Innovation in Mineral Exploration: advances in mineral exploration research

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PROMETIA Science Seminar

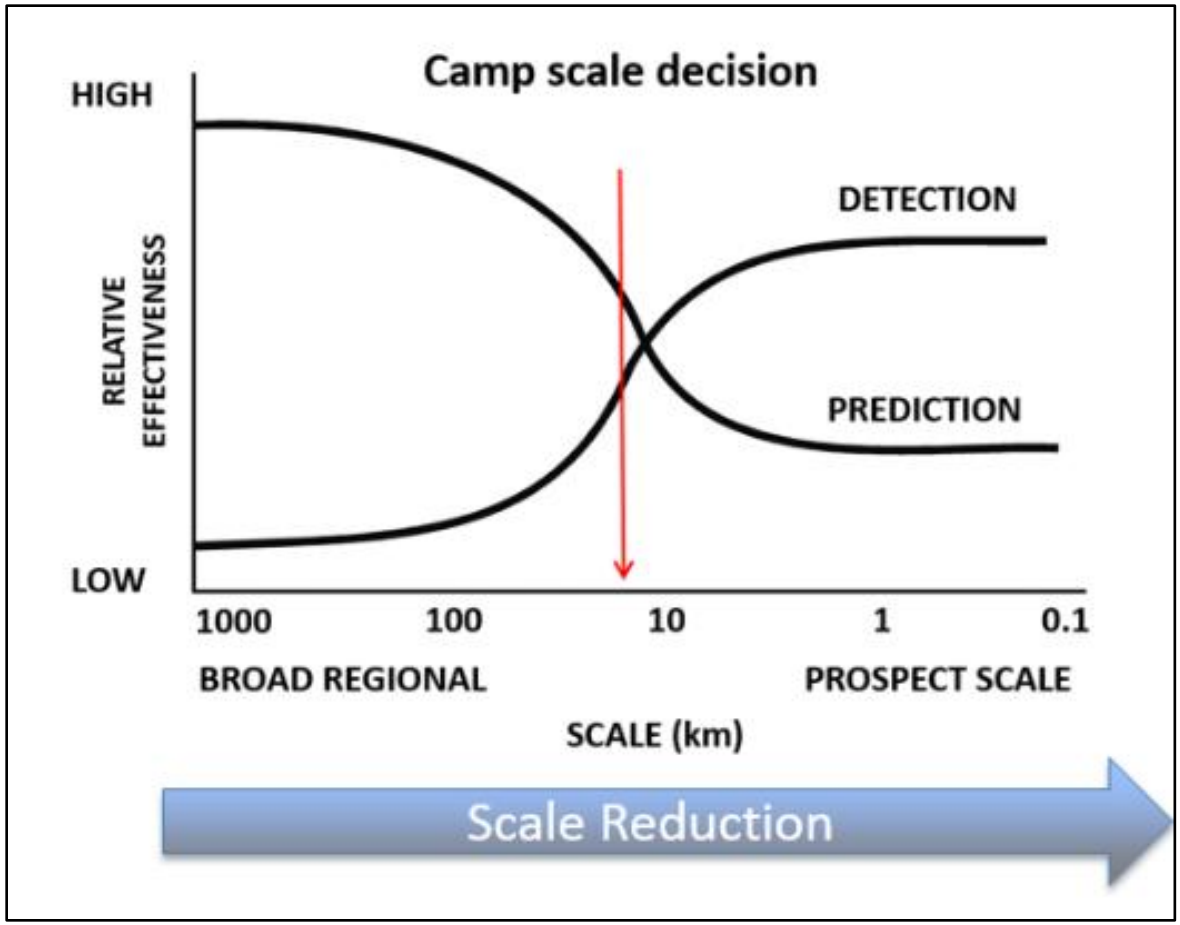
December 2016 Berlin

AMIRA INTERNATIONAL
Delivering solutions through collaboration

This presentation

- Why do we need innovation in mineral exploration?
- What is AMIRA International doing?
- Roadmap for Exploration Under Cover – pointing the way
- Example research initiatives
- Advances in geophysics?
- What else?
- Conclusions

Exploration reduction process



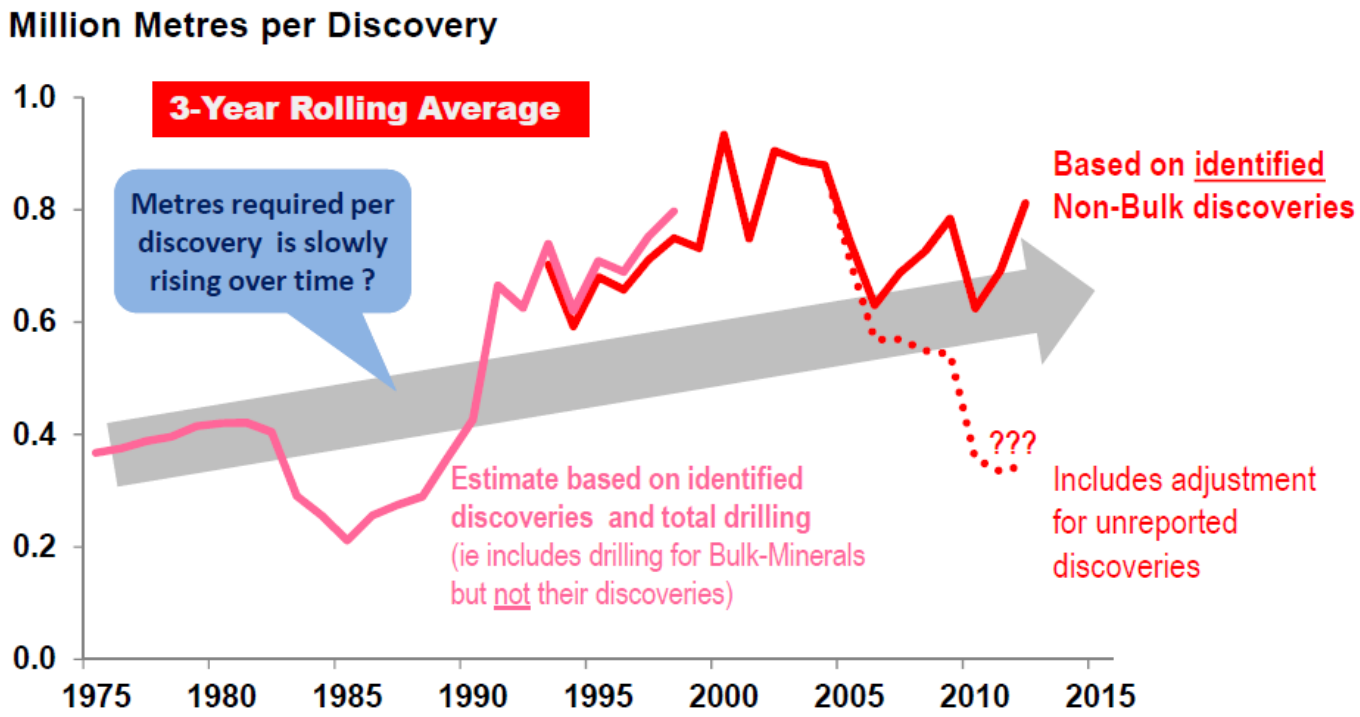
Terranne -> Regional -> Camp -> Deposit

Source: McCuaig et al., 2010

Why is innovation in exploration required?

Metres drilled per discovery

Australia: 1975-2012



Note: Analysis based on Moderate-, Major- and Giant-sized deposits
Excludes satellite deposits within existing Camps. Data for 1992-2012 excludes Bulk Mineral discoveries and spend.

Source: MinEx Consulting © November 2013

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Why is innovation in exploration required?

Discovery performance by Region: 2005-2014

Canada had lowest discovery costs, PAC/SEA was highest

Region	Explorn Spend (2015 $b)		Adjusted No of Discoveries		Adjusted Moz found Au	BP Credits	Moz-eq		Avg Size Moz-eq	Cost US$/oz-eq
Australia	$5.3	9%	48	11%	83	4	86	6%	1.8	$61
Canada	$11.6	19%	46	11%	306	75	380	27%	8.3	$31
USA	$5.7	9%	19	4%	78	3	80	6%	4.2	$71
Latin America	$14.4	24%	82	19%	275	78	353	25%	4.3	$41
Pacific/SE Asia	$4.0	7%	10	2%	10	2	12	1%	1.2	$334
Africa	$9.5	16%	128	30%	252	1	252	18%	2.0	$38
W Europe	$1.4	2%	16	4%	31	5	36	3%	2.3	$38
FSU+EE+China	$8.2	14%	64	15%	196	17	213	15%	3.3	$38
Rest of World	$0.5	1%	7	2%	18	3	21	1%	2.9	$26
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TOTAL	$60.5	100%	420	100%	1246	187	1433	100%	3.4	$42

Note: Includes adjustment for unreported discoveries

Source: MinEx Consulting © November 2015

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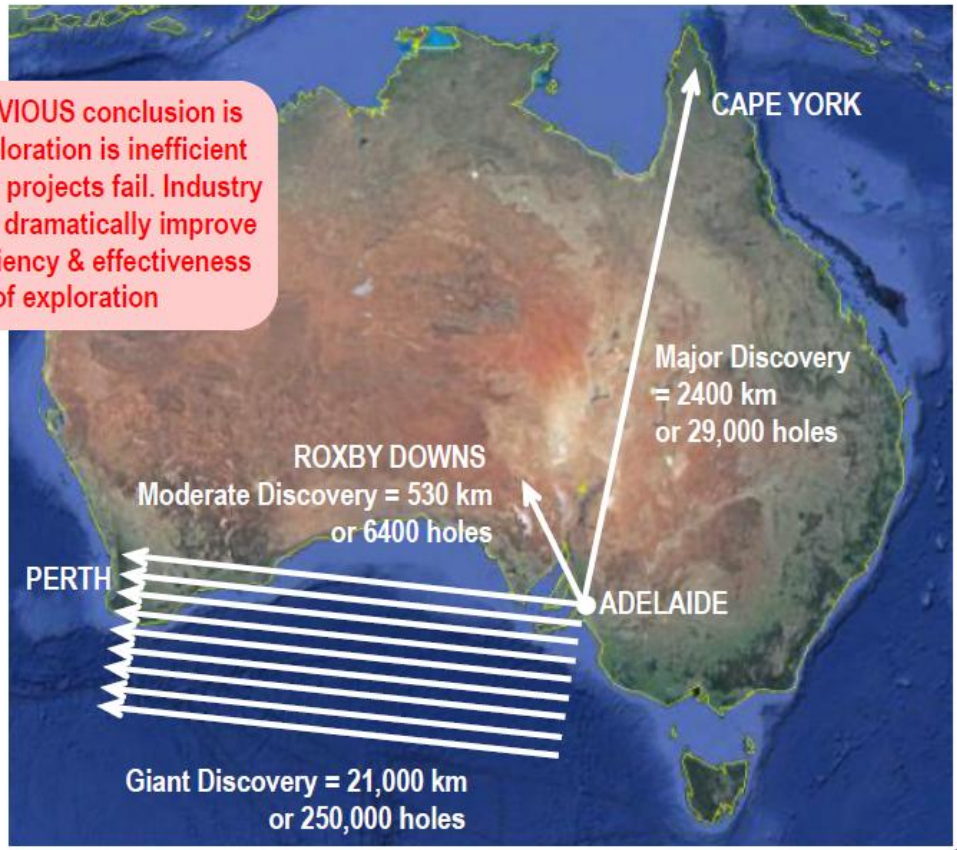
Why is innovation in exploration required?

The amount of drilling required is enormous and the Probability of Success is very low !!



Note:
Number of holes required is based on a average depth of 83 metres

Source: MinEx Consulting © March 2014

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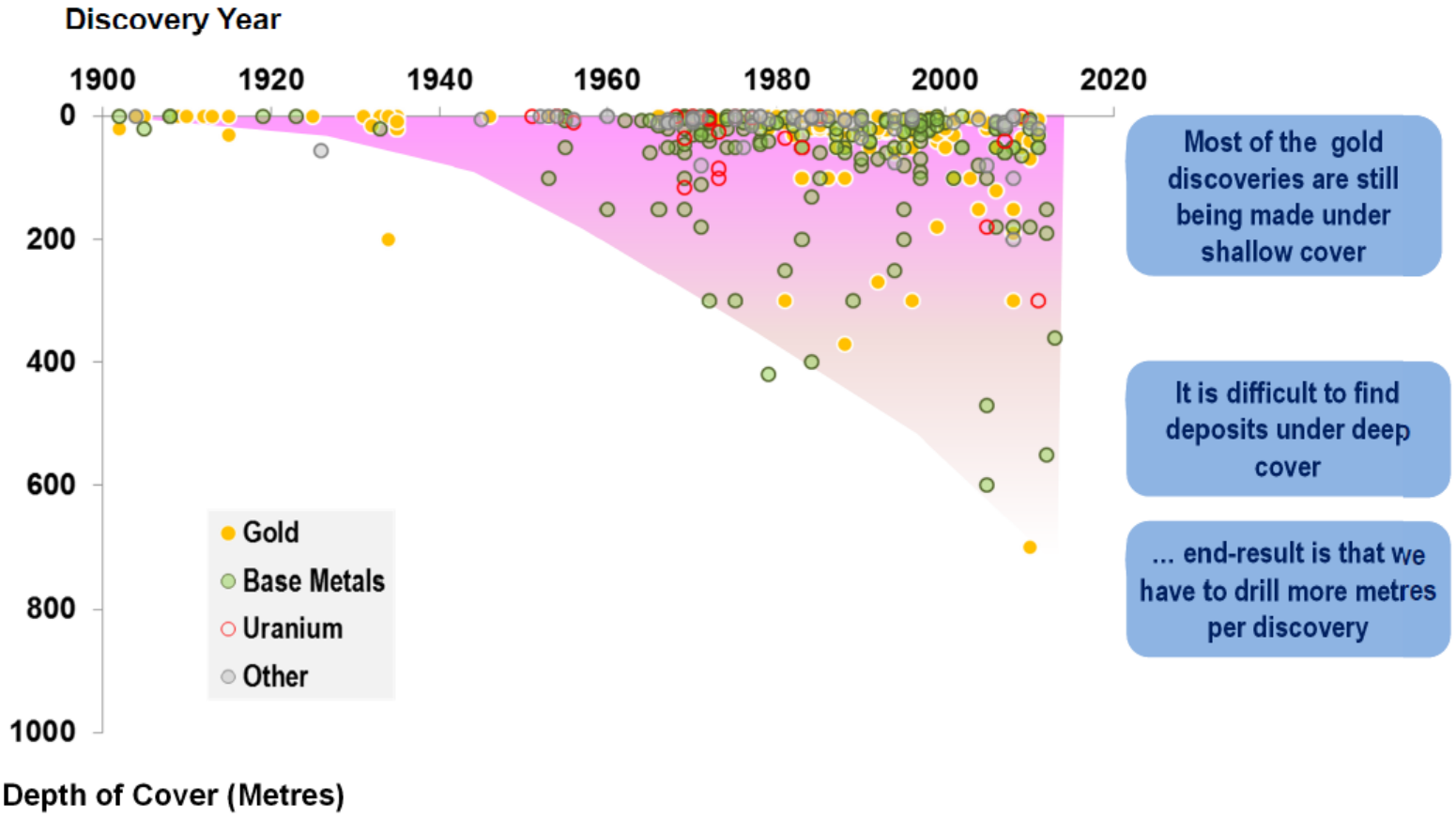
Why is innovation in exploration required?

Depth of cover for discoveries in Australia: 1900-2013



Note: Excludes satellite deposits within existing Camps. Also excludes Bulk Mineral discoveries..
Analysis based on Moderate-, Major- and Giant-sized deposits

Source: MinEx Consulting © November 2013

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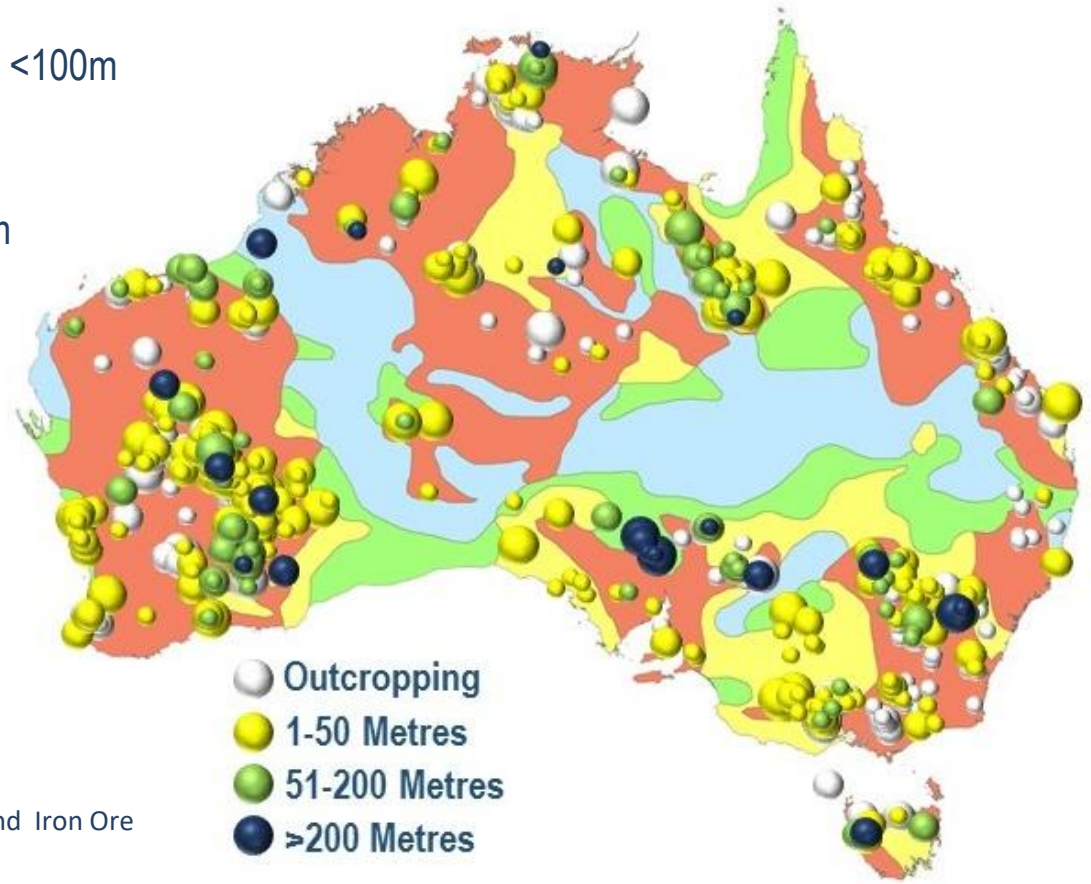
Why is innovation in exploration required?

INDICATIVE DEPTH OF COVER

- Outcrop & Shallow Basement <100m
- Basement depth 100 to 500m
- Basement depth 500 to 1000m
- Basement depth >1000m



Note: Excludes Bulk Minerals (such as Bauxite, Coal, and Iron Ore

Bubble-size refers to size of deposit
"Moderate" >100koz Au, >10kt Ni, >100Kt Cu equiv, 250kt Zn+Pb, >5kt U_3O_8
"Major" >1Moz Au, >100kt Ni, >1Mt Cu equiv, 2.5Mt Zn+Pb, >25kt U_3O_8
"Giant" >6Moz Au, >1Mt Ni, >5Mt Cu equiv, 12Mt Zn+Pb, >125kt U_3O_8

Sources: MinEx Consulting © September 2015
Geoscience Australia

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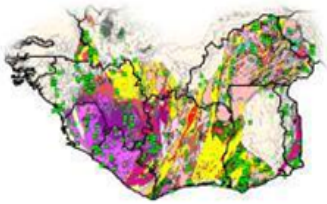
The critical challenge

What data, knowledge and technology is required to move between scales, and from prediction to direct detection particularly in areas with thick post-mineralisation cover?

Innovation: AMIRA International's lifeblood for 57 years

Regional Framework Studies

- West Africa Exploration Initiative (P934, P934A, **P934B**)
- South China Craton (P950)
- Yilgarn (P437, P482, P624, P763, P710)



Technology / Technique Development

- Geophysics (P223, P407, P1022, P1036, P1058)
- Geochemistry (P778, P778A, P710A, P972)
- Geometallurgy (P843, P843A)

Data Compilations & Roadmaps

- Data Metallogenica (P1040)
- Australian Geoscience Thesis Database (P874)
- Copper Technology Roadmap (P813)
- Drilling Technology Roadmap (P903)
- **Uncover Roadmap (P1162)**

Ore Deposit Model Studies

- Epithermal & Porphyry Deposits (P765A, P1060, **P1153**)
- Sediment-hosted Copper Deposits (P872)
- Stress Transfer Modelling of Gold Deposits (P718A)
- Nickel Deposits (P710A, P962)
- Sediment-hosted Gold Deposits (P923)
- Diamond Indicator Minerals (P891)

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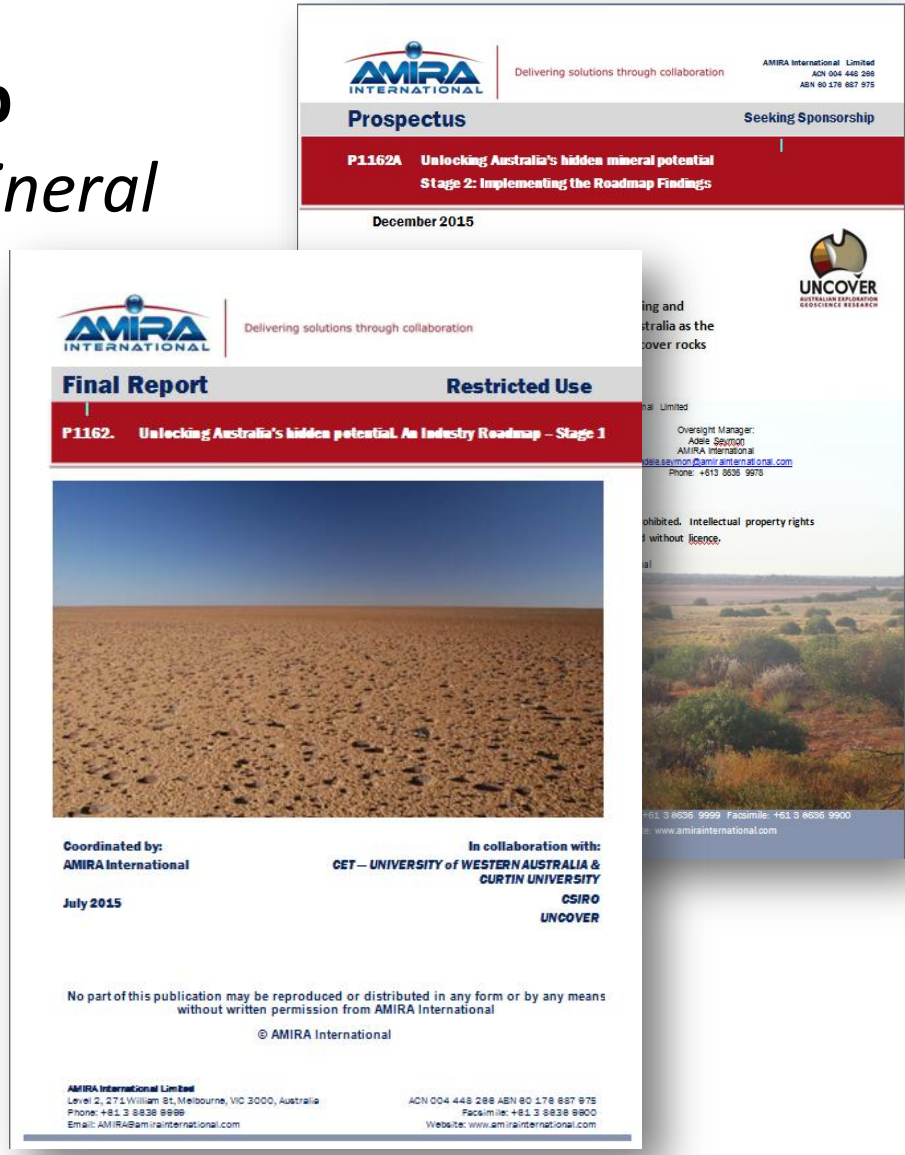
What are we doing to meet the challenge?

AMIRA International's **Roadmap**
'Unlocking Australia's hidden mineral potential'

The aim is to develop a blueprint for addressing the gaps in data, knowledge, technology capability and research capacity required to improve the exploration success rate in areas of post mineralisation cover



AMIRA International Exploration Under Cover Roadmap

Roadmap results – Priority 1-8

Rank	Program	Type
1	Understand type, age & depth of cover	R, DC
2	Characterise distal mineral system footprint signatures	R, DC
3	Improve understanding of mineral systems	R
4	Build 3D architecture of Australian lithosphere	R, DC
5	Depth-to-basement-imaging from new airborne National AEM surveys	DC, DA
6	Acceleration of national AusLamp long period MT acquisition	DA
7	Understand geochemical dispersion in post mineralisation cover sequences	R, DC
8	Acquire approximately ~4km grid of gravity over continent	DA

R- Research**, T-** Technology, **DC** - Data Compilation, **DA** Data Acquisition

Source – AMIRA P1162 Roadmap July 2015

AMIRA International Exploration Under Cover Roadmap

Roadmap results – Priority 9-16

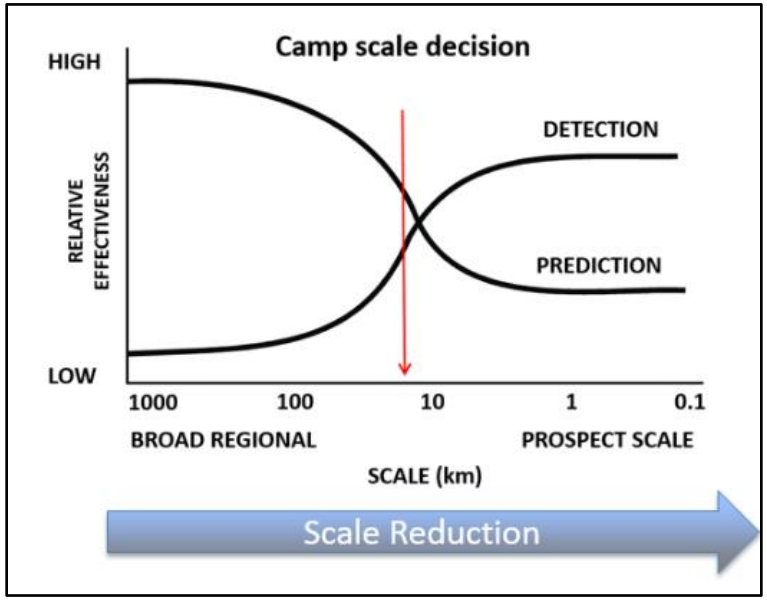
Rank	Program	Type
9	Undertake targeted paleosurface horizon and basement re-sampling and new sampling via onshore National Stratigraphic Drilling Initiative	DC, DA
10	Deploy the Australian Seismic Array	DC, DA
11	Undertake 3D current architectural interpretation of Australian lithosphere	R, DC
12	Understand fertility of lithosphere (Current state) Structures, Domains and Basins	R, DC
13	Undertake targeted geochronology data acquisition of mineral occurrences, priority basins and concealed basement	DA
14	Maximise size of detectable footprint signature	R
15	Create new fertility tools to understand and map metal fertilities	R, T
16	Understand the genesis and development of major trans-lithospheric geodynamic faults/lineaments through time	R, DC

R- Research**, T-** Technology, **DC** - Data Compilation, **DA** Data Acquisition

Source – AMIRA P1162 Roadmap July 2015

Key innovations required: data, knowledge & technologies

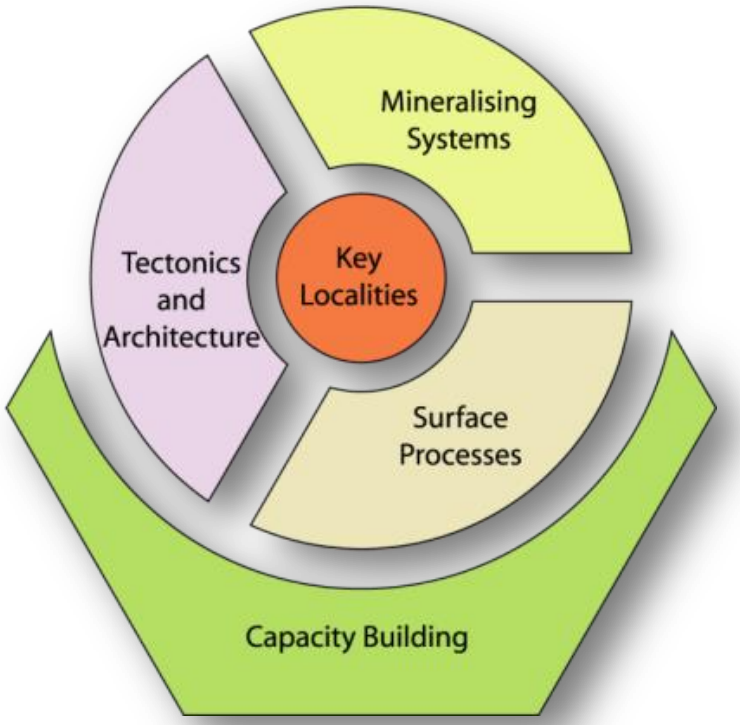
- Regional data acquisition
- Architecture
- Footprints
- Vectors to ores
- Geophysics
- 3D (joint) Inversion, data analytics, and visulisation



Innovations required: example 1

WAXI- West African Exploration Initiative
IXOA- L'Initiative d'Exploration Ouest Africaine

P934B West African eXploration Initiative (WAXI)



- Public-Private Partnership
- Integrated programs of research; West African scale data integration; and capacity building
- A powerful networking forum with the major stakeholders in West Africa (industry, government, universities, aid agencies)

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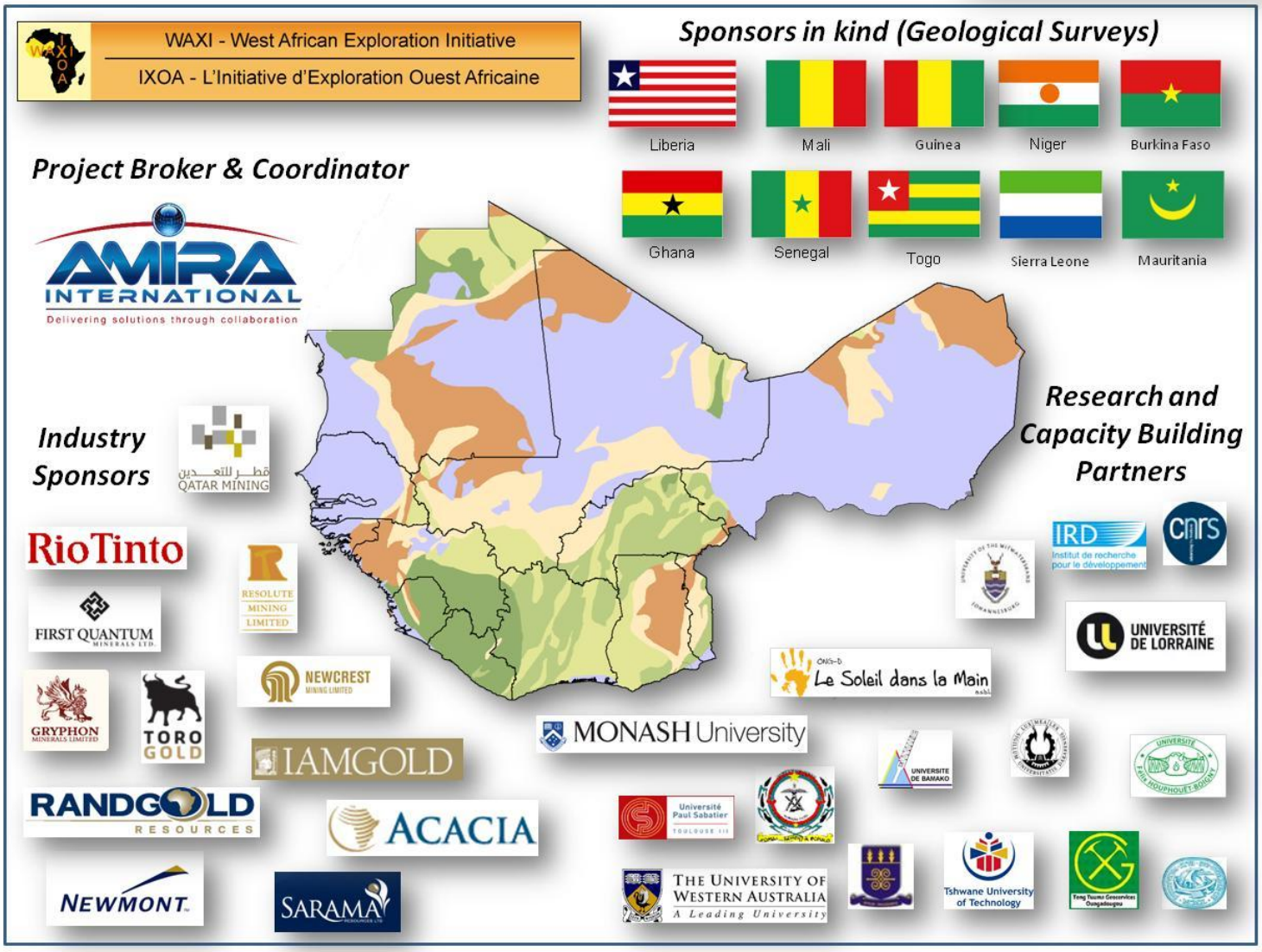
Innovations required: example 1



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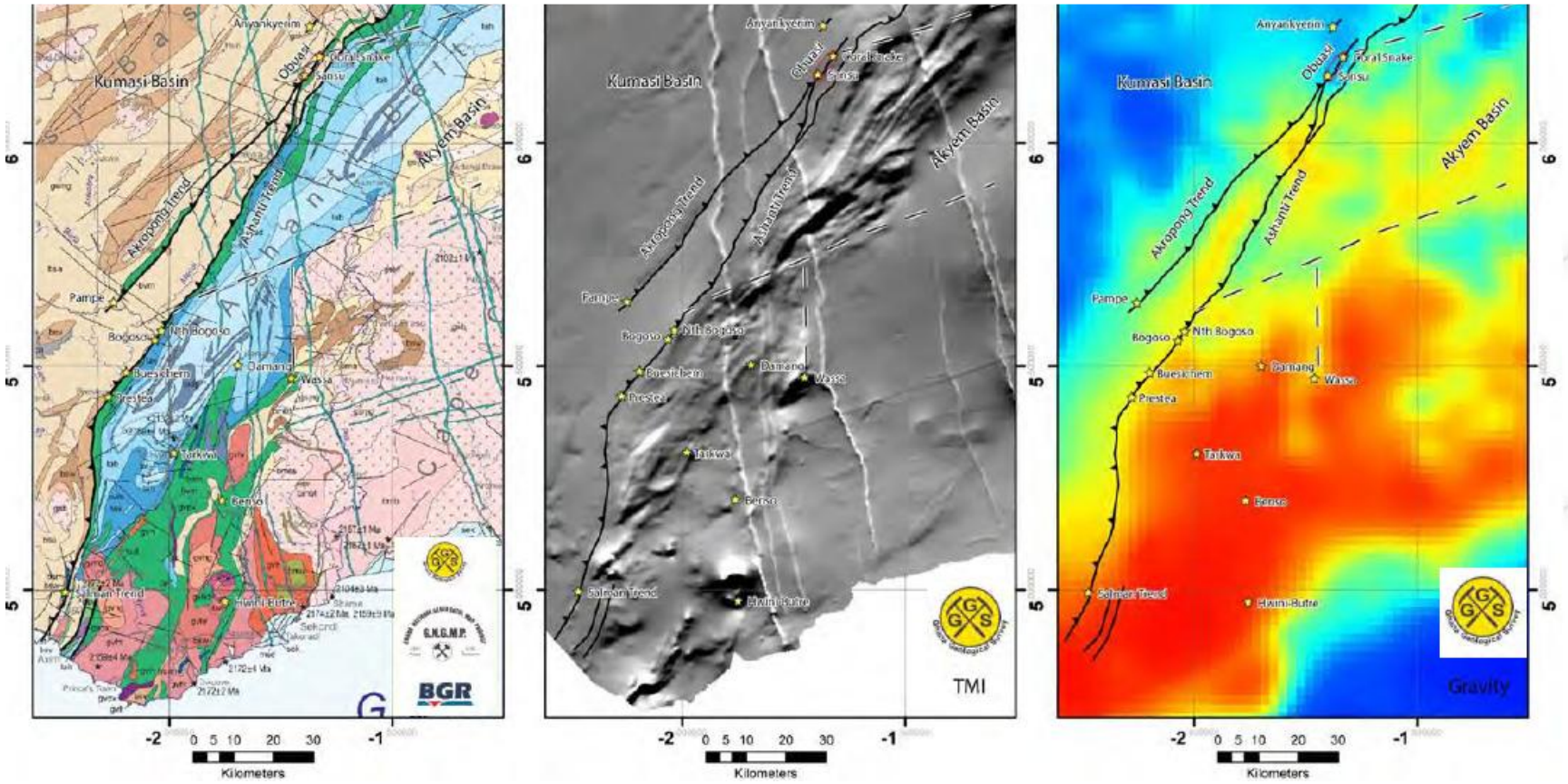
Innovations required: example 1

- New data at a range of scales (from craton to deposit) and syntheses -> New harmonised maps (across country boarders) and GIS dataset (with layers unique to the WAXI project)
- Major variations between individual deposits. Belt scale architectural controls appear to be a control on deposits location



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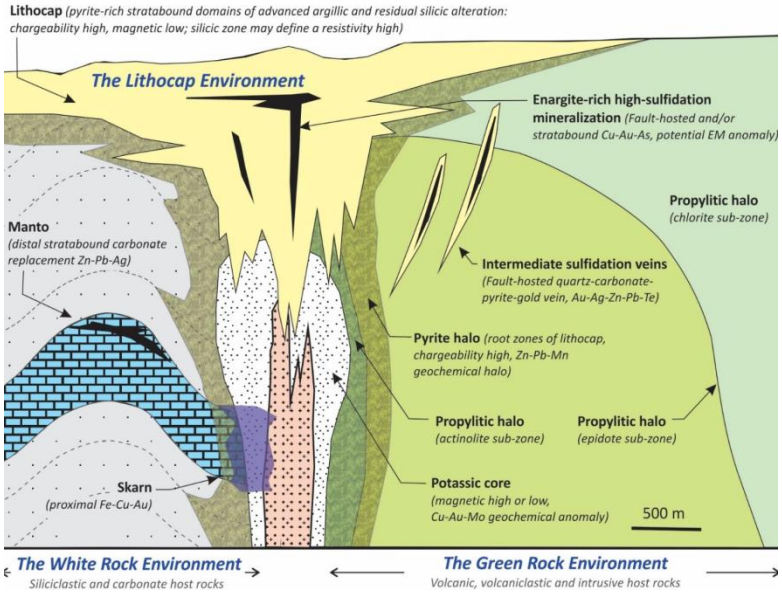
Innovations required: example 2

P1153 Explorers toolbox for porphyry + epithermal deposit discovery



- Improve exploration success
- Toolbox developed from research on deposits from around the world - geochemical, mineralogical & textural
- Detect distal footprints
- Vector towards ore
- Provide fertility assessment

CODES TMVC

Australian Government
Australian Research Council

NATURAL HISTORY MUSEUM

Guangzhou Institute of Geochemistry
Chinese Academy of Sciences

Lakehead UNIVERSITY

合肥工業大學
HEFEI UNIVERSITY OF TECHNOLOGY

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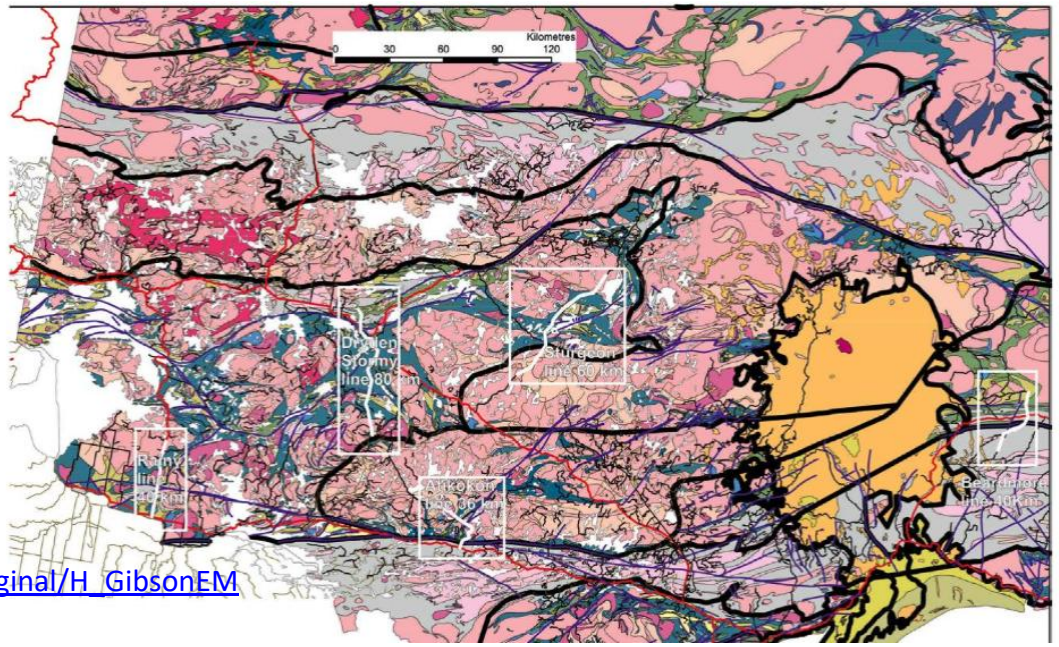
Innovations required: other geoscience initiatives

- Metal Earth – characteristics of fertile terranes & districts (Laurentian Uni. & MERC - Canada
- Geo-Mapping for Energy and Minerals (Nrcan - Canada)
- Targeted Geoscience Initiative (TGI 5) (Nrcan - Canada)
- Canadian Mining Innovation Council/NSERC – Footprints Project



Source: Metal Earth: proposed Wabigoon transects
http://www.mirageoscience.com/data/media/all/original/H_GibsonEM2016.pdf

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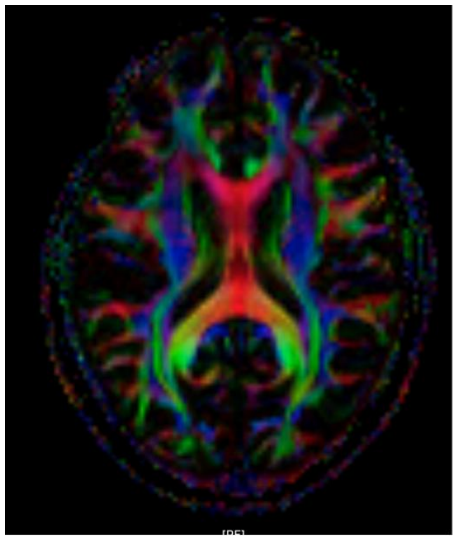
Innovations required: Geophysics to play an increasing role in exploration under cover: but what's on offer?

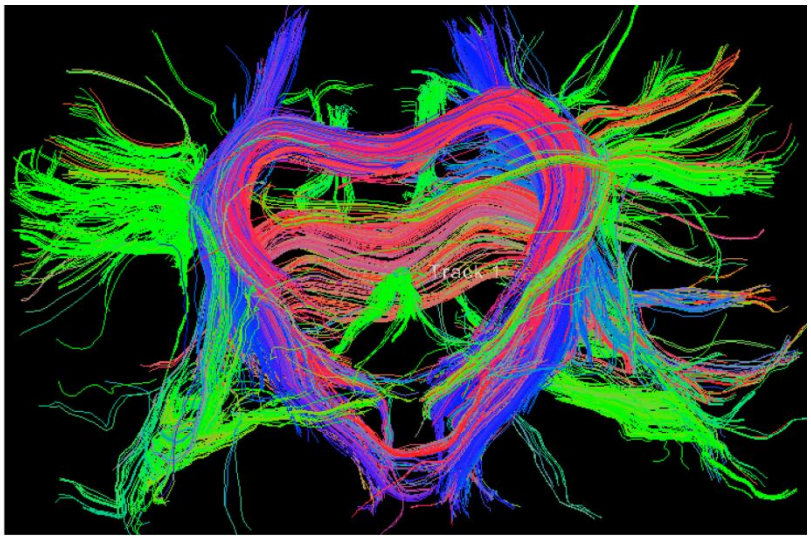
- Magnetics: susceptibility & remanence *stock standard*
- Gravity: density *newish airborne*
- Radiometrics: Chemical Concentration *shallow depth*
- Resistivity (conductivity) : (mineral composition, connectedness and through IP electrochemistry) *new*
- Electromagnetics: conductivity, susceptibility and dielectric permittivity and superparamagnetism - *many complex flavours*
- Seismics: density, rigidity *newish in hard rocks*
- Modelling and (*new Joint)* Inversion

Source: Prof. James Macnae – presentation at AMIRA International's "Ideas Factory", Dec 2016

Magnetics

- Significant improvements in detecting and modelling remanence, despite ambiguity; Squid tensor measurements improve spatial resolution.





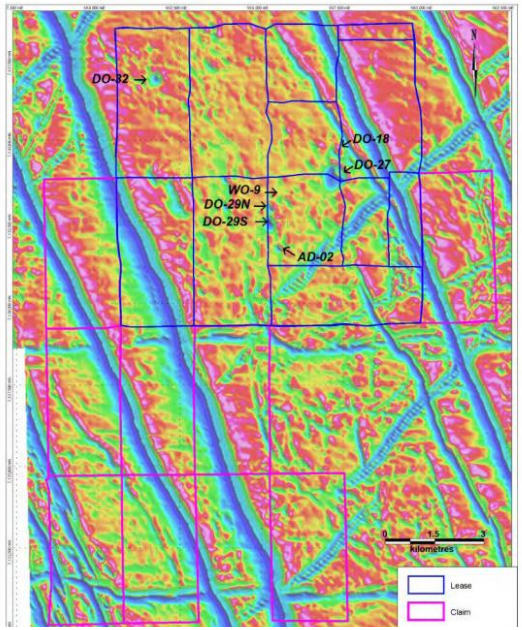
Magnetics still primarily used as spatial imaging tool: No new impacts

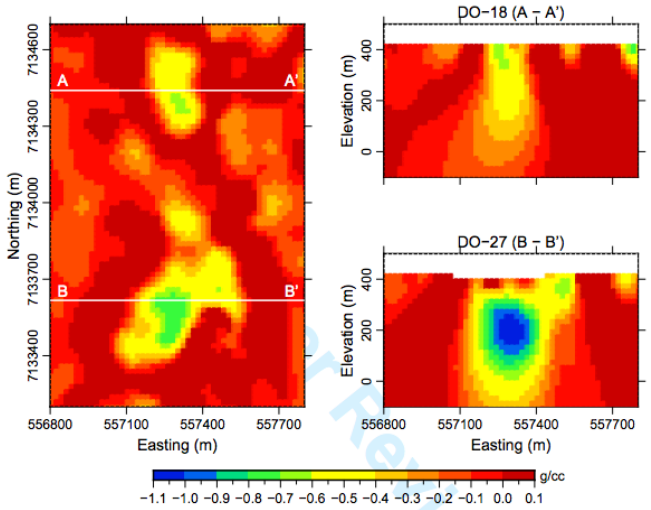
Source: Prof. James Macnae – presentation at AMIRA International's "Ideas Factory", Dec 2016

Gravity

- Ground gravity mature, newer instruments easier to use and more reliable.
- Borehole gravity instrumentation available for NQ holes. Expensive, reliability issues. Limited acceptance as a routine tool.
- Airborne gravity and gravity gradiometry relatively mature methodologies, incrementally improving. "Big" sums continue to be spent on getting a better airborne systems.

Figure 6-2: Example of 2001 Falcon™ Results with Kimberlites Discovered (courtesy of Peregrine, 2014)



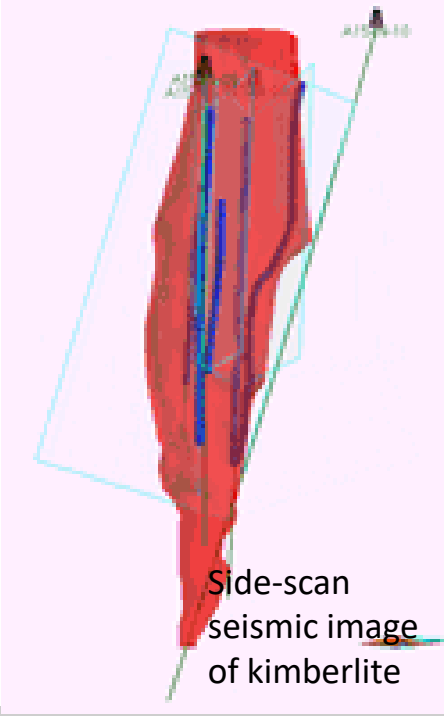


Falcon gravity gradiometry and UBC inversion: Tli Kwi Cho kimberlites

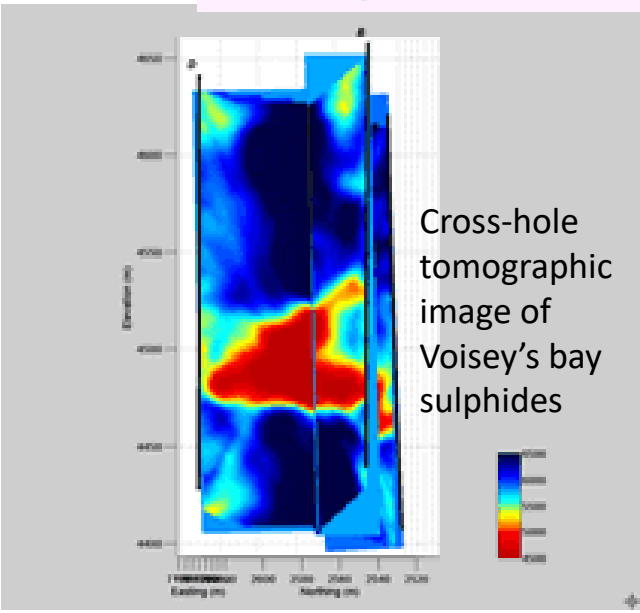
Source: Prof. James Macnae – presentation at AMIRA International's "Ideas Factory", Dec 2016

Seismics

- Well established in soft rocks
- Significant improvements in hard rock, non sub-horizontally layered environments.
- HI resolution but High cost
- 3D arrays, “big data”
- Will get better (but with no cost reductions of significance)
- Brownfields targets only in near future.



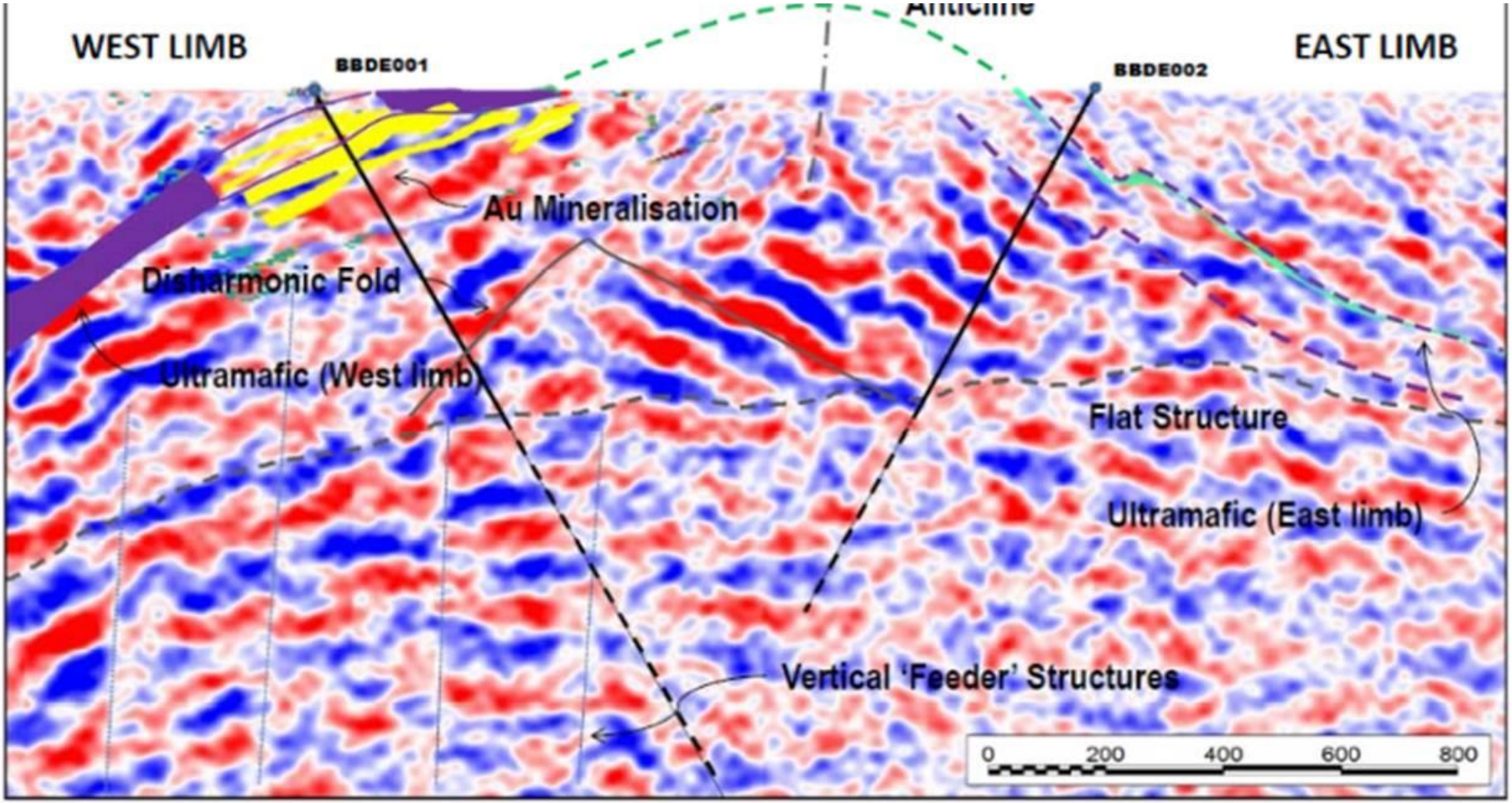
Side-scan seismic image of kimberlite



Cross-hole tomographic image of Voisey’s bay sulphides

Source: Prof. James Macnae – presentation at AMIRA International’s “Ideas Factory”, Dec 2016

HiSeis example



Cross-section on Seismic Line Showing Planned Drill Holes

Source: Prof. James Macnae – presentation at AMIRA International's "Ideas Factory", Dec 2016

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Resistivity - IP

- Higher powered transmitters and distributed arrays
- Massive OH&S issues (e.g. overhead wiring in the bush)
- No breakthroughs in the offing
- Continuing misguided pushes to get “mineral discrimination” from IP data
- Why: Because it is desirable!

Experts in the field believe that its not realistic once you understand the physics and electrochemistry

Source: Prof. James Macnae – presentation at AMIRA International’s “Ideas Factory”, Dec 2016

Radiometrics & Remote sensing: geochemistry of the near surface

- U K Th mapping with complications
- Alteration, core and geological “outcrop” mapping
- Better/smaller tools (self calibrating, easy to use)
- No breakthroughs of “geophysical” interest in the offing to find deep targets
- However, rumours of companies working on deep sensing geochemistry using “gases” persist

Source: Prof. James Macnae – presentation at AMIRA International’s “Ideas Factory”, Dec 2016

Electromagnetics

- Ground systems increased power: lower frequency, more signal, deeper penetration.
- Airborne systems power increase more difficult but incremental changes occur, usefully lowering base frequency has been virtually impossible to date.
- Airborne sensors much better, much lower noise.
  - SQUIDS. Cannot be operated close to high current transmitters. Logistical issues
  - Induction magnetometers (ARMIT) equivalent noise levels to high temp SQUIDS; extensive use in Canada
  - Fluxgates: Limited scope for improvement, but "good" near high power transmitters
  - Induction coils: no further improvements likely

Source: Prof. James Macnae – presentation at AMIRA International's "Ideas Factory", Dec 2016

Airborne IP and Low Frequency AEM

- Current topic of great interest
- Existing systems “see” IP, but only from very fine grain minerals or ice in very porous rocks
- Need to get lower frequencies to see larger grain sizes (CGG*2, Geotech, Vale, RMIT)
- Need to overcome suspension noise and limited averaging time in airborne system to get useful AIP
- Active development:
  - Two AMIRA International projects P1036, P1036a: System refined and has successfully mapped IP responses in NSW, data still being analysed.
  - B field sensor with rotation measurements for correction, will be low frequency AEM before it becomes an AIP system. Optimum system has wide Tx-Rx separation.

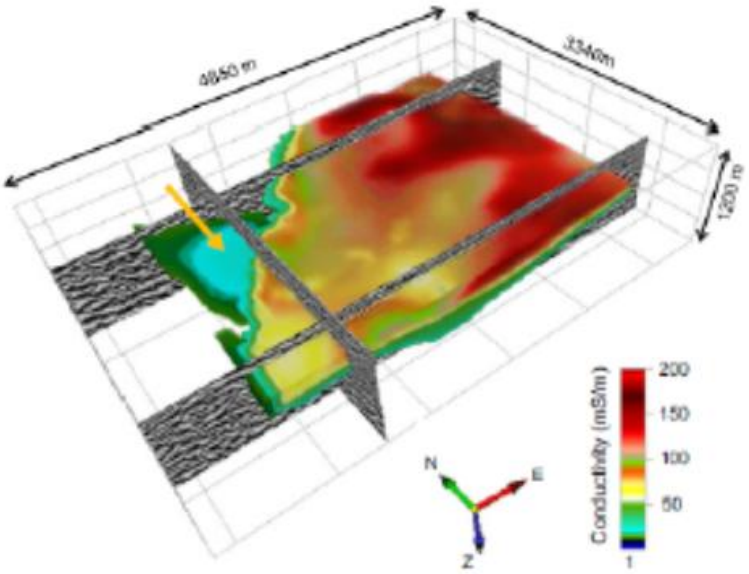
Source: Prof. James Macnae – presentation at AMIRA International’s “Ideas Factory”, Dec 2016

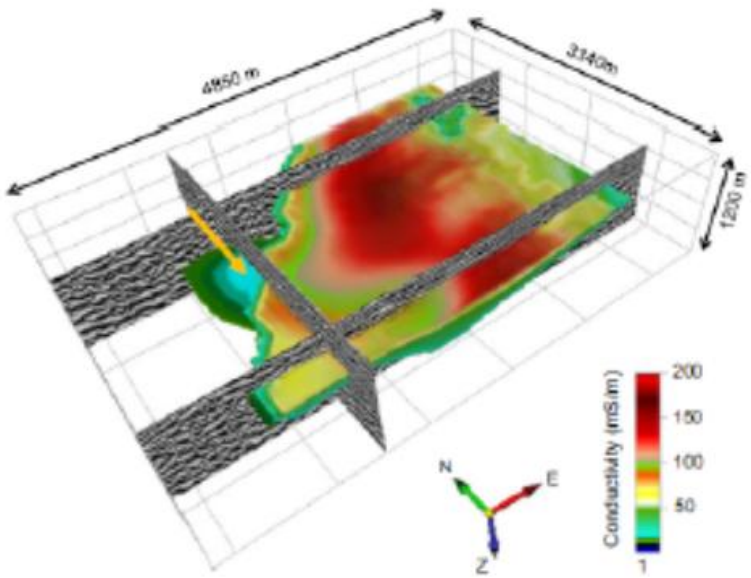
"Joint Inversion"

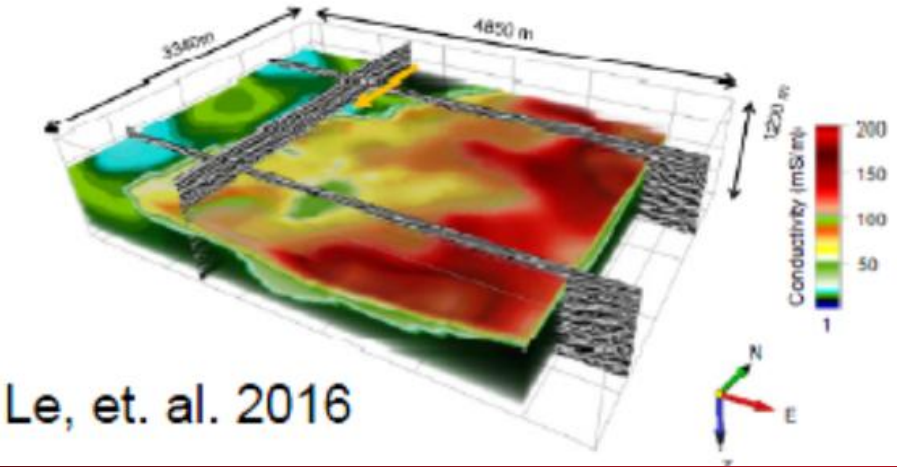
- Software to find a common "geological" model consistent with all information.
- Great in concept, yet to provide convincing case histories
- Work continues and will bring advances, but no breakthrough in the short term.
- Examples:
  - DET CRC - Modelling the Subsurface with Cooperative inversion of Seismics and MT
  - CSIRO - From a probabilistic geophysical inversion to optimal decision making in exploration
  - UBC Geophysical Inversion facility?

Source: Prof. James Macnae – presentation at AMIRA International's "Ideas Factory", Dec 2016

“Cooperative Inversion of Seismics and MT”







Le, et. al. 2016

Semiautomatic Cooperative inversion
Geometric mapping
Sharp. Cond.
Boundary coefficient (0.25).

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Prospects for advance in geophysics: a summary

- EM is the place with the most upside and hope for a breakthrough in mineral exploration at depth as EM and GPR systems go lower in frequency
- Airborne IP has the most upside but the greatest risk
- Seismics is likely to become the most accurate exploration tool, but probably not the most cost-effective exploration tool for deep targets
- Data analytics?
- Drones?

New Drilling Paradigm

DET CRC Coil Tube Rig

Conclusion

- To move from prediction to detection and between scales in exploration, new data, knowledge and technology is required
- Game changing innovations require collaboration across organisations and industries
- But the global minerals industry must improve how it collaborates to create - AMIRA International can facilitate this change but …….
- The AMIRA International *Exploration Under Cover Roadmap* is one example of how this is currently being achieved
- Many other research initiatives focusing on similar issues but with local flavors

WITH COLLABORATION

GREAT THINGS

RESULT

合作共贏

Con la Colaboración
Grandes Cosas Resultan

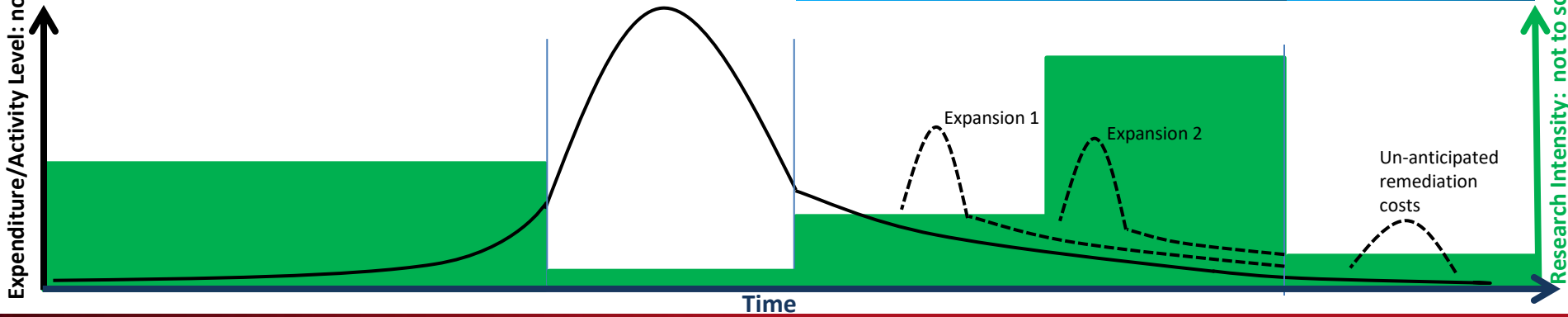
Thank you

Com cooperação,
há Grandes Resultam

Collaborer
C'est Aller Vers le Succès

The generalised minerals value chain

Exploration / Discovery		Development Design/Construction	Operations Mining	Operations Processing	Closure / Reclamation
					
Exploration by prospectors and companies leads to discoveries that could become mines	Discovery depends detailed field surveys, technical studies and finally drilling	Includes pre-feasibility, feasibility and engineering studies, raising capital and construction	Includes extraction, haulage, and stock piling	Includes milling & processing / metallurgy to produce concentrate or metal	Reclamation of sites to productive use begins during operation and continues after closure
1 - 10 years or more		1 - 5 years	2 - 100 years		decade to perpetuity



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Why collaborate?

- ✓ Scarce financial resources
- ✓ Poor or scarce infrastructure
- ✓ Reduced (shared) risk
- ✓ Synergies and strengths that can be leveraged
- ✓ Integrated cross-discipline approach
- ✓ Outcomes in directly applicable formats
- ✓ Scale of research

What needs to change in how we collaborate to gain value from innovation in exploration?

- Game changing innovations require collaboration across organisations and industries
- Many of the issues that companies, institutions and governments face are so big they are impossible to solve alone
- Teaming across organisations and across disciplines is essential, but challenging
- Cross-industry innovation projects:
  - Are characterised by uncertainty
  - Have complex, non-linear interdependencies
  - Have multiple and competing criteria
  - Have unclear and conflicting lines of authority

Source: HBR Webinar 'Teams that Build the Future' featuring Amy C. Edmondson. Sept 29, 2016

Why facilitators like AMIRA International are important

- ✓ Developing the connections and linkages between industry and research institutions is difficult
- ✓ A proven way of developing these linkages is through trusted intermediaries whose purpose to facilitate these linkages
- ✓ Such organisations, particularly those set up by business, are uniquely placed to facilitate industry-university collaboration
- ✓ AMIRA International was created by the mining industry in 1959 for this express purpose
- ✓ Since inception AMIRA has developed and managed almost 700 projects in which the mining industry has invested over AU$580 Million (in current dollar terms)

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