Core Description Directional Corebit Shuttle Desamplification Rig Monitoring	 SHARE FASTER Data collection and storage Data integration Data distribution and sharing Data analysis	 MINE SMARTER Geochemical Consulting Geochemical Data Analysis Geochemical Training Software
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The Exploration Challenge

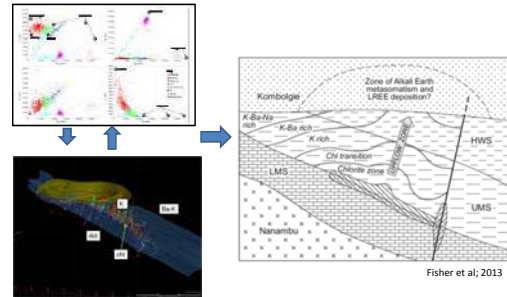


Where am I?
Where do I go next?
What is cover?

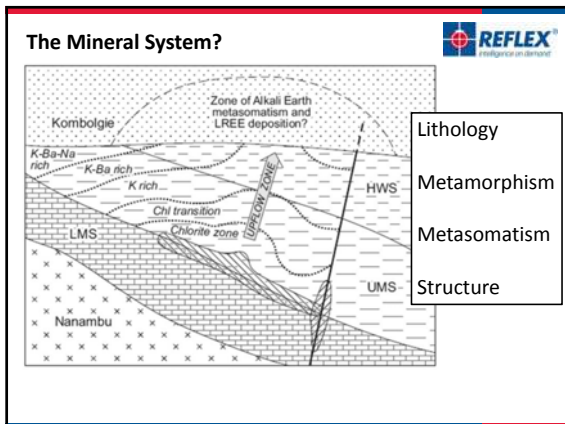
"Can we collect enough information to de-risk hole 2 before the rig has moved on?"
Steve Hill, Director GSSA

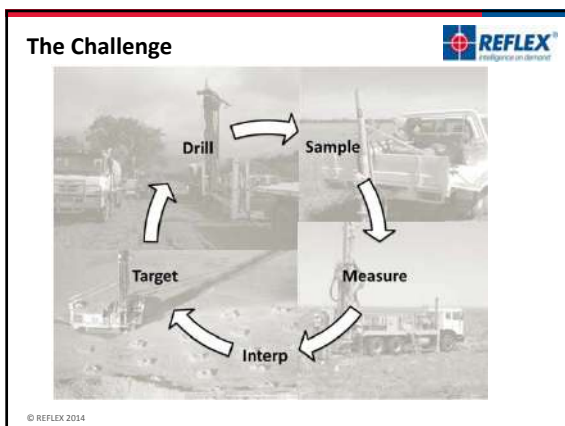


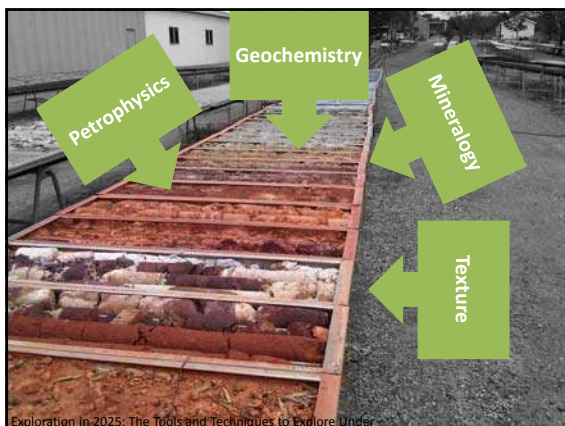
Targeting Distal Footprints



Fisher et al; 2013






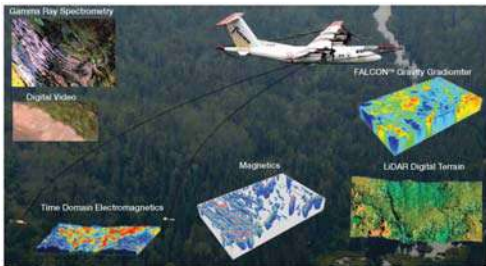





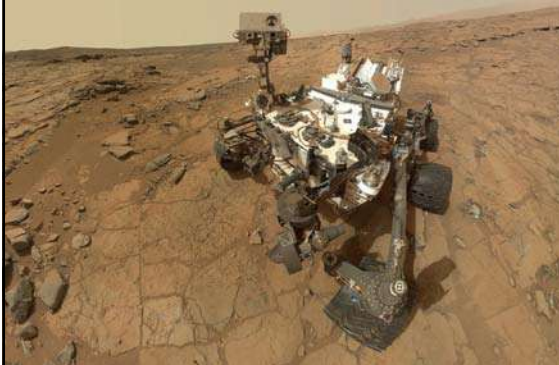
TECHNOLOGY PLATFORMS

 KNOW MORE Downhole Burnring Core Description Directional Control Drillbit Diagnostics Rig Monitoring	 SHARE FASTER Data collection and storage Data integration Data distribution and sharing Data analysis	 MINE SMARTER Geochemical Consulting Geochemical Data Analysis Geochemistry Training Software
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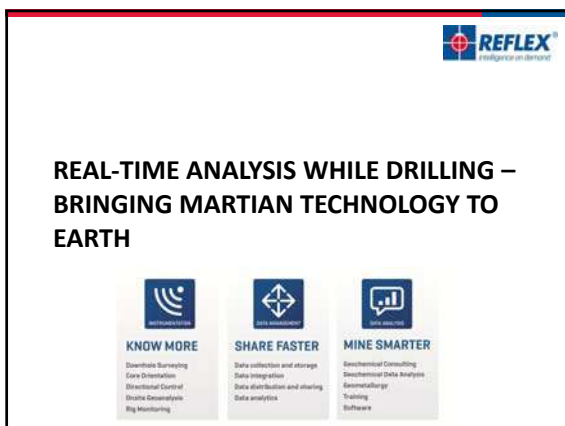
We have airbourne platforms ... 



.. and analysis platforms on Mars 















Weather information not data, consumer choice

The diagram illustrates the flow of weather information. On the right, the Australian Government Bureau of Meteorology logo is shown. An arrow points from this source to a cloud labeled 'Index of News Items'. From this cloud, arrows point to five different mobile weather application screens. The REFLEX logo is in the top right corner. © REFLEX 2014 is in the bottom left corner.

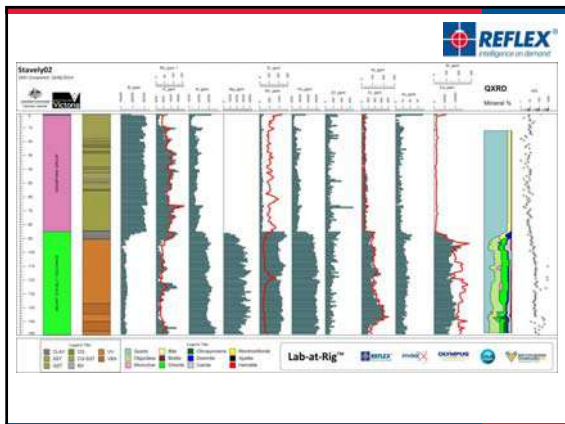
Decision support from sensor networks

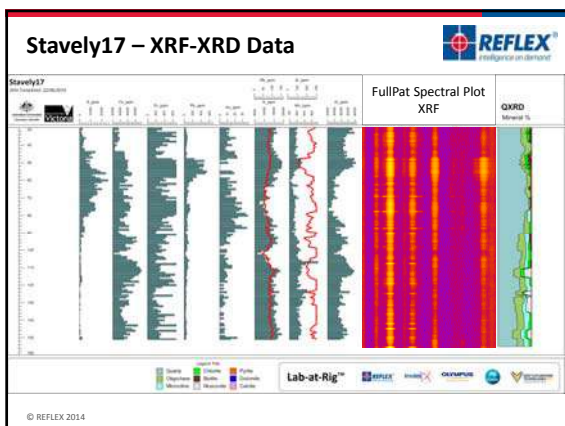
A photograph of an aircraft cockpit, showing various instrument displays and control panels, illustrating the use of sensor networks for decision support. The REFLEX logo is in the top right corner.

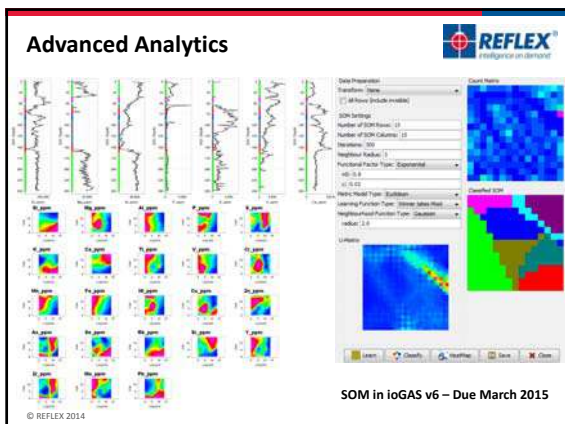
New technology will need data analytics

The diagram shows the SAAS architecture. On the left, 'Inputs' include 'Well Data', 'Plots', 'SWFO', 'Other Project Data', and 'Final Data Storage'. These feed into the 'Analytics Engine', which contains 'Inquiry Database', 'Data Processing', 'Analysis', and 'Final Reports'. The engine outputs 'Results', 'Reports', 'Visuals', and 'Dashboards'. A 3D geological model is shown on the right. A green arrow points from the text below to the Analytics Engine. The REFLEX logo is in the top right corner.

Algorithms to turn data into information (SAAS architecture)







Big Data Analytics

Large geochemical/mineralogical datasets will require new approaches to support decision making

S/Ti from pXRF during drilling

Down hole S/Ti value
Sulphide veins
Broad sulphide zones
Sulphide porosity

REFLEX
REPERFORATION TECHNOLOGIES
CSIRO

June Hill, CSIRO

Data to Decisions

Wavelet Tesselation techniques:
Auto-domaining
Data Fusion

REFLEX
REPERFORATION TECHNOLOGIES
CSIRO

June Hill, CSIRO

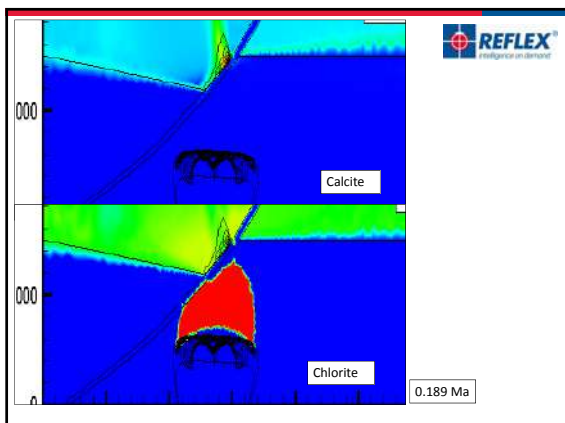
Physical properties from chemistry

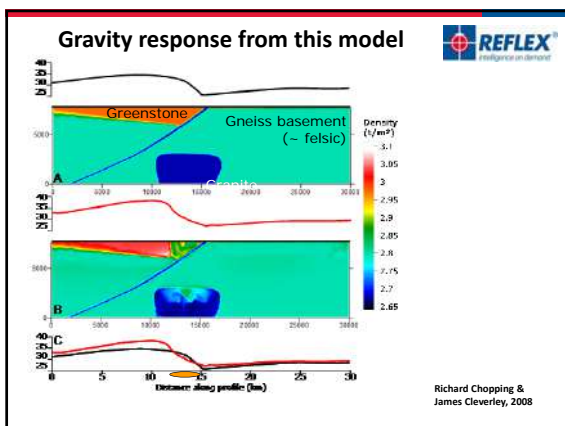
Density	Mineral	R1
2620	Quartz	0.3
2560	K-Feldspar	0.2
2820	Muscovite	0.4
5150	Magnetite	0.1
Rock Density		2941

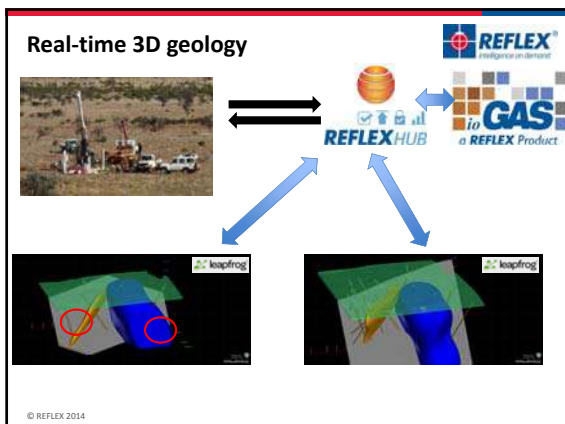
pmc/CRC
Project A3 Final Report 2008
Geophysical signatures of alteration
Richard Chopping

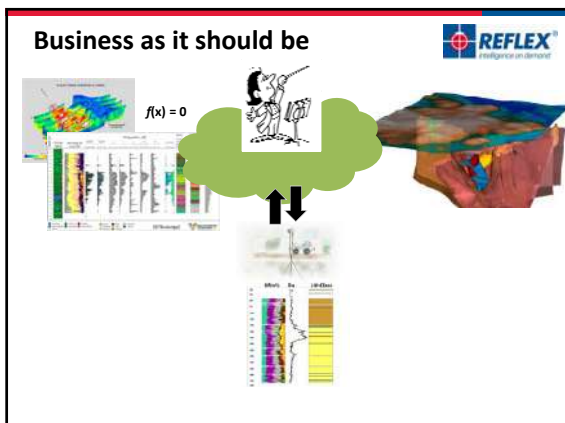
REFLEX
REPERFORATION TECHNOLOGIES
CSIRO

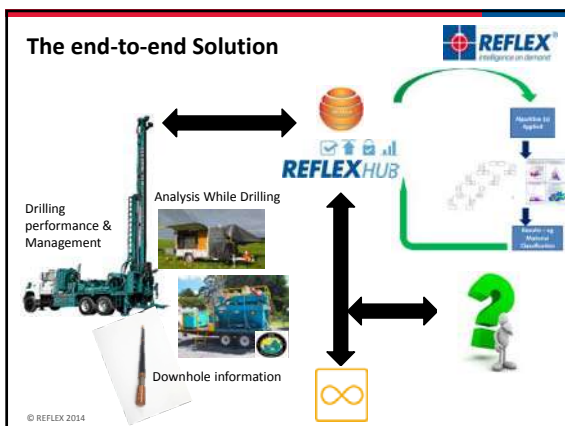
© REFLEX 2014







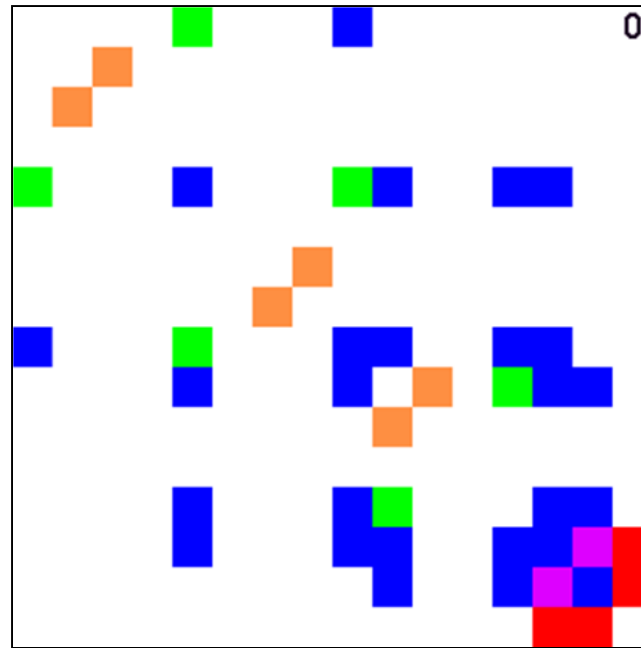




Conclusions

- Industry challenges are forcing us into **reconsider the way we do the business of mineral exploration and mining**
- Timely decisions are critical – **need information to support decision making**
- We need to **integrate our geological and geophysical information** to provide meaning to the bumps ..
- Customisable data management, storage and analytics - **I want information not data my way**
- **Drill rigs are becoming technology platforms ... what does this mean for your business?**
- What does all of this mean for **research, development and the skills of our people?**

From 3D geology to 3D Geophysics, what next?



Mark Jessell^{1,2,5}, Laurent Aillères², Eric de Kemp³, Mark Lindsay¹,
 Florian Wellmann¹, Michael Hillier³, Gautier Laurent², Thomas Carmichael²,
 Roland Martin⁴


¹Centre for Exploration Targeting, University of Western Australia, Australia

²School of Geosciences, Monash University, Australia

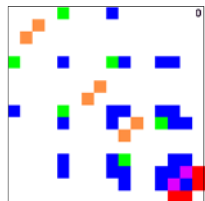
³Geological Survey of Canada, Ottawa, Canada

⁴Géosciences Environnement Toulouse, GET, Toulouse, France

⁵Institut de Recherche pour le Développement, Toulouse, France




From 3D geology to 3D Geophysics, what next?



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ASEG 18 Feb 2015



3D Interest Group

Friday 20th Feb UWA Robert Street Theatre
 2pm onwards??

- Yaoguo Li CSM *Inversion of Remanently Magnetised Bodies*
- Roland Martin CNRS *Toulouse Geophysical Inversion using SPECFEM and TOMOFAST3D*



SAYING GOODBYE TO A 2D EARTH

INTERNATIONAL CONFERENCE AUGUST 2 - 7, 2015
 QUALITY INN, MARGARET RIVER, WESTERN AUSTRALIA

INVITED SPEAKERS

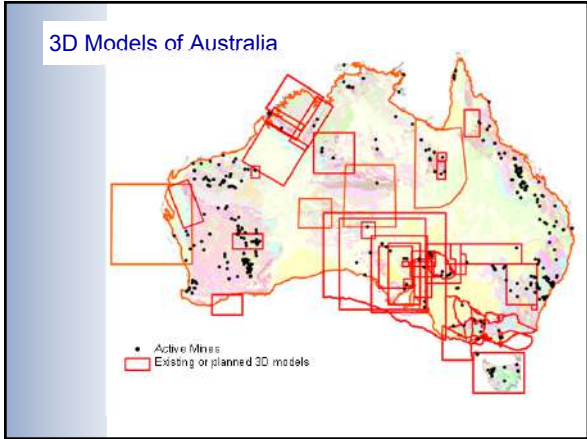
- Clare Bond University of Aberdeen, Scotland
- Eric de Kemp Geological Survey of Canada
- Florian Wellmann RWTH Aachen, Germany
- Gaby Courrioux BRGM, Orleans France
- Hoshin Gupta The University of Arizona
- Laurent Ailleres Monash University, Australia
- Peter Fullagar Fullagar Geophysics
- Peter LeLievre Memorial University of Newfoundland
- Roland Martin CNRS Toulouse, France

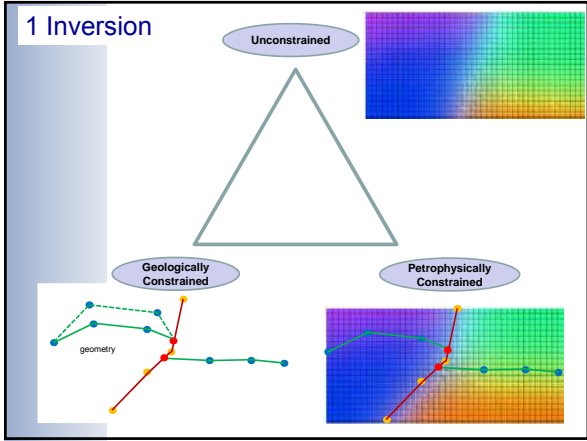
Sponsoring and Demonstration Opportunities

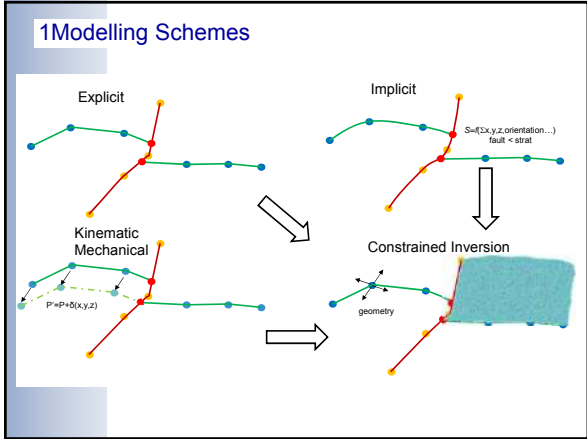
- Opportunities for presenting latest commercial and research codes
- Seeking named sponsors for invited speakers

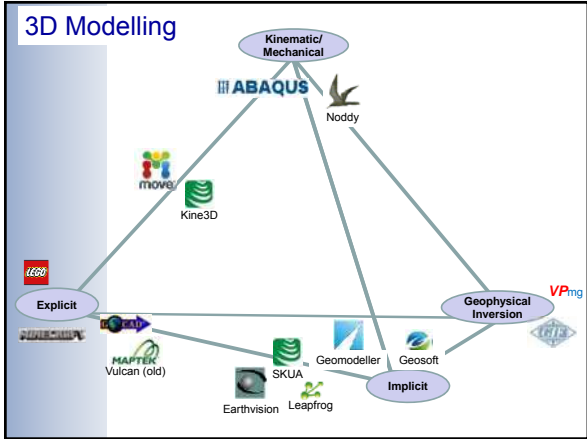
Further Information and Registration

<http://www.cet.edu.au/news-and-media/>









3D geomodelling scenarios

	Sedimentary Basins	Mines	Regional	Lithosphere
3D Constraints	RICH (3D seismic, deep boreholes, gravity)	RICH (dense boreholes, magnetics, seismic, electromagnetics)	POOR (rare boreholes, surface outcrops, gravity, magnetics)	RICH (Teleseismic, seismic, gravity, MT)
Structural Complexity	SIMPLE(R)	COMPLEX	COMPLEX	SIMPLE(R)
Dedicated Software	Gocad 1989, Geomodeller 1999...	MicroMine 1986, Leapfrog 2003...	Noddy 1981	Gocad 1989

Best practice: The single "best guess model"

1. Works for maps & 3D data rich areas, but a lower 3D data density reduces the value of this approach
2. No separation of data and interpretation
3. No error bars
4. Not reproducible
5. Fixed geometry & topology of input for process modelling and geophysical inversion

3D geology is an under-constrained problem

We do not have sufficient geological and/or geophysical data to define a unique 3D model



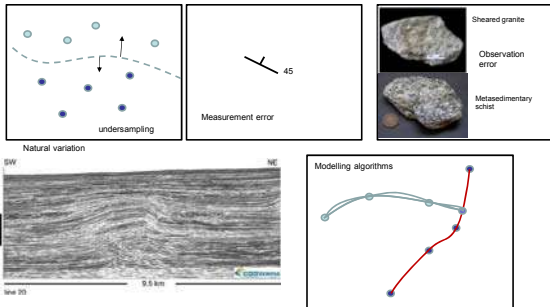
So we must not restrict ourselves to a single 3D model (we need error bars, just like a real science)



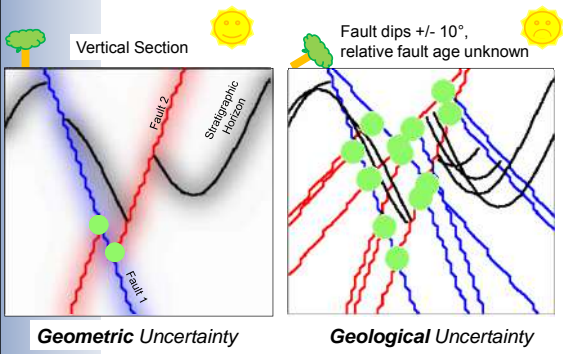
Therefore 3D Modelling tools that require continual manual intervention are a dead end

2: Uncertainty: What causes it?

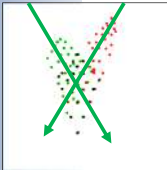
Sources of uncertainty



2) Geometric vs geological uncertainty

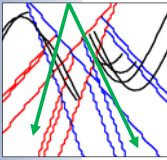


Which Targeting Strategy?



Short term:
drill where you are most likely to hit intersection

≠

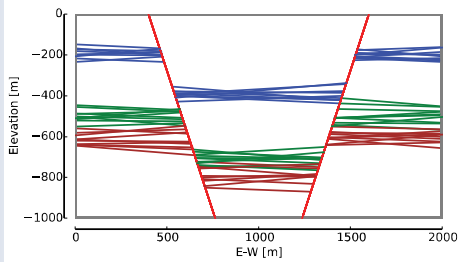


Long term:
drill where you are most likely to understand system

≠

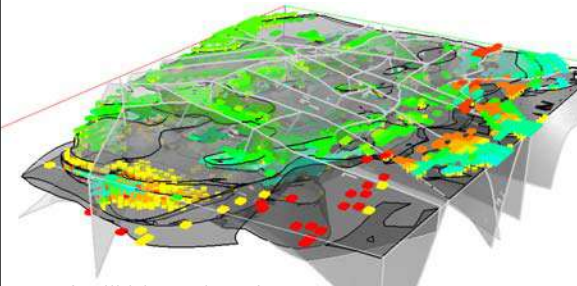
Optimal:
maximise stable share price increase

Visualising Geological Uncertainty



Local Geometric Variation: probability of hitting a surface at a given depth

Stratigraphic Variability = number of possible lithologies



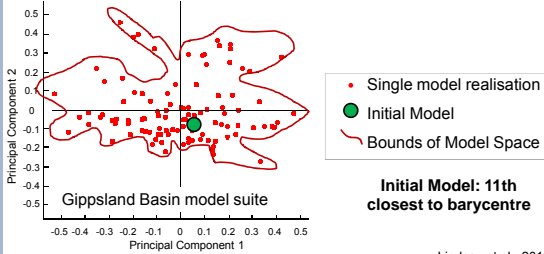
Where do we need to collect more data?

Lindsay et al., 2012

Geodiversity via Principal component analysis

Based on multiple *geological* attributes of the 3D model, e.g.:

- unit volume,
- unit depth,
- surface complexity,
- topological complexity

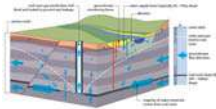


Why does Topology matter?

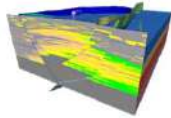
a) Connectivity

- Flow simulations
- Electrical measurements

⇒ *Massively reduced dimensionality*



b) Litho-structural contacts form the limiting containers for property simulations

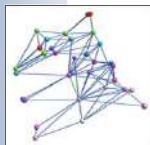
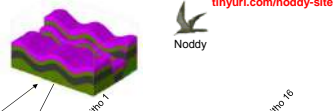
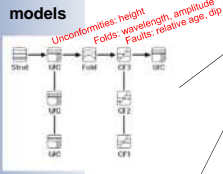


c) Geophysical inversions often assume fixed topology to constrain the model space

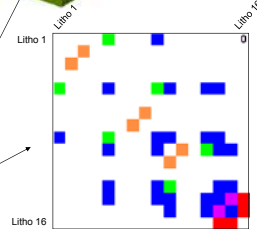


Topological Uncertainty

1000 models

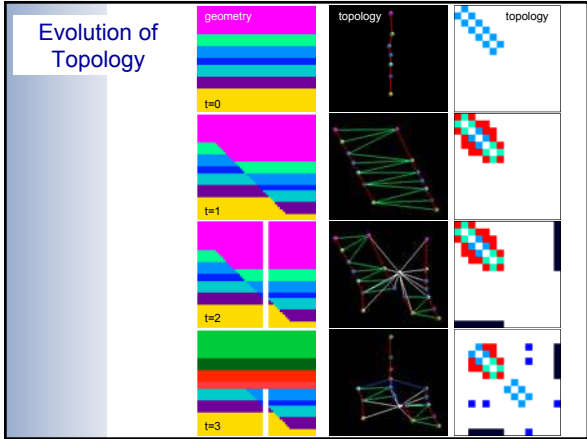


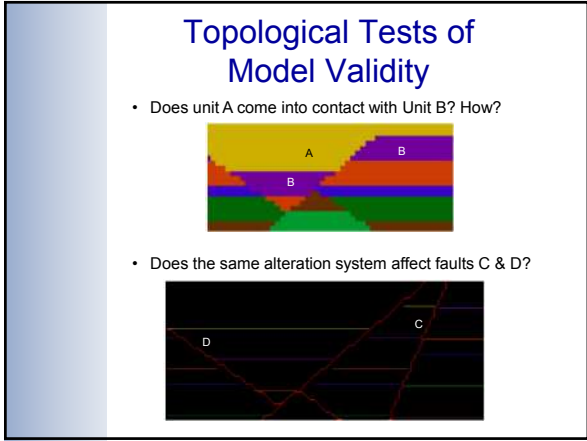
Network Graph for one model

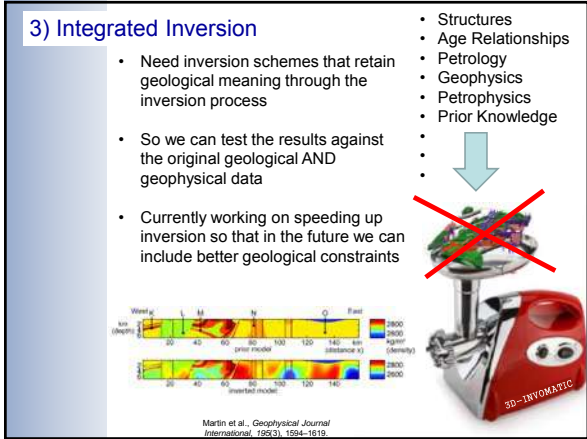


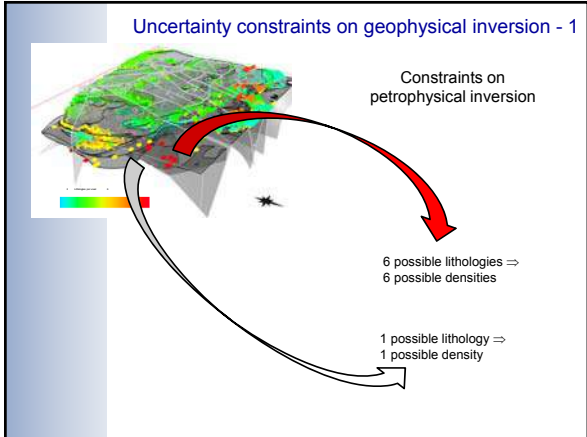
Adjacency Matrix of all unique topologies

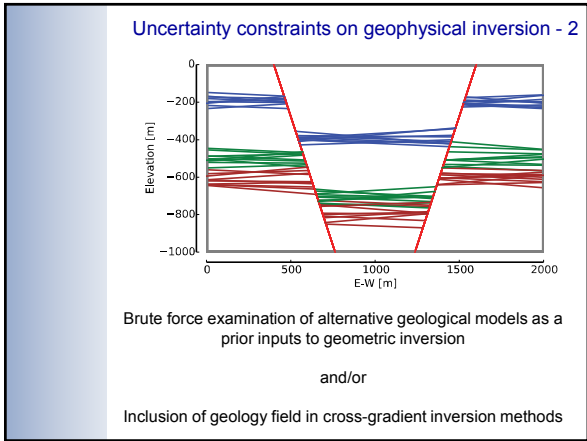
- Not neighbours
- Stratigraphic
- Unconformity
- Strat & fault
- Fault
- Unc & fault

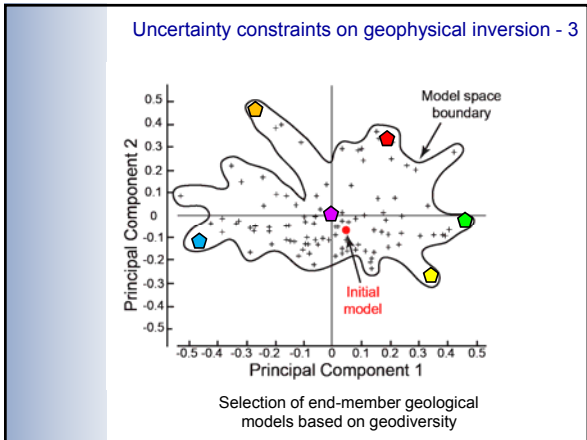




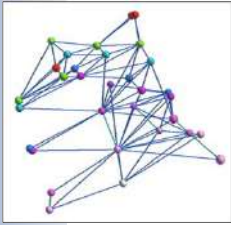




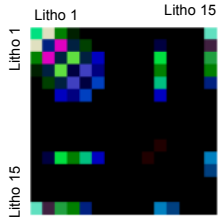




Uncertainty constraints on geophysical inversion - 4



Network Diagram



Adjacency Matrix

Massive reduction in dimensionality for systems where topology is a major constraint on behaviour:

e.g. Test conductivity/fluid flow models for each topology before settling on a suite of full prior models for inversion

Conclusions

1. Geologically constrained inversions require more than just the single best guess of the geologist
2. Uncertainty analysis helps transform 3D models from psycho-kinetic art to scientific tools
3. Implicit schemes allow us to explore geological uncertainty
4. The use of uncertainty and topology metrics suggests several pathways to improved exploration of the model space prior to handing off to geophysical inversion schemes



Finding the right bump under glacial till in the Central Lapland Greenstone Belt

Janne Kaukolinna

Contributions: Fathom Geophysics, Steve Beresford and FQM Finnex Personnel



FIRST QUANTUM
MINERALS LTD.



Finding the right bump under glacial till in the Central Lapland Greenstone Belt

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Cautionary Note Concerning Forward-Looking Statements



Some of the statements contained in the following material are forward looking statements and not statement of facts. Such statements are based on the current beliefs of management, as well as assumptions based on management information currently available. Forward-looking statements are subject to various risks, uncertainties and other factors that could cause actual results to differ materially from expected results. Readers must rely on their own evaluation of these uncertainties.

Note: all dollar amounts in US dollars unless otherwise indicated

Finding the right bump



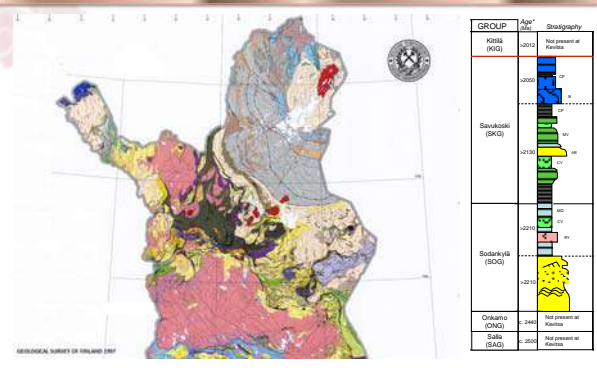
Outline:

- > Central Lapland Greenstone Belt (CLGB)
- > Magmatic Massive Sulphide Ni-Cu-PGE
- > Automated picking of magnetic anomalies
- > Further analysis of the results
 - > From PICKS to TARGETS
- >Lessons Learned and Next Step

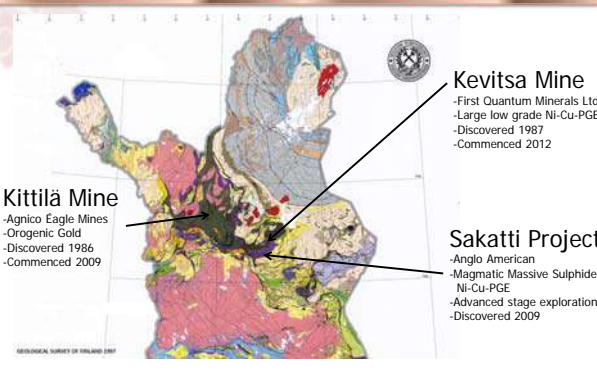
Central Lapland Greenstone Belt (CLGB)



Geology of CLGB



Main Deposits and Exploration History



Exploration conditions



- > 99% of the bedrock is covered with glacial till
 - > Due to transported cover geochemical samples have to be taken near bedrock surface by drilling (Base Of Till sampling)
 - > Large areas are covered by wet bogs limiting access



Exploration conditions



- > Winter provides excellent conditions for exploration and ground surveys
- > Although it tends to get chilly (-38C in pic)



Properties of Magmatic Massive Ni-Cu-PGE

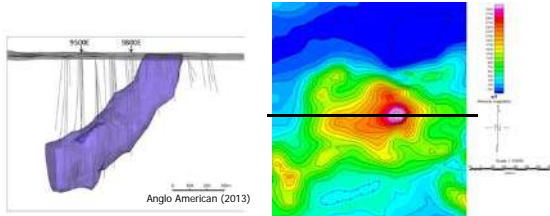


- > Very dense, extremely conductive and in most cases hosted in magnetically susceptible rocks -NICE GEOPHYSICAL TARGET
- > The application of ground and borehole geophysical methods to detect massive sulphide Ni-Cu-PGE is fairly straight forward
 - > Gravity surveys can be run effectively using country wide fixed DGPS reference network
 - > Moving loop EM with SQUID magnetometer is very effective and using snowmobiles allows good production
 - > The ground conditions allow most of the holes to stay open for borehole EM just with OVB casing (<20m generally)

Geometry of massive Ni-Cu-PGE deposit



- > Hosted in pipe-like intrusive ultramafic bodies (S. Beresford)
- > Host ultramafic rocks generally have good magnetic susceptibility (-0.03SI)



Exploration opportunity and challenge



- > Geophysical ground surveys capable of detecting even fairly small ore bodies can be run efficiently
- > But we will run out of time and money running ground surveys on top of every mag BUMP
- > We need to find ways to prioritise the anomalies and the intrusions

- > FINDING A NEEDLE IS EASY
 - > BUT FIRST NEED TO FIND A HAYSTACK

Available data



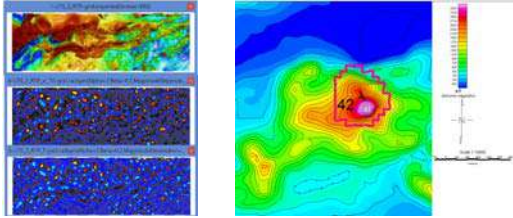
- > Available geophysical datasets in Finland
 - > Countrywide 200m line spaced low altitude airborne survey
 - > Magnetism
 - > Radiometrics
 - > FEM re/lm at 3kHz (partly 14kHz also available)
 - > Country wide petrophysical dataset (130000 samples)
 - > Density
 - > Magnetic Susceptibility and Remanence
 - > Resistivity and IP
 - > Regional ground gravity with 1-6 points/km²

Chonolith Hunt

Fathom Geophysics (D.Core, A.Buckingham)



- > A processing workflow to detect typical chonolith signature based on the response of synthetic magnetic body
- > Processing works regardless if remanence present



Amanda Buckingham (2013)
Magnetic Modeling and Filtering of Chonoliths

Results of "Chonolith picking"

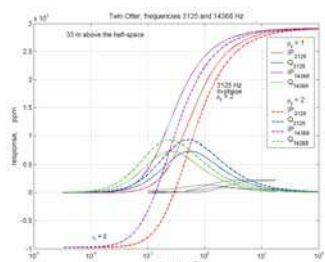


- > The processing of Eastern portion of CLGB produced 212 possible chonolith picks in 7436km²
- > Results of the processing include predicted top of the chonolith and also estimated dip and strike
- > Top of the chonolith polygons provide good dataset to place geochemical sampling
- > The dataset allows the detected magnetic anomalies to be prioritized in further processing and analysis

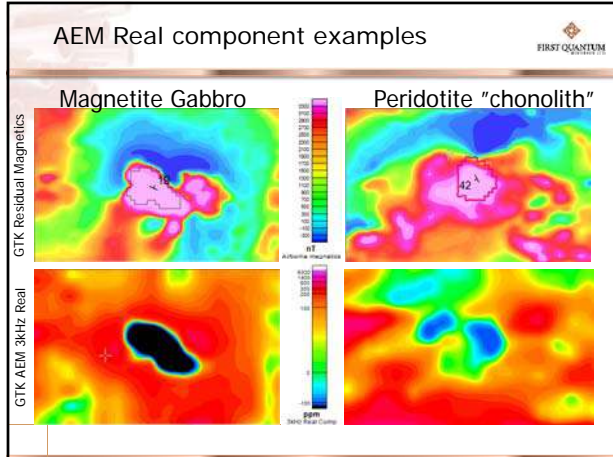
AEM Real component response

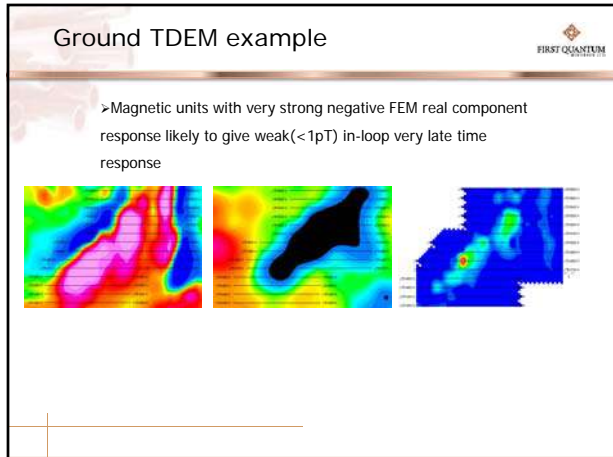


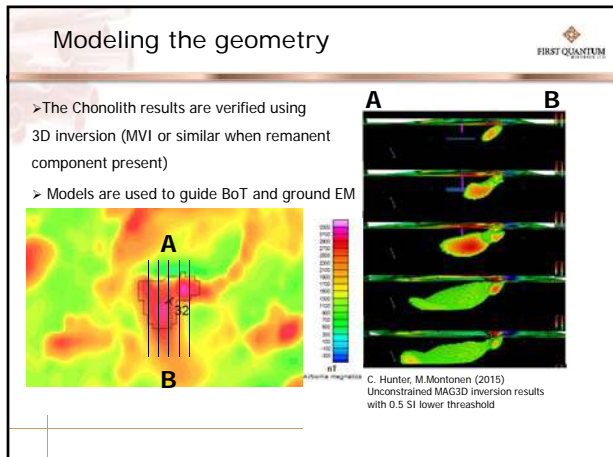
- > GTK AEM Real component is sensitive to magnetic susceptibility



Suppala, M. Okuma, H. Hongo (2009).
GTK AIRBORNE EM SYSTEM: CHARACTERISTICS AND INTERPRETATION GUIDELINES







Remanent magnetization



- > Remanent magnetization is present in most intrusions and must be taken to account in modeling
- > Understanding the remanent magnetization could provide very valuable tools in differentiating between magnetic suites
- > Work is being done as more samples come available
 - > Core samples are needed to capture remanent direction
 - > GTK samples can be used for good base dataset

Learned lessons and next step

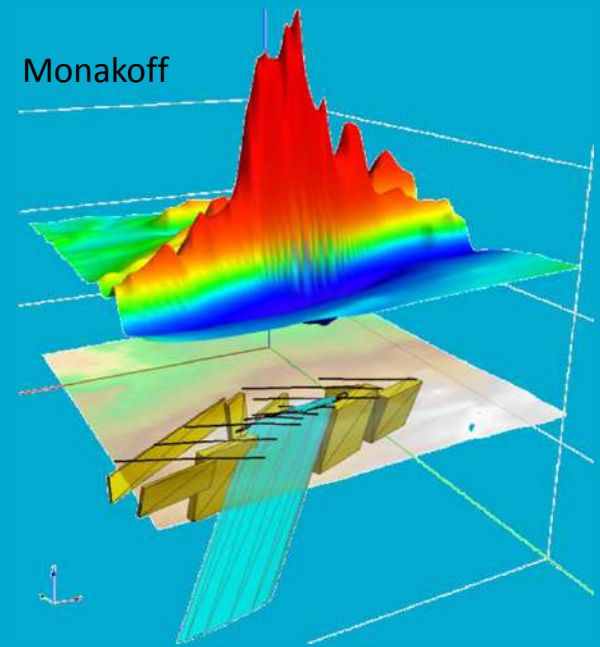
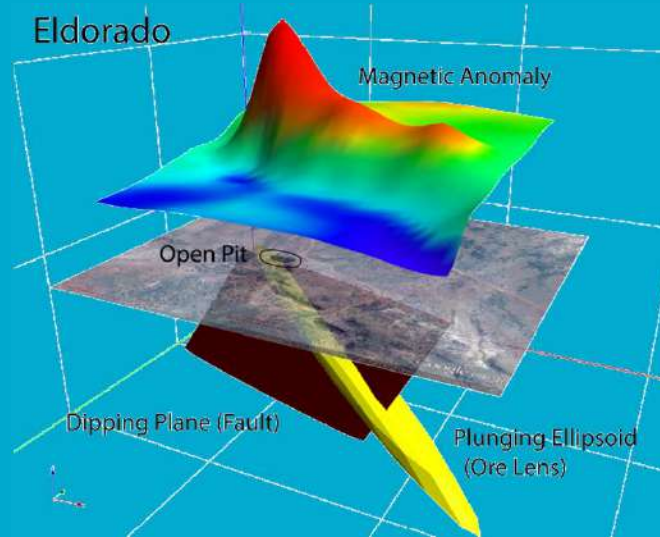
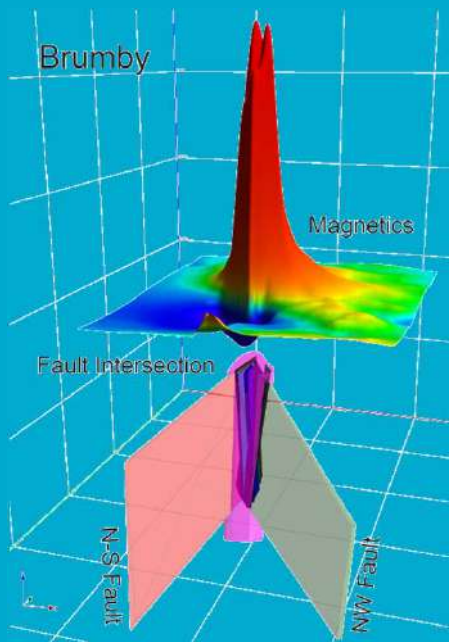


LEARNED LESSONS

- > Magnetic anomalies are much more than just bumps
- > Automated picking is very useful to create priority dataset for further analysis
- > Understanding the geometry and associating multiple geophysical parameters is very useful

NEXT

- > Better understanding of magnetization (remanence)
- > Modelling of the deeper sources and associating them to near surface anomalies



Thinking outside the Bullseye:

Petrophysical insights into targeting ore systems.

J.R. Austin | Research Scientist, CSIRO Mineral Resources Flagship

D.A. Clark | Principal Research Scientist, CSIRO Manufacturing & Mineral Resources Flagships

19th February 2015

Thinking outside the Bullseye:
Petrophysical insights into targeting ore systems.

J.R. Austin | Research Scientist, CSIRO Mineral Resources Flagship
 D.A. Clark | Principal Research Scientist, CSIRO Manufacturing & Mineral Resources Flagships
 19th February 2015

CSIRO MINERAL RESOURCES FLAGSHIP
 www.csiro.au

“We will increasingly be utilizing geophysical techniques”.

- **Therefore we need:**
 - **Better geophysical techniques and technologies;**
 - **Better understanding of the geophysical properties of geologic materials (both ore and waste);**
 - **Integrated geological/geophysical models of ore deposits.**

- Murray Hitzman, SEG Mining Lunch, October 2014

2 | Thinking outside the Bullseye | J.R. Austin & D.A. Clark

Magnetics

2 | Thinking outside the Bullseye | J.R. Austin & D.A. Clark

Outline

1. How do we use Magnetism and why it could be better
2. Magnetic Minerals and relationships to mineralisation
3. Structural Controls, Petrophysical zonation and Redox
4. Porphyry Copper Deposits – Examples of Predictive Magnetic Exploration Models
5. Remanence, susceptibility and somewhere in between

4 | Thinking outside the Bullseye | J.R. Austin & D.A. Clark

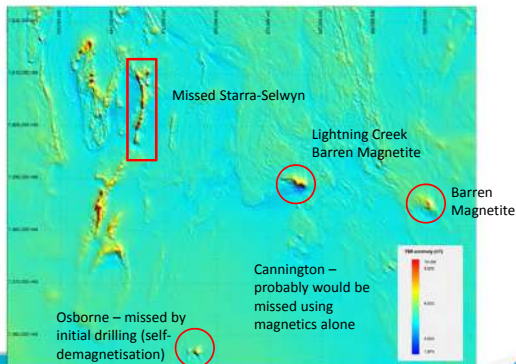


How do we use Magnetism & Why it could be better

5 | Thinking outside the Bullseye | J.R. Austin & D.A. Clark



How magnetism is often used



6 | Thinking outside the Bullseye | J.R. Austin & D.A. Clark



How do we usually interpret magnetics?

Gravity Field = X

Body with density contrast = Y

Magnetic Field = X

Body with MagSus = Y

- Gravity Anomaly $\propto Y$
- Invert the anomaly **assuming**
 - Uniform Density (e.g., ModelVision) OR
 - Smooth Variation Density (Voxel Inversion)
 - Uniform Gravitational Field

- Magnetic Anomaly $\propto X \times Y$
- Invert the anomaly **assuming**
 - Uniform MagSus (e.g., ModelVision) OR
 - Smooth Variation MagSus (Voxel Inversion)
 - Uniform Magnetic Field

X

7 | Thinking outside the Bullseye | J.R. Austin & D.A. Clark

Magnetisation: A vector, not a simple scalar property

Magnetic Field = X

Body with MagSus = Y

- Remanence
- Total Magnetisation
- Anisotropy (from defm)
- Self Demagnetisation Effect

- Assumption that **ALL** magnetisation is induced?
 - In some cases a decent estimation.
 - E.g., Mt-IOCGs
 - **But** the assumption **always** false.
- So in reality the way we interpret magnetics is:
 - Convenient
 - **BUT**, based on poor assumptions
- We can do much better

8 | Thinking outside the Bullseye | J.R. Austin & D.A. Clark

Homogeneity and boundary conditions

Our approach is often based on one of two end-member assumptions

1. Petrophysical properties have smooth transitions (no sharp edges)
2. Petrophysical properties have only sharp edges (no smooth transitions)

<http://www.pitneybowes.com/pbencom/products/geophysics/>

9 | Thinking outside the Bullseye | J.R. Austin & D.A. Clark

Magnetic Minerals & Relationships between magnetisation and mineralisation

10 | Thinking outside the Bullseye | J.R. Austin & D.A. Clark



Magnetic MINERALOGY

- Ore deposits are geologically, geochemically and geophysically complex, both spatially and temporally.
- They contain multiple magnetic minerals,
 - deposited at different times,
 - overprinting each other in complex ways.
- Physical factors that affect how a magnetic grain will behave are:
 - mineralogy, chemistry, crystal structure, and grainsize
- These influence:
 - intensity of its remanent magnetisation
 - and magnetic susceptibility,
 - how easily it can be remagnetised (its coercivity)
 - and at what temperatures it may be reset (Blocking Temperature, Curie Point).

11 | Thinking outside the Bullseye | J.R. Austin & D.A. Clark

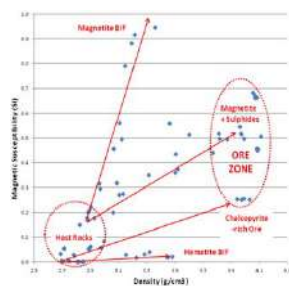


Magnetic Minerals

- In any given deposit there can be:
 - Multiple magnetic minerals
 - Large variations in % of various magnetic mineralogy
- Density, susceptibility and remanence are all highly heterogeneous

Mineral	Formula	Mag Sus (SI)	Q	Curie point
Magnetite (MD)	$Fe^{2+}Fe^{3+}O_4$	3.8-10.0	0.05-0.5	580°C
Maghemite	Fe_2O_3	variable	0.05-0.5	545-675°C
Ilmenite	Fe_2TiO_5	0.03 - 3.5	?	50-300°C
Pyrrhotite (m-cln)	Fe_7S_8	variable	1-700	320°C
Hematite	$Fe^{3+}O_3$	0.0005 - 0.01	30-1000	685°C

Density vs MagSus Monakoff (IOCG)



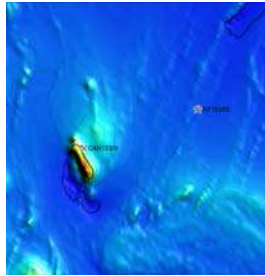
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- Data from Monakoff (Austin et al., 2013)



Effects of mineral microstructure: Pyrrhotite

- There are two types of Pyrrhotite.
- Monoclinic & hexagonal
- Magnetic & non-Magnetic
- Canteen vs Artemis
- Pyrrhotite can have extreme remanence.
 - J up to 1000 A/m
 - Q up to 700
- Q is Commonly 20-30

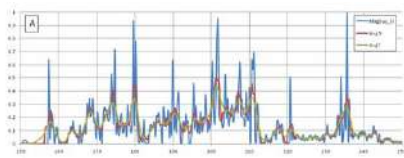


13 | Thinking outside the Bullseye | J.R. Austin & D.A. Clark

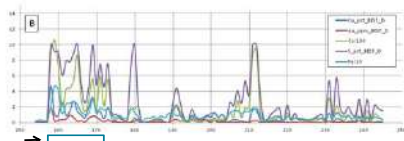


Magnetisation ≠ Mineralisation

A. 25 cm sampled MagSus



A. 1m composite Assay for Cu, Au, Co, S, Fe



Area of high Min/low MagSus is a Massive Pyrrhotite Zone →

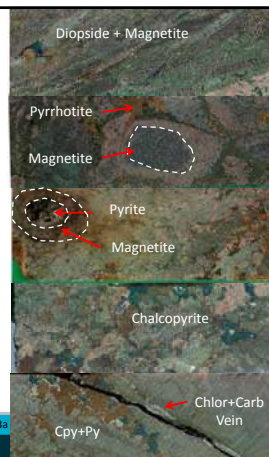
NB: Rolling Average used to minimize nugget effect

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Magnetite Constructive vs Destructive Alteration (From a Mt-rich IOCG)

- Stage 1 - Albitisation
- Stage 2A - Infilling with Magnetite, Albite, & Quartz
- Stage 2B - Main brecciation Event
 - diopside, magnetite, titanite & amphibole
- Stage 2C - Albite
- Stage 3A - Magnetite-Quartz veins
- Stage 3B - Magnetite-Pyrite
- Stage 4A - Amphibole-Biotite-Epidote
- Stage 4B - Chalcopyrite, chlorite, calcite
 - ± pyrite, pyrrhotite, K-feldspar
- Stage 5 - Calcite, chlorite + pyrite veins
- Stage 6 - Supergene



Overprinting Relationships based on Foster, 1993; Austin et al., 2013a

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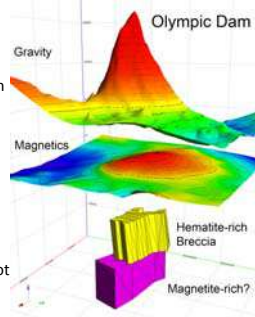
Structural Controls, Redox & Petrophysical zonation

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Hematite Dominated Breccias

- Can have huge gravity anomalies (20 mGal)
- Often have subtle magnetic anomalies
- They can be modelled as zones of brecciation sitting at the intersection of faults:
 - either simple pipe geometries (e.g., Oak Dam)
 - more complex architectures (e.g., Olympic Dam):
- The magnetic and gravity anomalies are:
 - broadly "coincident" at surface,
 - Bodies may be at different depths, e.g., Olympic Dam
- Most IOCGs outside of South Australia are not hematite dominated.



Understanding IOCG magnetic targets from the inside out



IOCG Gravity and Magnetic Anomalies – not "coincident", but superposed (or juxtaposed)

- The Olympic Dam deposit is inferred to have formed at very shallow depths and is dominated by sericite-hematite ± quartz ± chlorite ± siderite ± fluorite ± barite alteration.
- Magnetite has been totally replaced by hematite in the central and upper portions of the deposit, but is present in deeper and peripheral zones.
- IOCG systems tend to be zoned vertically from magnetite-dominant at depth to hematite-dominant at upper levels. Magnetite is also abundant peripheral to the ore zones.

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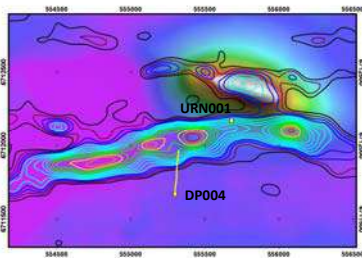


IOCG Gravity and Magnetic Anomalies – not “coincident”, but superposed (or juxtaposed)

- Therefore the magnetic and gravity signatures of complete, intact IOCG deposits should generally reflect *superposed* gravity and magnetic anomalies. Positive gravity anomalies arise from both magnetite-rich and hematite-rich zones, whereas the deeper, peripheral, or adjacent magnetic sources correspond to the magnetite-rich zones.
- The inverted centre of magnetisation lies beneath the centre of mass.
- Post-mineralisation faulting or tilting may modify the signature and give rise to *juxtaposed* gravity and magnetic anomalies (e.g. Prominent Hill).



Prominent Hill – juxtaposed gravity and magnetic anomalies



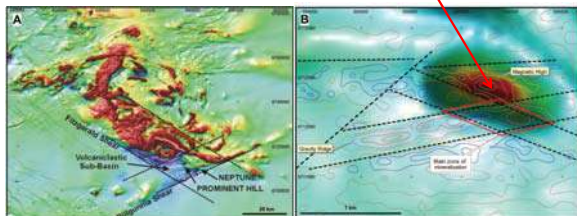
Hart & Freeman, 2003. Geophysical responses of the Prominent Hill Fe-Cu-Au-U Deposit. ASEG Extended Abstracts

Positive Second Horizontal Derivative Contours on RTP Ground Magnetic Data. Location of URN001 and DP004 shown.



Prominent Hill – juxtaposed gravity and magnetic anomalies

Up-faulted original deep mt-dominated alteration system?



Belperio, Flint & Freeman, 2007. Prominent Hill: A Hematite-Dominated, Iron Oxide Copper-Gold System. *Economic Geology*, **102**, pp. 1499–1510.



Ironstone Hosted deposits

- Cause narrow elongate anomalies
- Modelled as a sub-vertical sheets or elongate elliptical prisms.
- High density (4 g/cm³ at Monakoff)
 - too narrow to be mapped with gravity data, because resolution is inadequate.
- Magnetite and Fe-Sulphides can be:
 - syngenetic and/or
 - precipitated by replacement of Fe-oxide.
- laterally zoned:
 - magnetite ± sulphides in the core
 - hematite distal

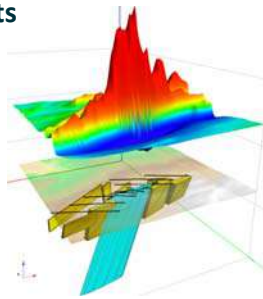
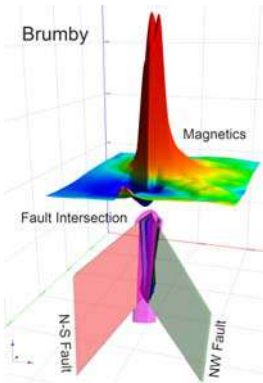


Figure 4: Magnetic Model of the Monakoff ICOG, showing lateral zonation of magnetite. - from Austin et al, 2013b.



Magnetite Breccia Pipes

- Cause a bullseye magnetic anomaly,
- Coincident gravity anomalies.
- They can be modelled as:
 - Pipes at the intersection of faults
 - Within fault jogs (e.g., Ernest Henry).
- Magnetite and sulphides may be concentrically zoned.
- Sulphides are both
 - syngenetic with magnetite precipitation,
 - overprint oxides via metasomatism



Candelaria-type deposits

- Cause narrow repetitive anomalies along faults zone
- Modelled as sub-horizontal sheets
 - Highly magnetic
 - Prone to self-demagnetisation
- Magnetite and Fe-Sulphides are:
 - syngenetic and/or
 - precipitated by replacement of Fe-oxide.
 - Sulphides are localised by relatively late faults that cut the mantos

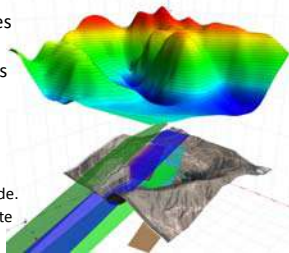
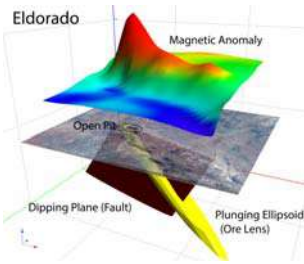


Figure 4: Magnetic Model of the Candelaria ICOG, showing sub-horizontal magnetite mantos - from Austin et al, 2014b.



Modelling Tennant Creek type IOCGs

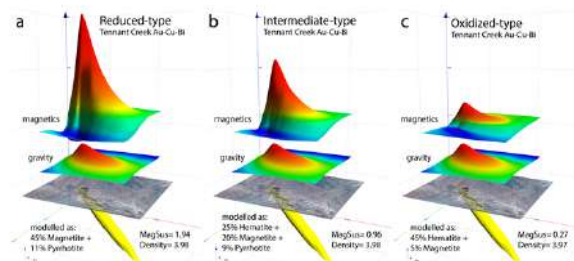
- Their anomalies can be modelled as ellipsoidal (pod-like) bodies
- The Eldorado deposit can be modelled as:
 - a sheet-like body or
 - an ESE plunging ellipsoid
- However, in reality the deposit architecture is most likely intermediate, i.e., the anomaly is:
 - partly due to magnetite in a Fe-rich host horizon/ shear zone
 - partly due to magnetite in an ellipsoidal shape, plunging to ESE.



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Pyrrhotite, Magnetite, Hematite: Reduced to Oxidised systems at a glance



A simplified magnetic model of the Eldorado deposit, Tennant Creek Area, modified to represent: (A) reduced, (B) intermediate and (C) oxidised mineralogies

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- Data from Monakoff/Austin et al., 2014



Petrophysical Zonation

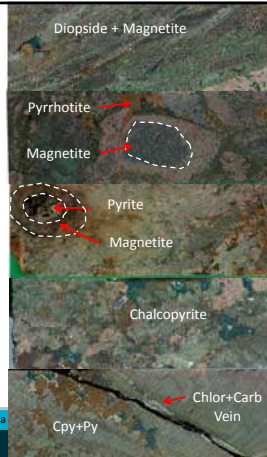
- Interpretation tools usually make the assumption that bodies:
 - Have finite extent and constant properties
 - Or Have smooth/gradual variations
- In reality most types of ore deposits will be closer to one or the other
- But neither are really representative of real geological bodies
- Defining petrophysical zonation is:
 - Geologically simple, **but**
 - petrophysically very difficult
- MagSus vs remanence, e.g., Magnetisation is a vector not just a property
- Orders of magnitude variation
 - Nugget effect
- Magnetite con- vs de-structive alteration

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Magnetite Constructive vs Destructive Alteration

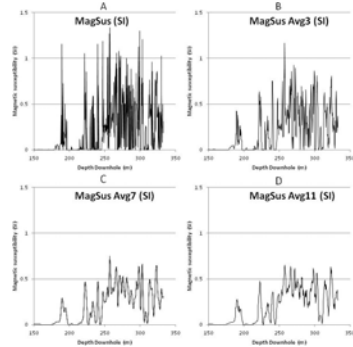
- Stage 1 - Albiteisation
- Stage 2A & Quartz - Infilling with Magnetite, Albite, & Quartz
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- Stage 5 - Calcite, chlorite + pyrite veins
- Stage 6 - Supergene



Overprinting Relationships based on Foster, 1993; Austin et al., 2013a
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Magnetic Nugget Effect

- Ore deposits are not homogeneous
- Why do we model them as such?



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- Data from Brumby (Austin et al., 2013)

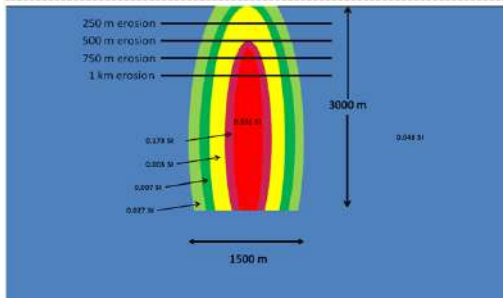


Porphyry Copper Deposits – Examples of Predictive Magnetic Exploration Models

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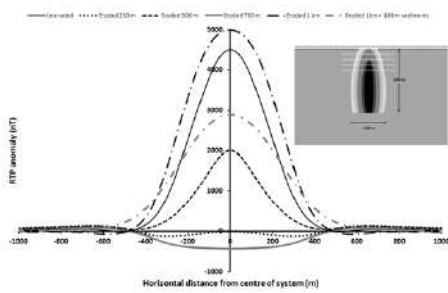
Gold-rich Porphyry Copper Model, Hosted by Mafic Igneous Rocks – type example: Alumbra



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Signature Depends on Erosion Level



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RTP signature of Bajo de la Alumbra

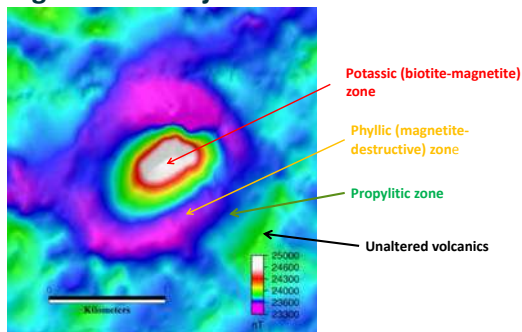
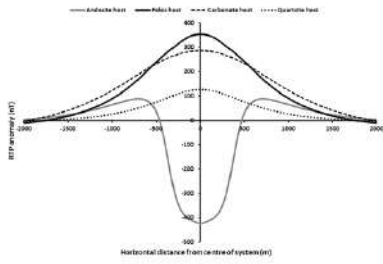


Image courtesy of Terry Hoschke

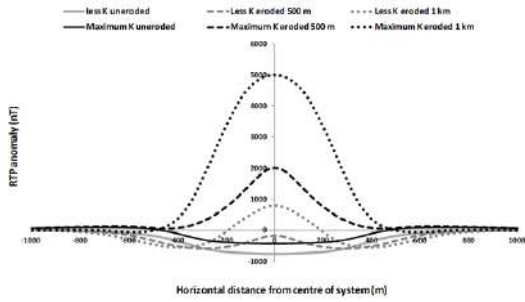
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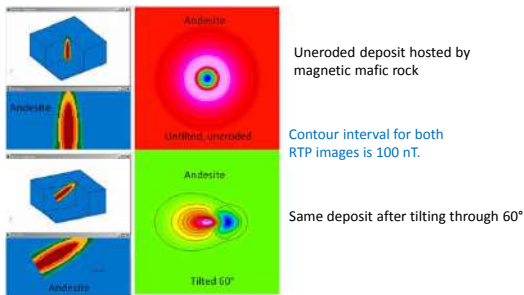
Signature Depends on Host Rock Type



Signature Depends on Magma Type and Tectonic Setting: controls development of potassic zone



Signature Depends on Post-emplacment Tectonic Movements – tilting or faulting



Predictive Magnetic Exploration Models for Porphyries: Some Conclusions

Magnetic signatures vary greatly depending on:

- Magma type and tectonic setting
- Host lithology
- Current level of exposure
- Depth of burial beneath younger cover
- Post-emplacement tilting and/or faulting
- Asymmetric zoning if emplaced along lithological contact

BUT

- These effects are reasonably predictable

SO

- These factors *must* be considered to search for appropriate signatures, and
- Searching for look-alikes of a known deposit is unlikely to be successful, if the local geological setting differs



Remanence, Susceptibility & Somewhere in between



Remanence and Susceptibility

- Rocks contain two magnetic components, induced and remanent magnetisation,
 - Induced magnetisation is equal to the product of the magnetic susceptibility and the inducing field.
 - Remanent magnetisation is a more-or-less permanent magnetisation present in the rock, i.e. it is not induced by the earth's field
- Natural Remanent Magnetisation (NRM) is often acquired during thermal or metasomatic events.
- As the rocks cool through the Curie point, or (re)crystallise below the Curie point, they acquire a remanence along the magnetic field direction of the earth at that time.
 - The orientation of remanent magnetisation can be stable for billions of years,
 - or it can be highly dynamic, acquiring new magnetisation over days to years.
- Its stability is primarily a function of grain size.



Stability of Remanence

Where grains are $>10\mu\text{m}$ there are scores of domains within the grain

- These are multidomain (MD) grains.
- Remanence in MD magnetite is "soft" and easily changed
 - by exposure to magnetic fields
 - due to movement of domain walls

In finer grained magnetite (e.g., $<0.1\mu\text{m}$)

- energy required to form magnetic domain walls is too great,
- so a single domain structure is retained
- Remanence in single domain magnetite is very stable.

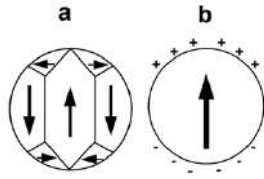
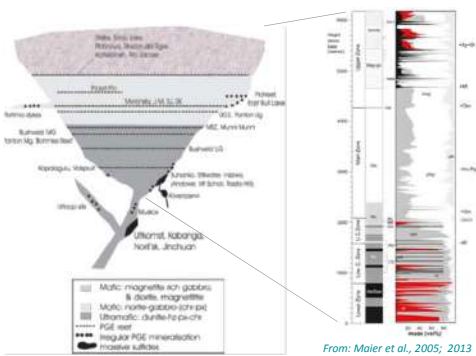


Figure 1: Shows the difference between Multi domain magnetism and Single domain magnetism. A. Grain of ferromagnetic material subdivided into domains (Multidomain) which reduces the magnetostatic energy of the grain. B. Uniformly magnetized (single-domain) grain where magnetisation is shown by the arrow, and surface charge by + / -. Grains that are intermediate are called pseudo single domain. (from: Butler, 1998).

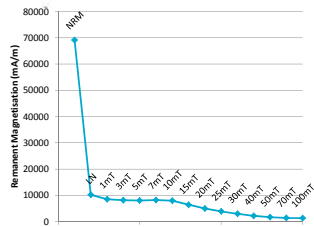
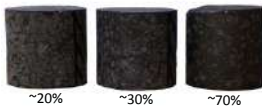
Layered Igneous Intrusive Complexes

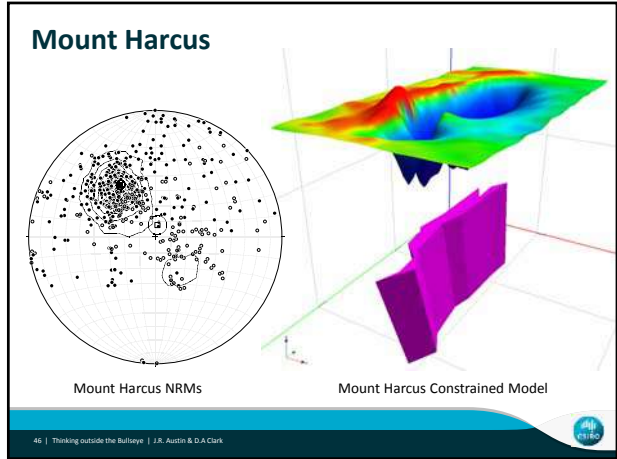


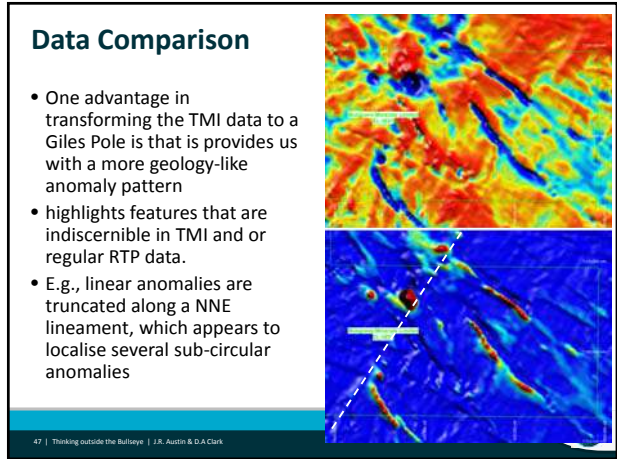
Multidomain Magnetite

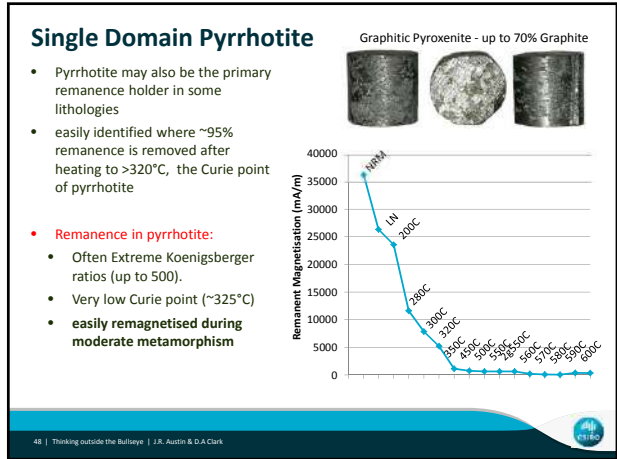
- Some lithologies, e.g., Kalka Intrusion cumulates have $>50\%$ magnetite
- Have very high magnetic susceptibilities (e.g., $>1\text{ SI}$).
- Remanence is very soft and held in multidomain magnetite
- 80% of remanence is lost after Liquid Nitrogen cleaning
- Remanence directions are **drilling-parallel**

Mt-rich Wehrlite- up to 70% Magnetite



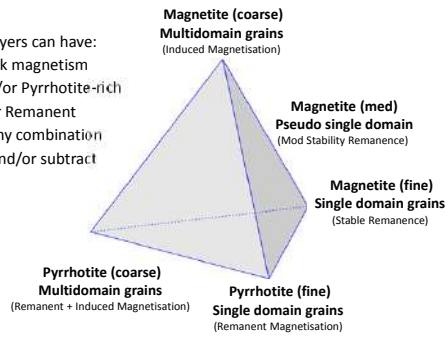






Layered Igneous Intrusive Complexes

- The different layers can have:
 - Strong or weak magnetism
 - Magnetite and/or Pyrrhotite-rich
 - Induced and/or Remanent
 - There can be any combination
 - They can add and/or subtract



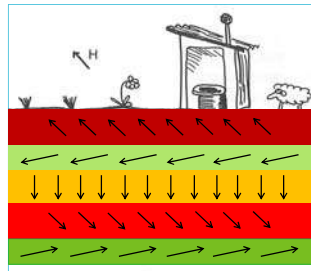
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Layered Igneous Intrusive Complexes

- Magnetisations can add or subtract depending on orientation and intensity

- MD Magnetite – in Earth's Field
- Po-rich pyroxenite - Carb overprint
- Ti-rich pyroxenite – Exsolved L. Prot
- Mt-rich layer – recrystallised Cenozoic
- Po-rich pyroxenite - Carb reversal

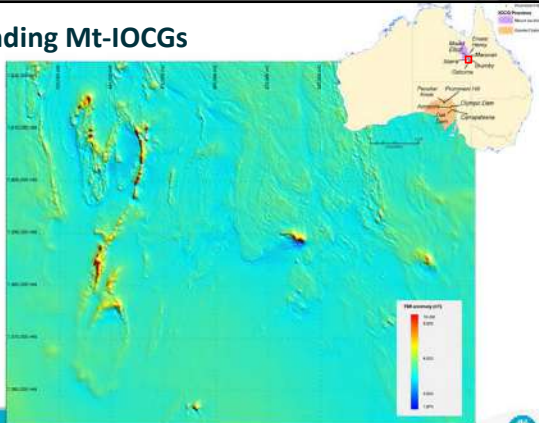


From: "Our Magnetic Earth" by Ronald T. Merrill

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Finding Mt-IOCGs



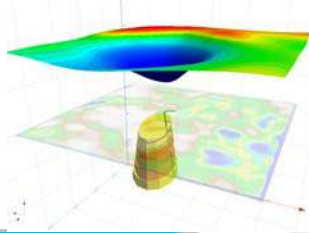
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Rover 3 (former IOCG target, near Tennant Creek)

- Drilled due to large negative magnetic anomaly
- Drilling found intermediate volcanics with low susceptibility.
- Anomaly source is remanent magnetisation within the volcanics

- Remanence is minimal in IOCGs
 - due to coarse MD magnetite.
- Negative magnetic anomalies = remanent magnetisation
- Remanence can't be measured with a MagSus meter.



Conclusions



Murray Hitzman Says we need:

- **Better geophysical techniques and technologies;**
 - Yes, BUT we are not currently using the techniques we have very well
 - We are investing in geophysics, BUT... Mostly in data.
 - We need to invest more in Geophysicists (i.e., Understanding the data)
 - Better training for Geophysicists (so we are not just inverting everything)
- **Better understanding of the geophysical properties of geologic materials**
 - This is an arduous task and hence, almost nobody is doing this in Australia (cf. CSIRO)
 - Extrapolating point data to volumes is also problematic, because magnetic properties are multi-directional vectors, are highly zoned and vary by orders of magnitude over cm scale.
- **Integrated geological/geophysical models of ore deposits.**
 - This is easy once we have the data
 - The hard part is trying to correlate petrophysics to the **geological logs** (which have usually been completed by 15+ different geos, and sometimes bear little resemblance to reality)





Finding the right bump under glacial till in the Central Lapland Greenstone Belt

Janne Kaukolinna

Contributions: Fathom Geophysics, Steve Beresford and FQM Finnex Personnel



FIRST QUANTUM
MINERALS LTD.



Finding the right bump under glacial till in the Central Lapland Greenstone Belt

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Cautionary Note Concerning Forward-Looking Statements



Some of the statements contained in the following material are forward looking statements and not statement of facts. Such statements are based on the current beliefs of management, as well as assumptions based on management information currently available. Forward-looking statements are subject to various risks, uncertainties and other factors that could cause actual results to differ materially from expected results. Readers must rely on their own evaluation of these uncertainties.

Note: all dollar amounts in US dollars unless otherwise indicated

Finding the right bump



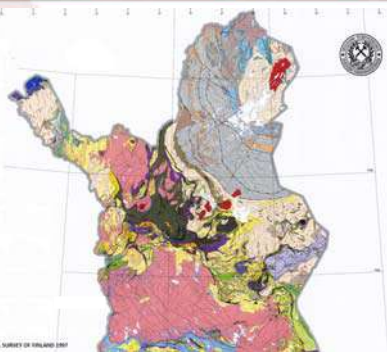
Outline:

- > Central Lapland Greenstone Belt (CLGB)
- > Magmatic Massive Sulphide Ni-Cu-PGE
- > Automated picking of magnetic anomalies
- > Further analysis of the results
 - > From PICKS to TARGETS
- >Lessons Learned and Next Step

Central Lapland Greenstone Belt (CLGB)

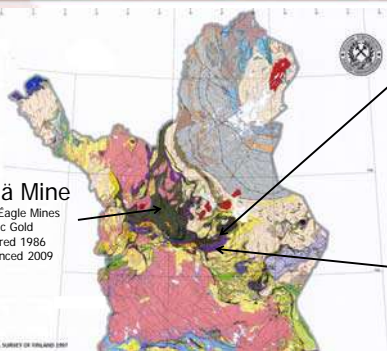


Geology of CLGB



GROUP	Age	Stratigraphy
Kittilä (KIG)	2013	Not present at location
Savakkola (SOG)	2010	OP
	2010	OP
Sodankylä (SOG)	2010	OP
	2010	OP
Oriskany (ONG)	2040	Not present at location
Saana (SAG)	2000	Not present at location

Main Deposits and Exploration History



Kittilä Mine

- Agnico Eagle Mines
- Orogenic Gold
- Discovered 1986
- Commenced 2009

Kevitsa Mine

- First Quantum Minerals Ltd
- Large low grade Ni-Cu-PGE
- Discovered 1987
- Commenced 2012

Sakatti Project

- Anglo American
- Magmatic Massive Sulphide Ni-Cu-PGE
- Advanced stage exploration
- Discovered 2009

Exploration conditions



- > 99% of the bedrock is covered with glacial till
 - > Due to transported cover geochemical samples have to be taken near bedrock surface by drilling (Base Of Till sampling)
 - > Large areas are covered by wet bogs limiting access



Exploration conditions



- > Winter provides excellent conditions for exploration and ground surveys
- > Although it tends to get chilly (-38C in pic)



Properties of Magmatic Massive Ni-Cu-PGE

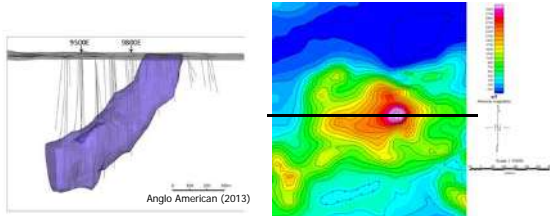


- > Very dense, extremely conductive and in most cases hosted in magnetically susceptible rocks -NICE GEOPHYSICAL TARGET
- > The application of ground and borehole geophysical methods to detect massive sulphide Ni-Cu-PGE is fairly straight forward
 - > Gravity surveys can be run effectively using country wide fixed DGPS reference network
 - > Moving loop EM with SQUID magnetometer is very effective and using snowmobiles allows good production
 - > The ground conditions allow most of the holes to stay open for borehole EM just with OVB casing (<20m generally)

Geometry of massive Ni-Cu-PGE deposit



- > Hosted in pipe-like intrusive ultramafic bodies (S. Beresford)
- > Host ultramafic rocks generally have good magnetic susceptibility (-0.03SI)



Exploration opportunity and challenge



- > Geophysical ground surveys capable of detecting even fairly small ore bodies can be run efficiently
- > But we will run out of time and money running ground surveys on top of every mag BUMP
- > We need to find ways to prioritise the anomalies and the intrusions

- > FINDING A NEEDLE IS EASY
 - > BUT FIRST NEED TO FIND A HAYSTACK

Available data



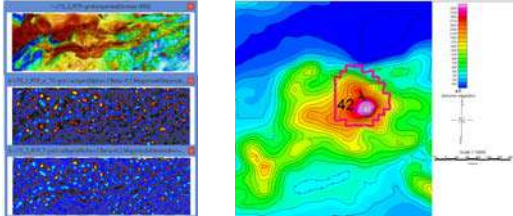
- > Available geophysical datasets in Finland
 - > Countrywide 200m line spaced low altitude airborne survey
 - > Magnetism
 - > Radiometrics
 - > FEM re/lm at 3kHz (partly 14kHz also available)
 - > Country wide petrophysical dataset (130000 samples)
 - > Density
 - > Magnetic Susceptibility and Remanence
 - > Resistivity and IP
 - > Regional ground gravity with 1-6 points/km²

Chonolith Hunt

Fathom Geophysics (D.Core, A.Buckingham)



- > A processing workflow to detect typical chonolith signature based on the response of synthetic magnetic body
- > Processing works regardless if remanence present



Amanda Buckingham (2013)
Magnetic Modeling and Filtering of Chonoliths

Results of "Chonolith picking"

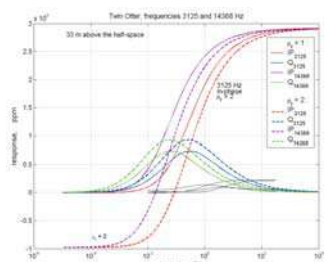


- > The processing of Eastern portion of CLGB produced 212 possible chonolith picks in 7436km²
- > Results of the processing include predicted top of the chonolith and also estimated dip and strike
- > Top of the chonolith polygons provide good dataset to place geochemical sampling
- > The dataset allows the detected magnetic anomalies to be prioritized in further processing and analysis

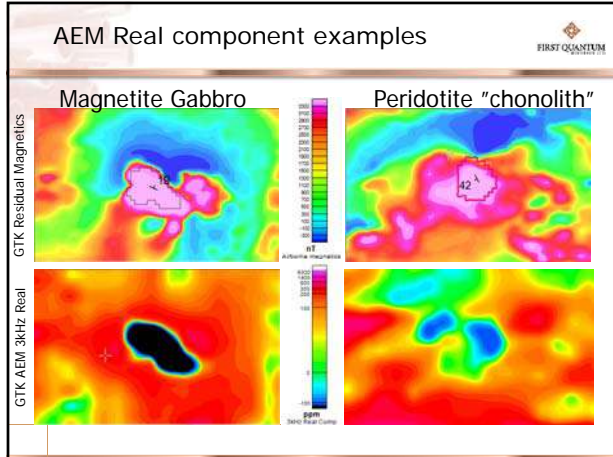
AEM Real component response

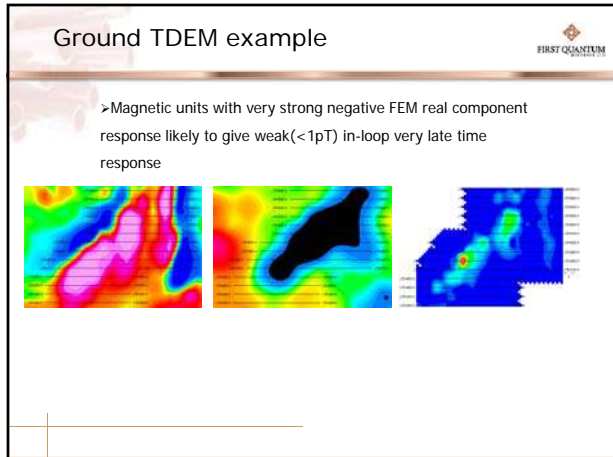


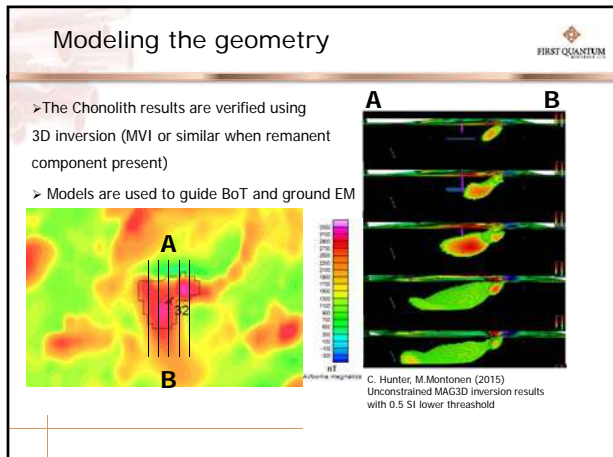
- > GTK AEM Real component is sensitive to magnetic susceptibility



Suppala, M. Okuma, H. Hongo (2005).
GTK AIRBORNE EM SYSTEM: CHARACTERISTICS AND INTERPRETATION GUIDELINES







Remanent magnetization



- > Remanent magnetization is present in most intrusions and must be taken to account in modeling
- > Understanding the remanent magnetization could provide very valuable tools in differentiating between magnetic suites
- > Work is being done as more samples come available
 - > Core samples are needed to capture remanent direction
 - > GTK samples can be used for good base dataset

Learned lessons and next step



LEARNED LESSONS

- > Magnetic anomalies are much more than just bumps
- > Automated picking is very useful to create priority dataset for further analysis
- > Understanding the geometry and associating multiple geophysical parameters is very useful

NEXT

- > Better understanding of magnetization (remanence)
- > Modelling of the deeper sources and associating them to near surface anomalies



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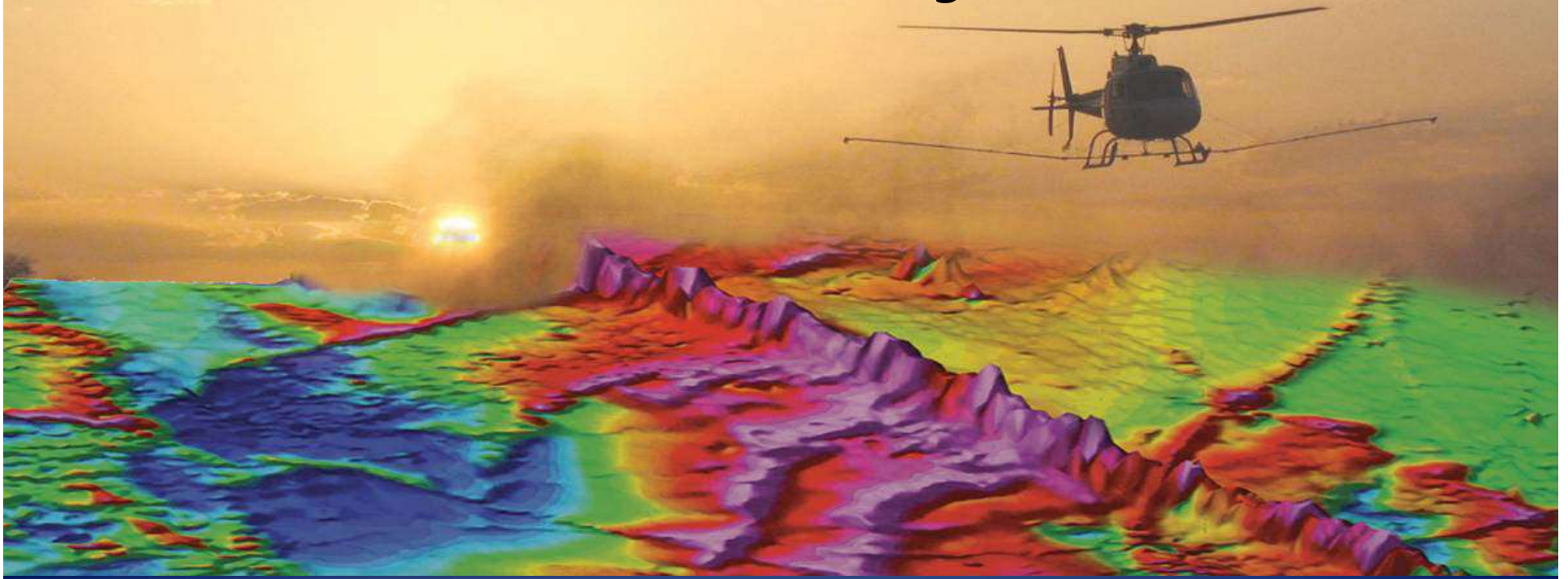
Geophysics and Geology together for Discovery

24th International Geophysical Conference and Exhibition
15-16 February 2015 Perth, Western Australia

Following the mineral system and tracking it under cover

Gavin Selfe

GRS Consulting



ASEG-PESA 2015
Geophysics - A Challenge Learning For Students
The Australian Society of Exploration Geophysicists

Following the mineral system and tracking it under cover

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Statement

- *It is no longer enough to use geophysics purely for bump detection. We need to use it more intelligently and holistically.*
- *The new objective is to be able to map geology, structure and alteration as accurately as possible in order to be able to make informed decisions about the mineral system.*

ASEG-PESA 2015
Geophysics - A Challenge Learning For Students
The Australian Society of Exploration Geophysicists

This talk covers the use of the following techniques:

- *Airborne EM, gravity and magnetics*
- *Audio magneto-tellurics*
- *Ground gravity*

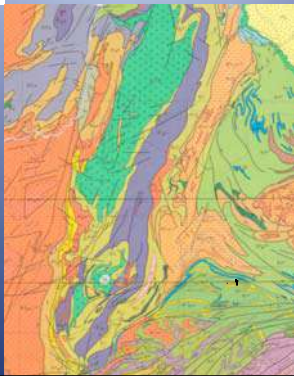
ASEG-PESA 2015
Geophysics in a Changing World for 2015

Rovuma Project Mozambique

- *I would like to acknowledge Rovuma Resources and African Rainbow Minerals for allowing me to publish some images*
- *They have requested that the precise location of the project remain unspecified*

ASEG-PESA 2015
Geophysics in a Changing World for 2015

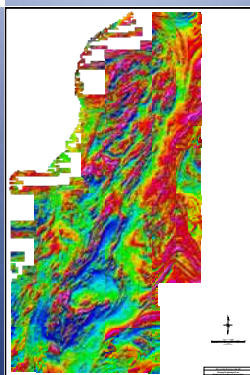
Geology of the Rovuma project



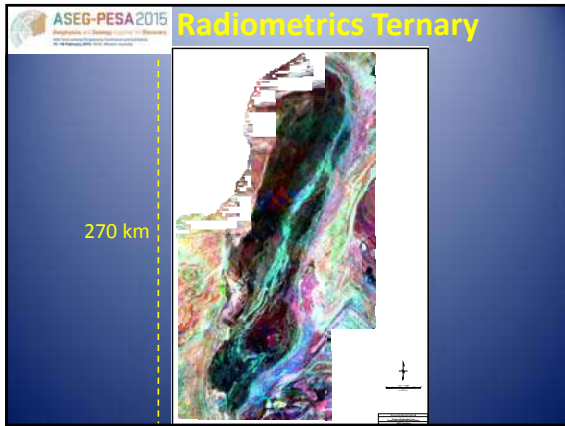
270 km

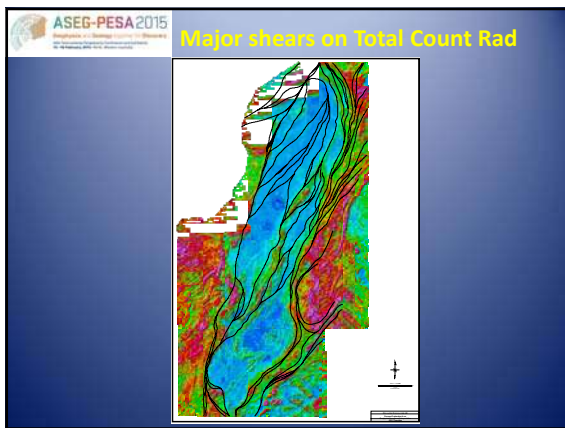
ASEG-PESA 2015
Geophysics in a Changing World for 2015

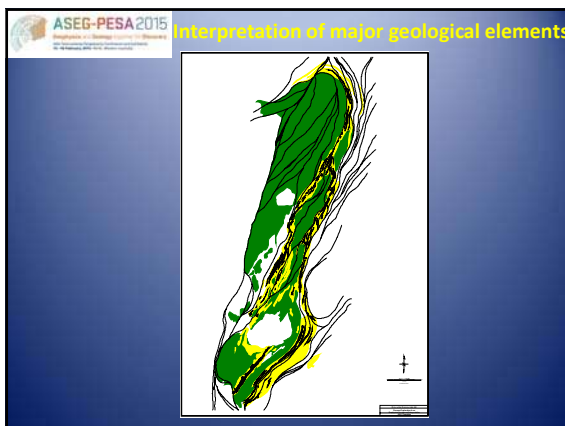
Aeromagnetics over Rovuma project

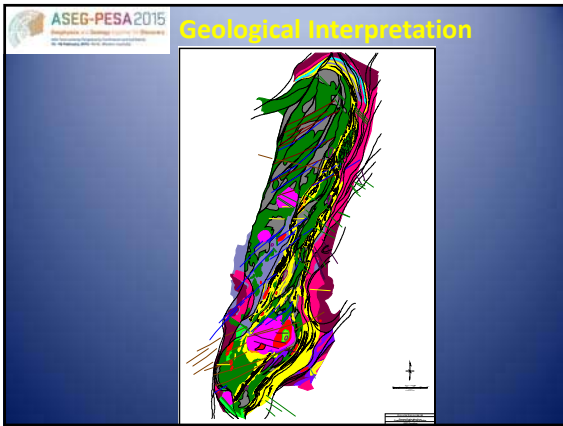


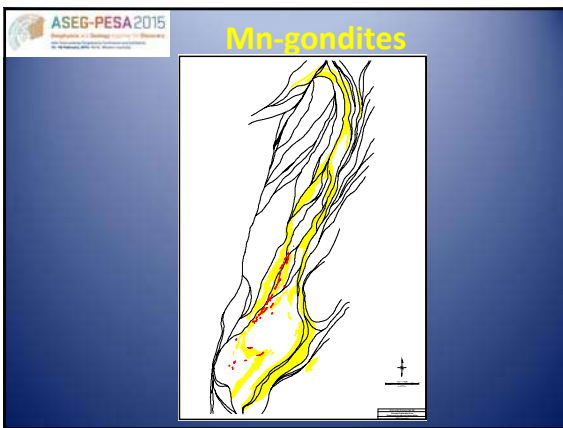
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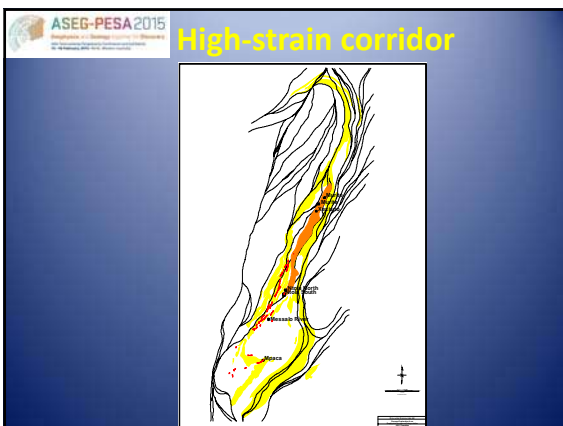


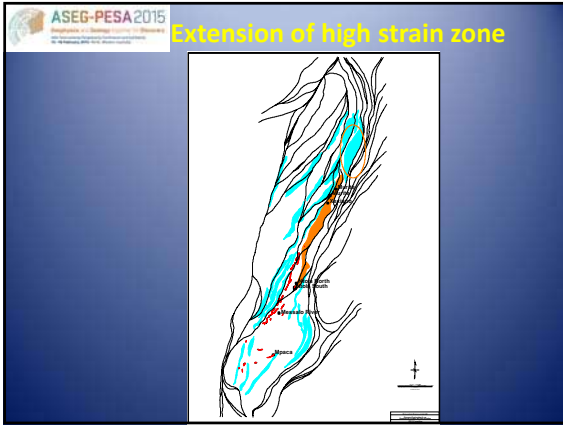


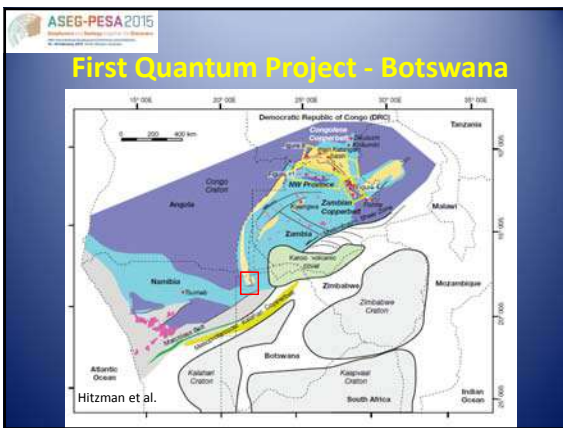


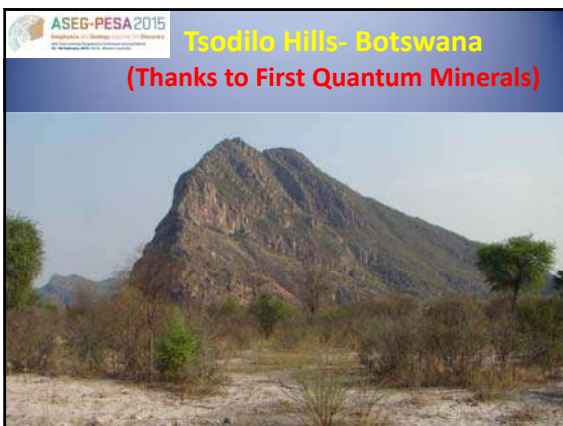


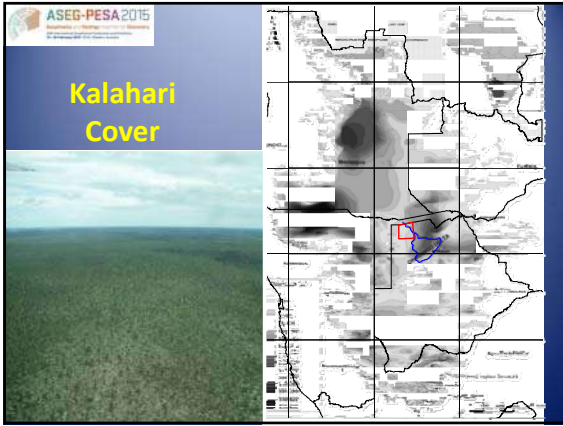


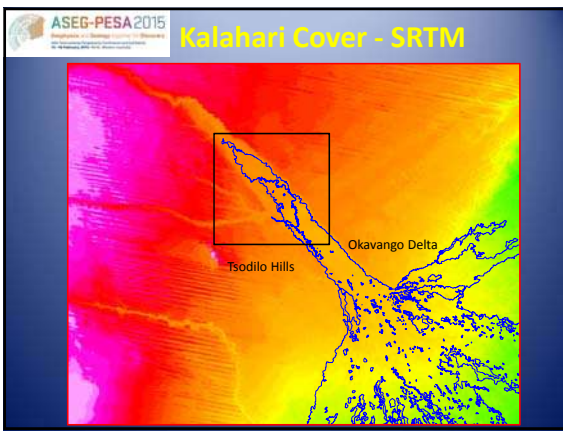


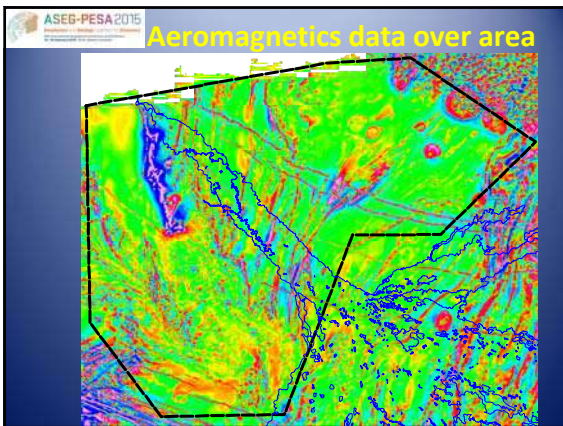


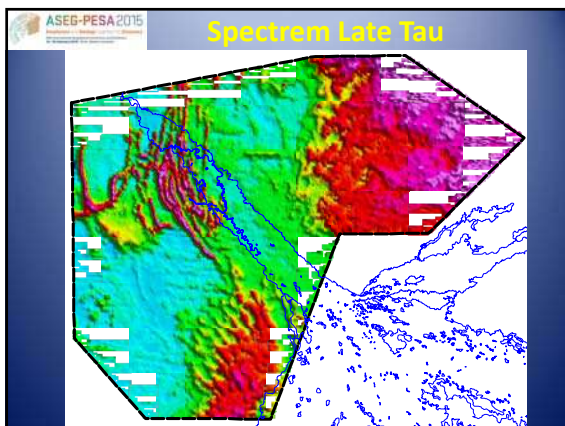






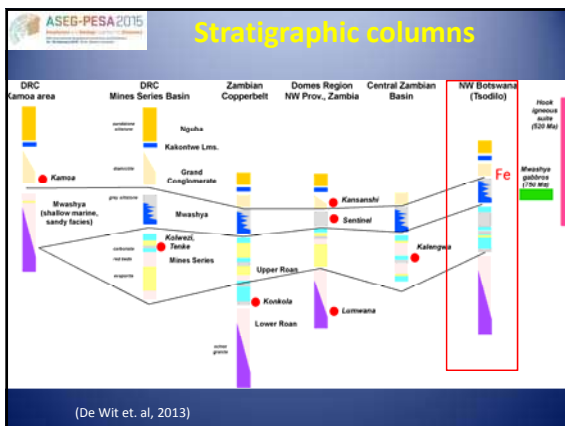






ASEG-PESA 2015
Prospecting Philosophy in the FQM-Tsodilo JV

- *The most conductive units in the Spectrem EM survey are the graphitic shales, which lie beneath the sand*
- *These are the target hosts for copper mineralisation*
- *The shale unit closest to basement is the most likely to host copper mineralisation*




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Basement stratigraphy

Stratigraphy: Basement Rocks

- Mainly granitic gneisses and quartz-biotite-muscovite-feldspar schists
- This rock is 2.6 Ga (2 548±65 Ma Gaisford 2010 2 641±82 Ma Witbooi 2011)

(De Wit et. al, 2013)



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Mwashya shales

Stratigraphy: Mwashya Phyllites & Schists

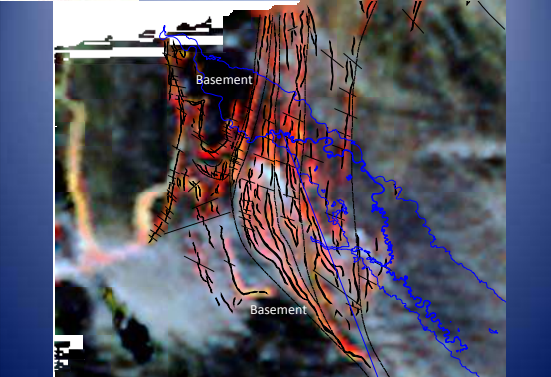
- Originally shales and siltstones.
- Commonly garnetiferous (especially upper Mwashya), graphitic, and contain sulfides (py, po, cpy).
- Becomes more carbonate rich down section.

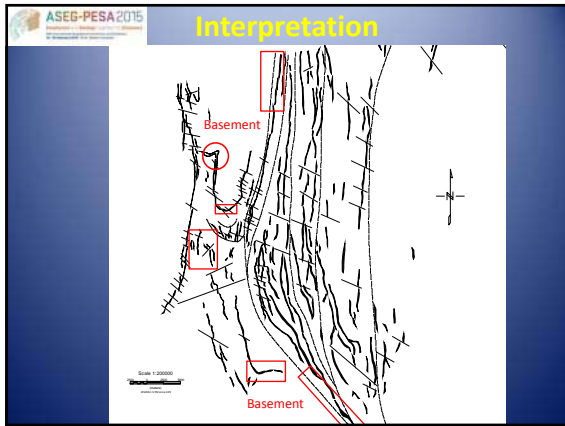


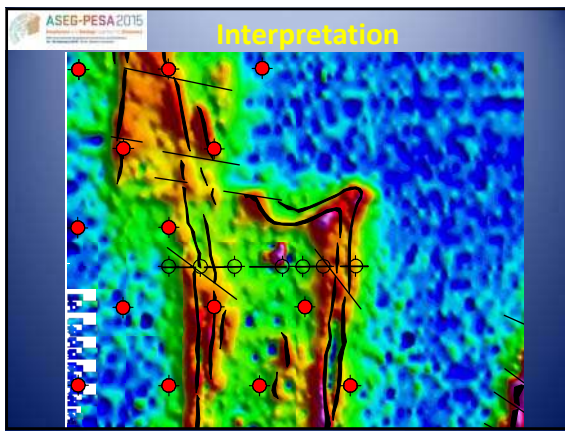
(De Wit et. al, 2013)

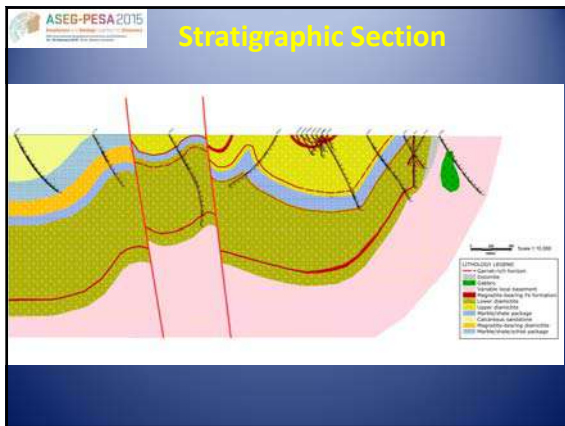
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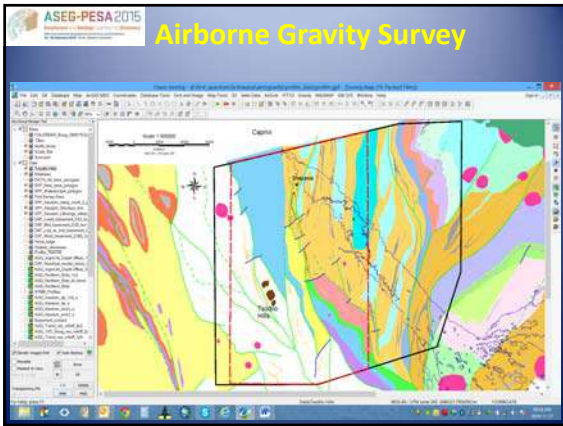
Spectrem Tau Ternary image

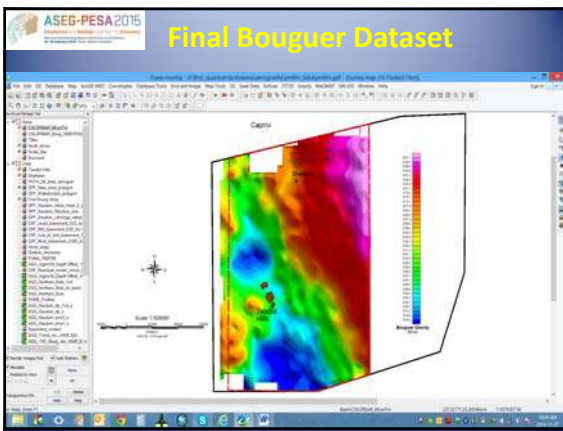


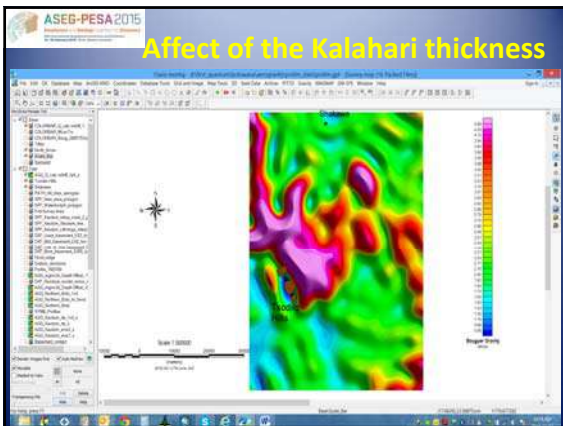


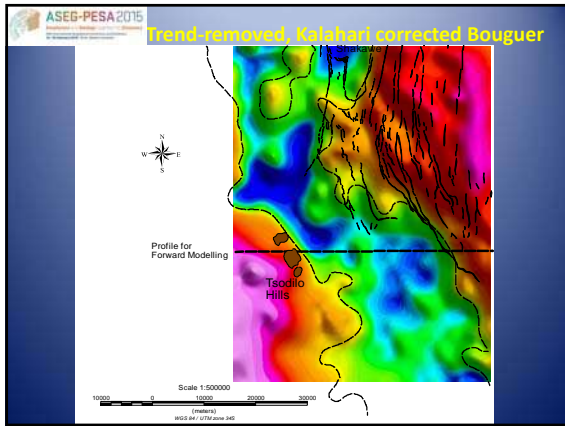


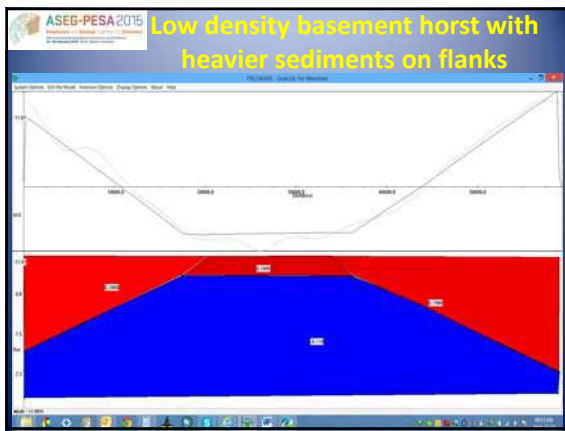


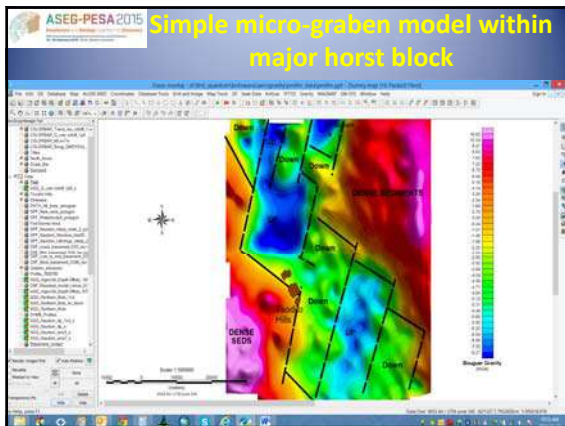


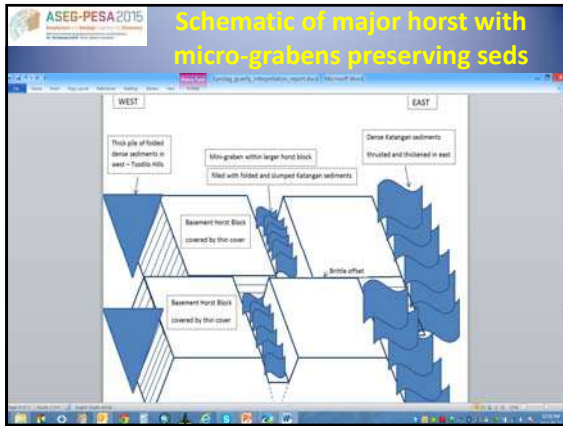


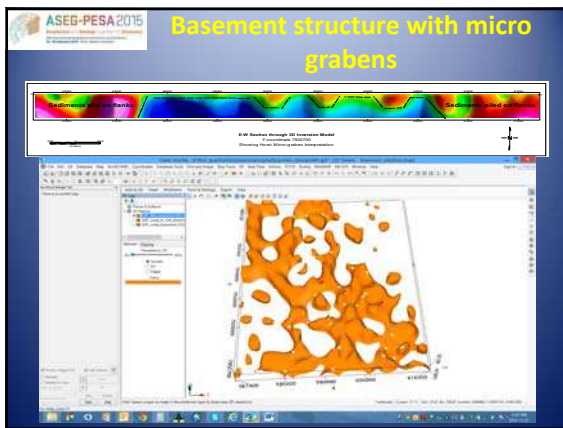


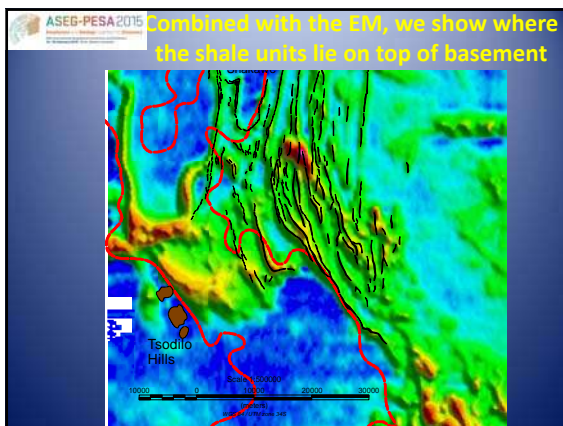


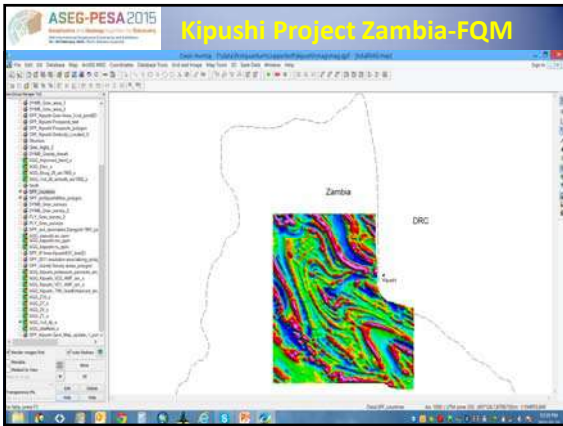


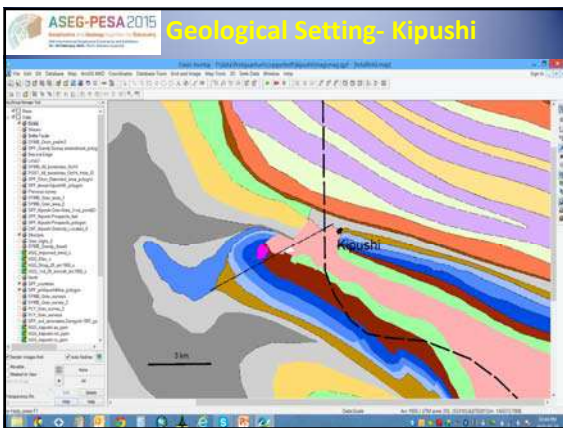


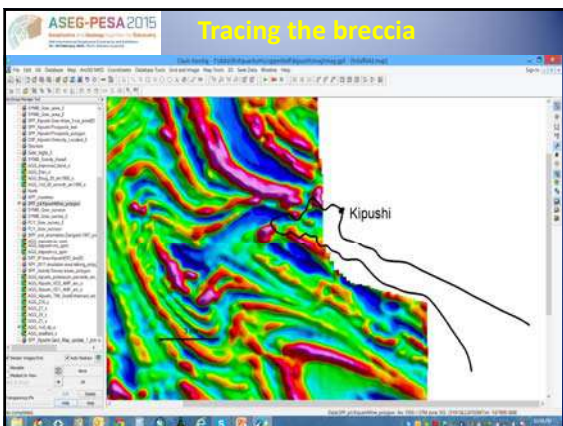


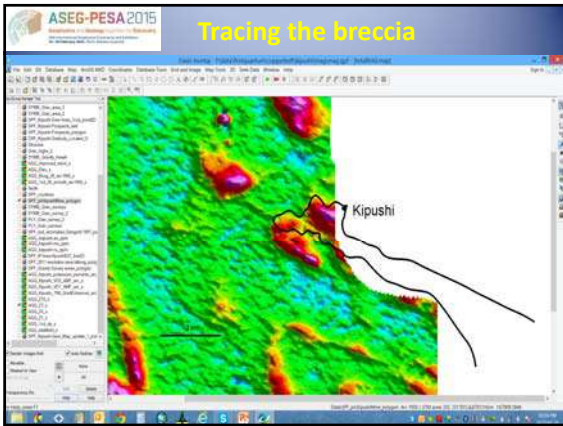


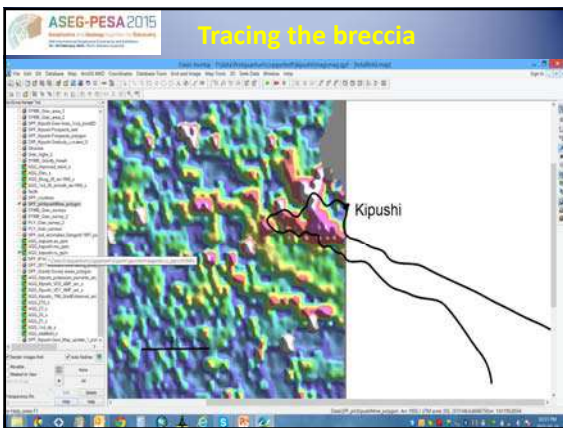


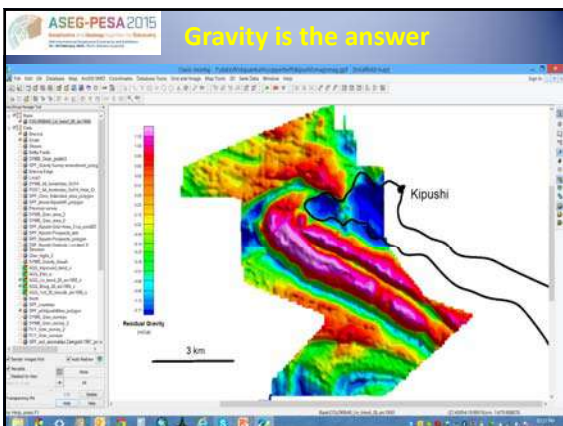


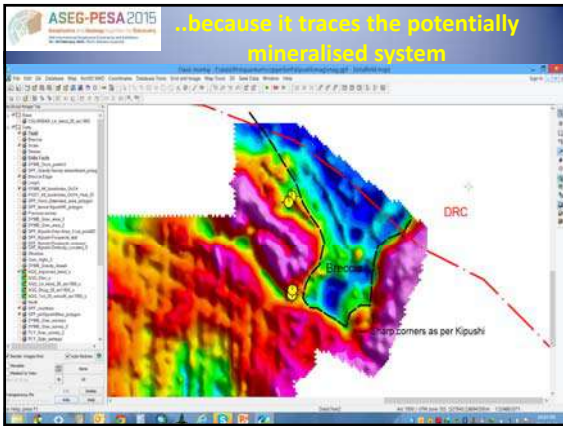


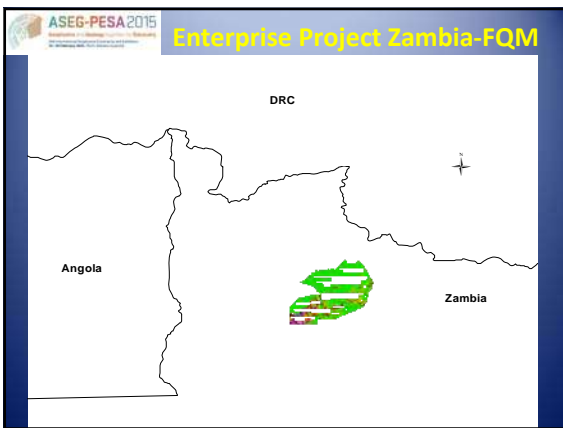


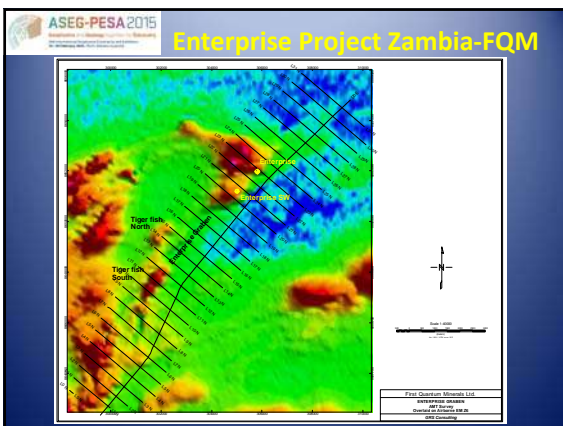


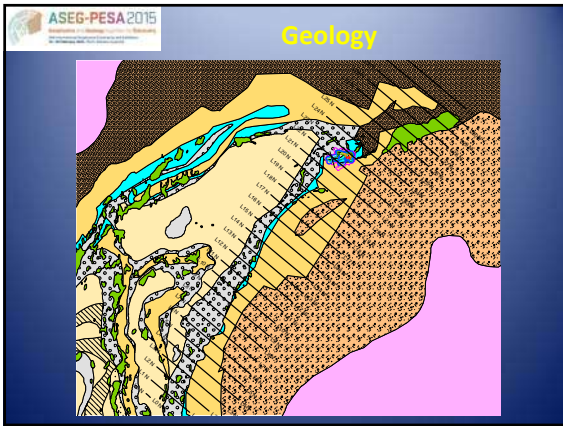


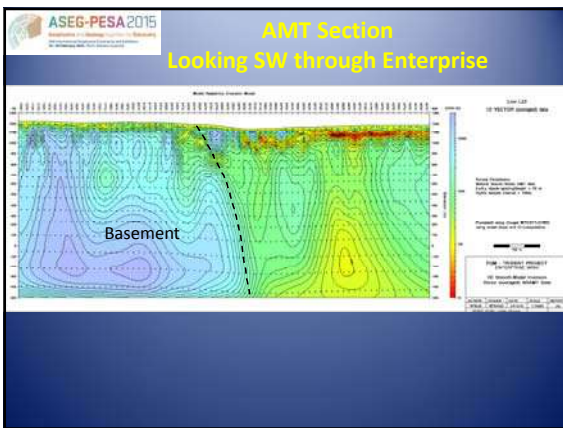


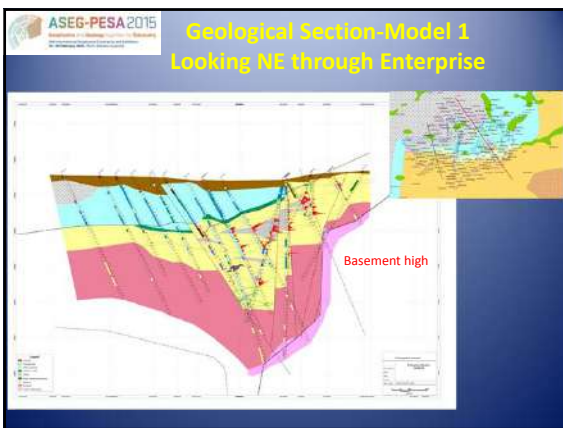


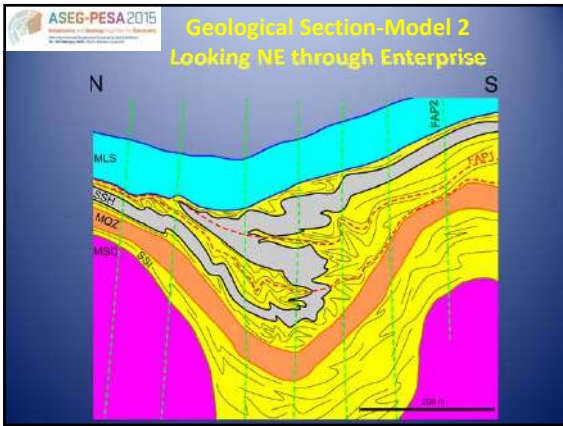


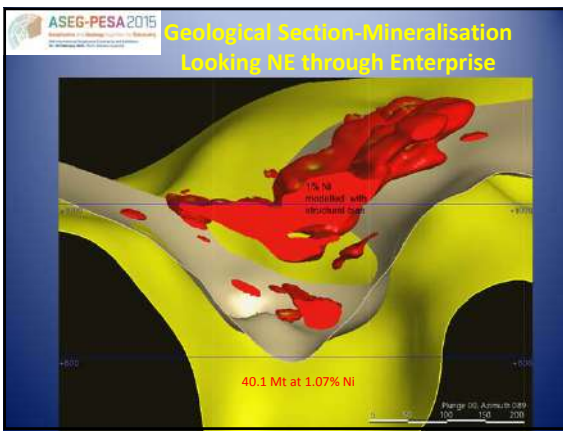


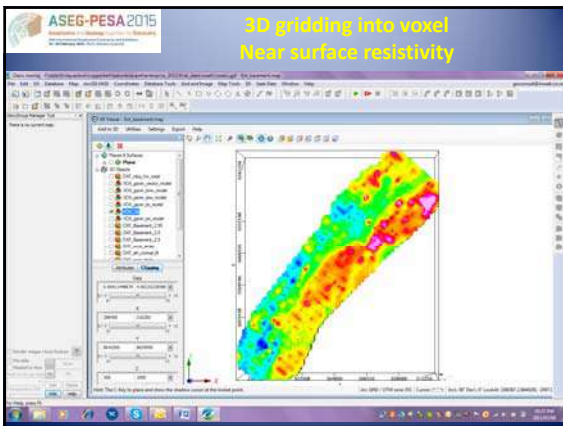


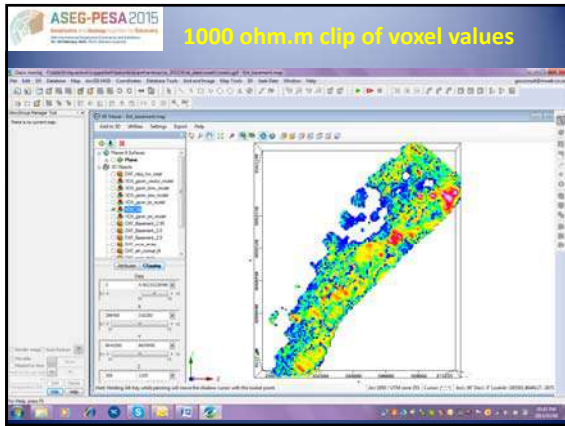


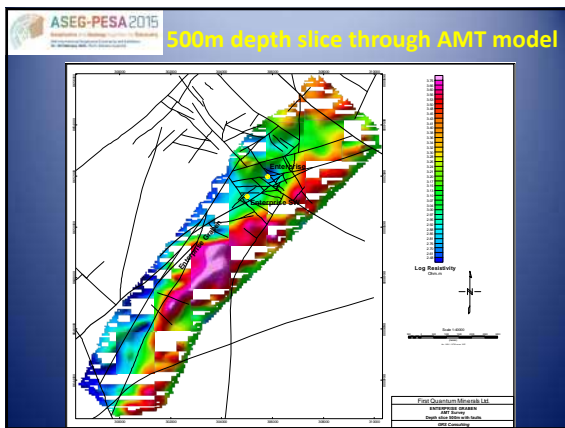


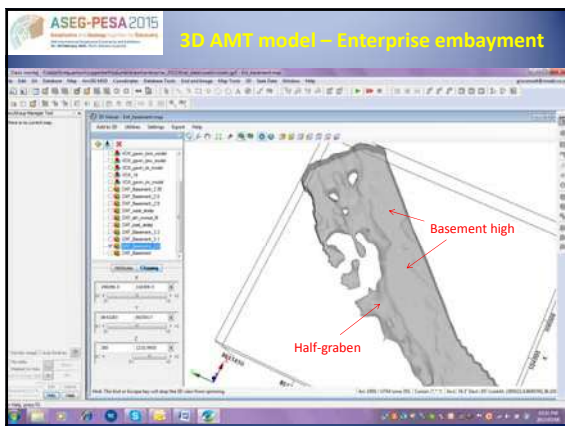


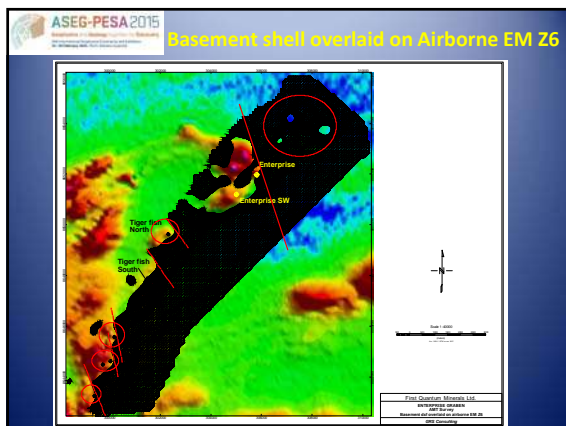




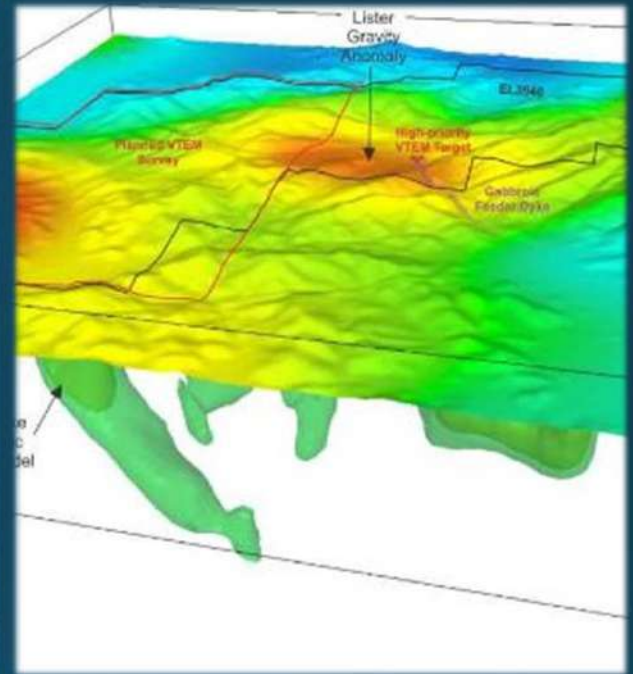












ASEG 2015 Perth

Signatures of Mineral Systems; A Perspective from the Financially Challenged

Graham Ascough /Mithril Resources




ASEG 2015 Perth

**Signatures of Mineral Systems;
A Perspective from the Financially Challenged**

Graham Ascough Mithril Resources

Explorers are facing the most challenging time in decades...

Cash Reserves and Expenditures have dropped dramatically
METASIS Australian Junior Explorations Company - 1996-June 2014



During a downturn, Cash Reserves, Exploration & development expenditures are not the most.

Cash Reserves are at a 10 year low

Adverse events tend to be 'clustered'

- Financing of Junior companies is not supported in the current investment climate
- Juniors account for over half of all the exploration spend in Australia (...historically at least)
- Junior companies live within the constraints imposed by their ability to raise capital
- Difficulties in raising funds directly translates into reduced exploration activity - particularly greenfield exploration

Signatures of Mineral Systems

- Are they relevant in a commercial environment?
- Improved understanding of Minerals Systems should increase greenfield success and shorten the discovery timeline
- Recognition of decreased risk should result in increased value and be attractive to investors
- Currently investors are risk-adverse and greenfield exploration is not supported
- Can Mineral Systems Models help change this negative sentiment?

Managing Expectations



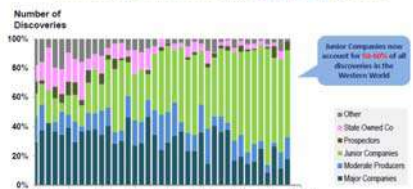
- Investors generally expect most activity and drillholes will be a "success"
- Lack of success in recent years has resulted in a loss of confidence in the exploration business
- For effective greenfield exploration from concept to discovery funding is raised sequentially from milestone to milestone
- Difficult to communicate the significance of technical successes and positive results pre-discovery
- There is a need to communicate expected signatures of mineral systems in simple terms not only amongst geoscientists but also for the benefit of investors and decision makers
- Positive results, pre-discovery, de-risk a project towards an economic success BUT this is rarely value adding in the view of the market

Classification of Mining Companies



- Major and Mid-tier are much the same (difference is scale):
 - Producers
 - Developers
 - Brownfield Explorers
 - Limited Greenfield Exploration
- Expectation that Junior Explorers will deliver the greenfield discoveries
- Often partner with junior explorers to support greenfield projects however this is limited to the "good-times"
- Junior Companies
 - Focus mainly pure exploration and/or Feasibility stage projects
 - Rely on equity financing as their principal means of funding exploration and development

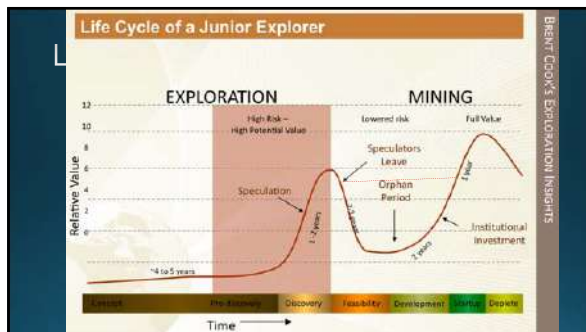
Percentage of discoveries made by Company Type
Moderate+Major+Giant discoveries in the Western World: 1975-2013

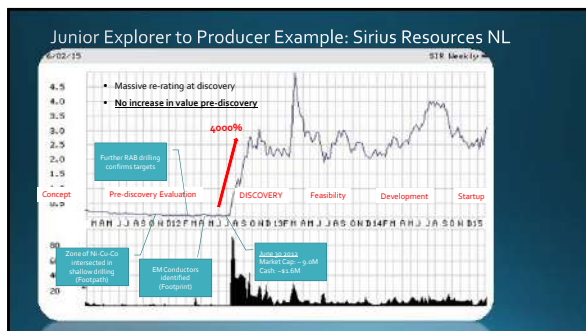


MinEX Consulting Strategic advice to industrial corporations & exploration 17

Reluctant Greenfield Explorers

- Juniors often first movers into greenfield terrains however;
- Reality is that most investors in juniors are not interested in backing long-term exploration in unproven, high-risk areas.
- Majority of juniors explore in brownfields areas where shorter term, more certain (but more modest) outcomes are likely to be found.
- Can an improved mineral system framework impact the ability of Companies to raise capital (and the timing of returns)?
- Again - from concept to discovery funding is raised sequentially from milestone to milestone.
- Communicating the technical achievements as a de-risking process pre-discovery is key to implementation of a Mineral Systems Framework





Proposed frameworks can facilitate communication of positive results at an early stage

Footpath-Footprint Framework

Decreasing response along extension axis

Geophysical Expression

Footprint

Foot path

Suggested Scales

Intersection of Favourable Conditions Framework

Fertility

Proximity to Lithosphere-scale Structure

Favourable (Transient) Geodynamics

Ore Genesis

Sources: Witherly 2014, and Hronsky, 2011

Fraser Range Mamba Project

MUSGRAVE Minerals Ltd

- Along trend from Sirius' Nova-Bollinger deposits
- Fraser Range also hosts the Tropicana gold Deposit
- 180km² Area
- No significant previous exploration
- Now detailed aeromagnetic survey completed 2014

Mamba Project

Trans-Australia Railway

Nova-Bollinger
14.2m @ 2.0% Ni, 0.8% Cu and 0.01% Co (Sirius Resources Ltd)

Fertility

Geodynamics

Structure

ASX: MGV

Musgrave Region

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

Musgrave-Fraser Range Link Crustal Reconstruction

After Karlstrom et al 2001
Musgrave & Albany Fraser Provinces joined during time of Ni-Cu deposit formation

C. 1.3 - 1.0 Ga

MUSGRAVE Minerals Ltd

Musgrave Project Regional Targets

- Under-explored
- Regional targets identified in gravity and magnetic data
- Very large land holding
- Partnering Opportunity

Regional gravity image with interpreted major structures

MUSGRAVE Minerals Ltd

Pallatu Deering Hills Project

- Demonstrated potential through initial drilling program

Analogous Setting to Huge World Class Deposits Nova, Voisey's Bay, Kabanga, Raglan etc.

MUSGRAVE Minerals Ltd

Regional Setting

- ❑ The right address
- ❑ Stark occurs adjacent to a crustal scale structure - "Youanmi Shear Zone"
- ❑ Extends to + 25km depth and has acted as a giant "plumbing system"
- ❑ **Big deposits need big "plumbing systems"**
- ❑ MTH has over 100 kilometres of the Youanmi Shear Zone covered

Stark Prospect

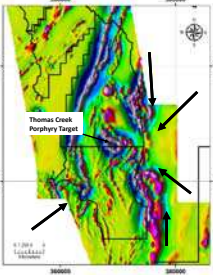
- ❑ Mithril discovery - no drilling prior to December 2014
- ❑ High tenor magmatic sulphides (chalcopyrite - pyrrhotite)
- ❑ Ground and downhole EM geophysics "sees" the mineralisation
- ❑ First ever drilling returns strong assay results from each hole drilled:
 - 16m @ 0.81% copper, 0.09% nickel, and 0.39g/t PGE's from 183 metres including **4m @ 1.91% copper, 0.18% nickel, and 0.9%g/t PGE's (NRC14008)**
 - 13m @ 0.44% copper, 0.08% nickel, and 0.24g/t PGE's from 144 metres including **2m @ 1.04% copper, 0.18% nickel, and 0.49g/t PGE's (NRC14003)**
 - 2m @ 1.32% copper, 0.03% nickel and 0.80g/t PGE's from 76 metres (NRC14007)
- ❑ Grade increasing with depth
- ❑ Mineralisation remains OPEN in all directions
- ❑ **Excellent size and grade potential**

Size and grade potential

- ❑ **NRC14003 - 008 cross-section**
 - Two RC holes drilled down dip of surface gossan targeting bedrock EM conductor
 - Multiple mineralised zones including semi massive sulphides at base of a mafic intrusion
 - Width and grade of mineralisation increasing down dip
 - **Remains OPEN in all directions**
- ❑ **300 metre diamond drill hole to confirm increasing grade and continuity of mineralisation commencing next week**

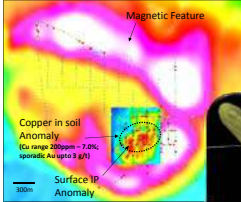
Thomas Creek Project

- Large scale geochemical and geophysical target
- Potential for a World Class Sized Deposit
- Classic demagnetised magnetic ring typical of porphyry copper deposits
- Associated with major rift / transfer fault intersection - regional dilational zone

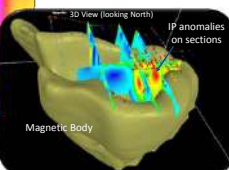


RTP aeromagnetic image and tenement outline

Thomas Creek Copper-Gold Target



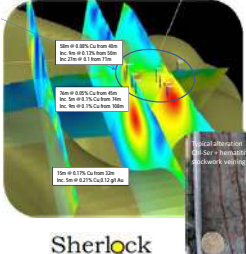
- Copper anomaly overlies IP target in centre of magnetic low consistent with the expected response from a porphyry system



3D View (looking North)
IP anomalies on sections
Magnetic Body

Historic Shallow Drilling at Thomas Creek

- 8 shallow BQ sized holes completed in 1996 do not test the IP anomaly and appear to be drilled down dip. Significant core loss (clays - highly weathered).
- Broad zones of low grade Cu intersected - i.e. TC02 - 58m @ 0.08% Cu from 40m, TC05 - 15m @ 0.17% Cu from 32m
- Intersect strongly altered porphyritic diorite to andesite with extensive hematite stockwork vein system (after primary sulphide?). Alteration - Silica - K-spar, sericite, chlorite
- Finely disseminated chalcopyrite observed in Fresher Ksp-silica altered crystalline rock samples.
- Drilling to 60-90m vertical depth (if no uplift)



3D view of drilling holes showing intersections with magnetic features and IP anomalies.

Greenfield Exploration Continues to Struggle

- Decision-makers in large companies and investors that fund junior explorers will continue to favour brownfield over greenfield exploration
 - returns are more immediate;
 - shorter and more certain timeline to discovery; and
 - historically, greenfields has not delivered enough quality projects.
- Need to lower risk of greenfield exploration by increasing success rates
- Fiscal return on exploration has declined – need to lift our game
 - Demonstrate significant return on Invested Capital
 - Lower risk and shorten time frames
- To measure this; Enterprise Value should grow in-line (or faster) than Invested Capital
- No (or limited) growth during the targeting stage is an issue for explorers and their investors

The Imperative For Greenfield Exploration



- Readily identifiable large resources in accessible areas largely discovered
- Next tier of major deposits will likely come from greenfield areas – areas that have been considered too deep, too remote, too risky or too difficult to explore
- Style of exploration will need to change (conceptual driven)
- Mineral Systems Frameworks can play a role if effective workflows and clear milestones are incorporated
- BUT: Will they influence investors to buy-in to greenfield projects?

"That being said, to expose yourself to potentially mind-numbing, tax-bracket-altering returns in precious metals investing, you have to consider allocating a piece of your portfolio in a collection of high-potential junior explorers and developers"

• Source: Lunndin, B, 2013 – Investment Guide to Gold and Silver
