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Ways to integrate inversion in your interpretation

ASEG WORKSHOP – SEPTEMBER 2014

Tim Chalke, Mira Geoscience, Brisbane
John McGaughey, Mira Geoscience, Montreal
Glenn Pears, Mira Geoscience, Brisbane
Peter Fullagar, Fullagar Geophysics, Vancouver

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Outline

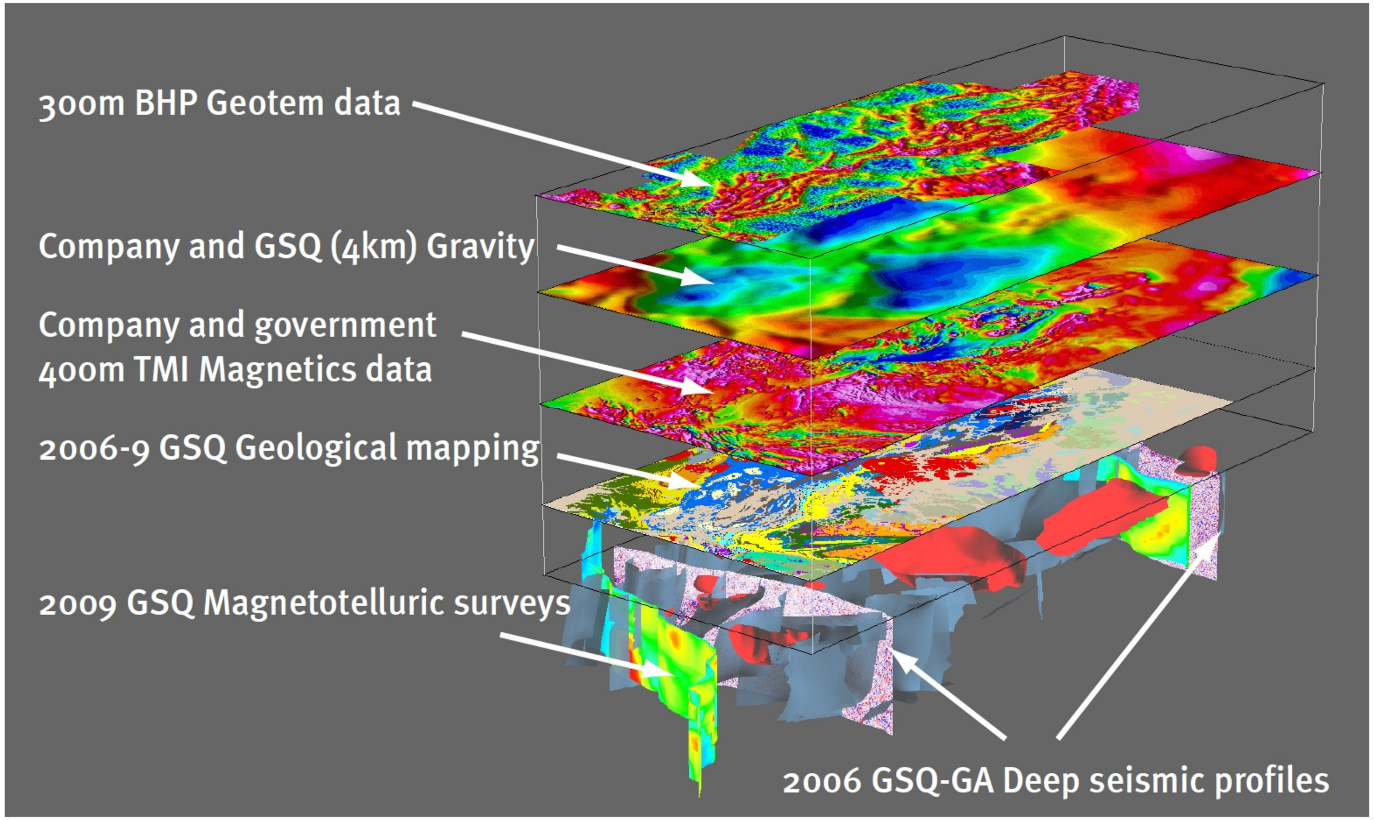
Focusing on Mineral Exploration – examine how we can use geophysical data as part of the interpretation involved in exploring using ore system footprints.

Methods to utilise geophysics in this ‘model’ space rather than ‘data’ space.

- the modern mineral exploration context
- role of geophysical data
- mechanics of interpreting ore system footprint
- case studies

The modern exploration context

- under weathering or cover, at depth, complex brownfields settings
- ore system footprint recognition rather than anomaly recognition
- multi-disciplinary interpretation in model space rather than data space



courtesy Geological Survey of Queensland

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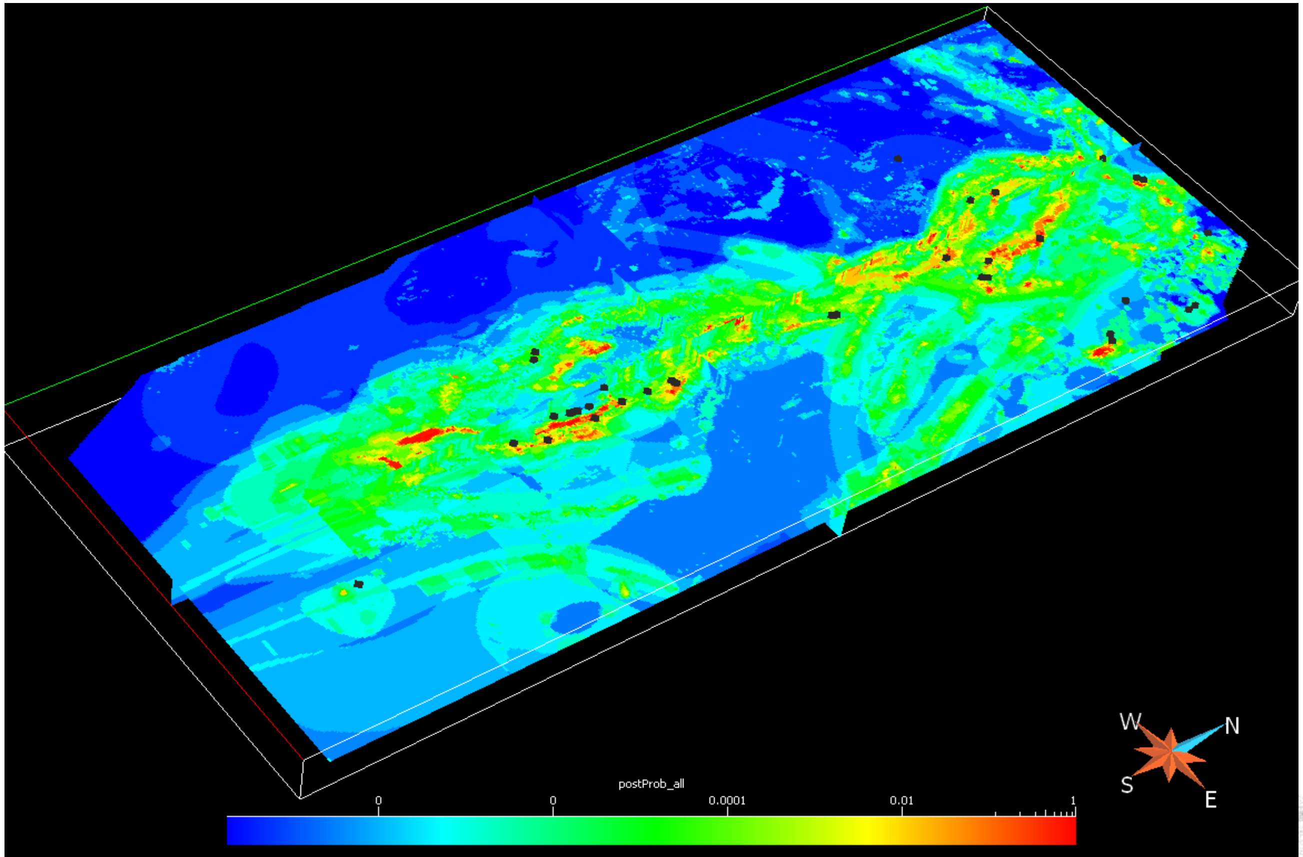
The modern exploration context

- the Eureka moment might be in model space, not data space
  - Image depicts the Mineral Potential Index (IOCG); NOT an inverted rock property



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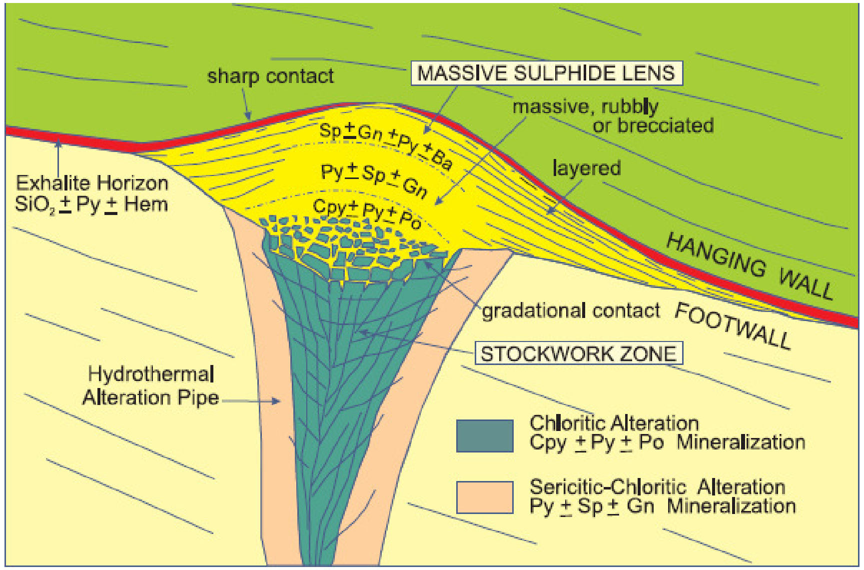
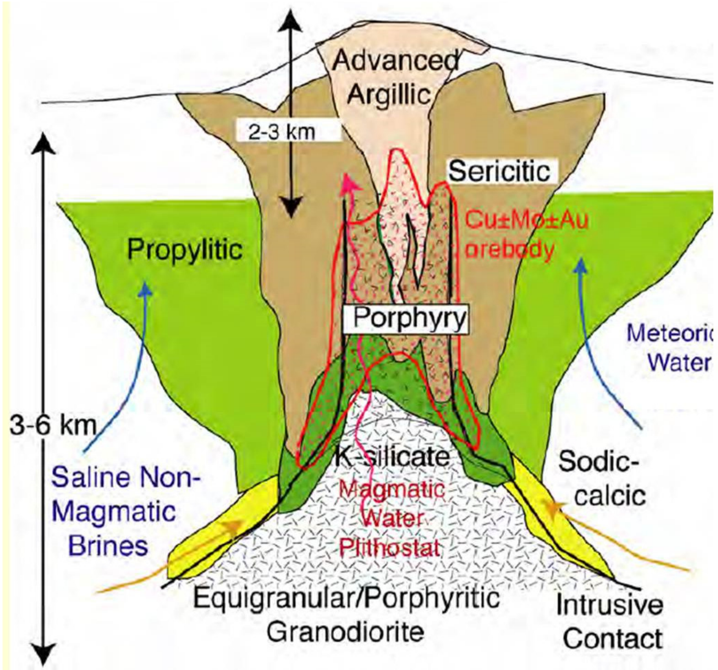
The modern exploration context

- exploration models must capture many target footprint criteria:
  - proximal and distal characteristics, formation, lithology, variable alteration complexes, geometrical and topological relationships, physical properties





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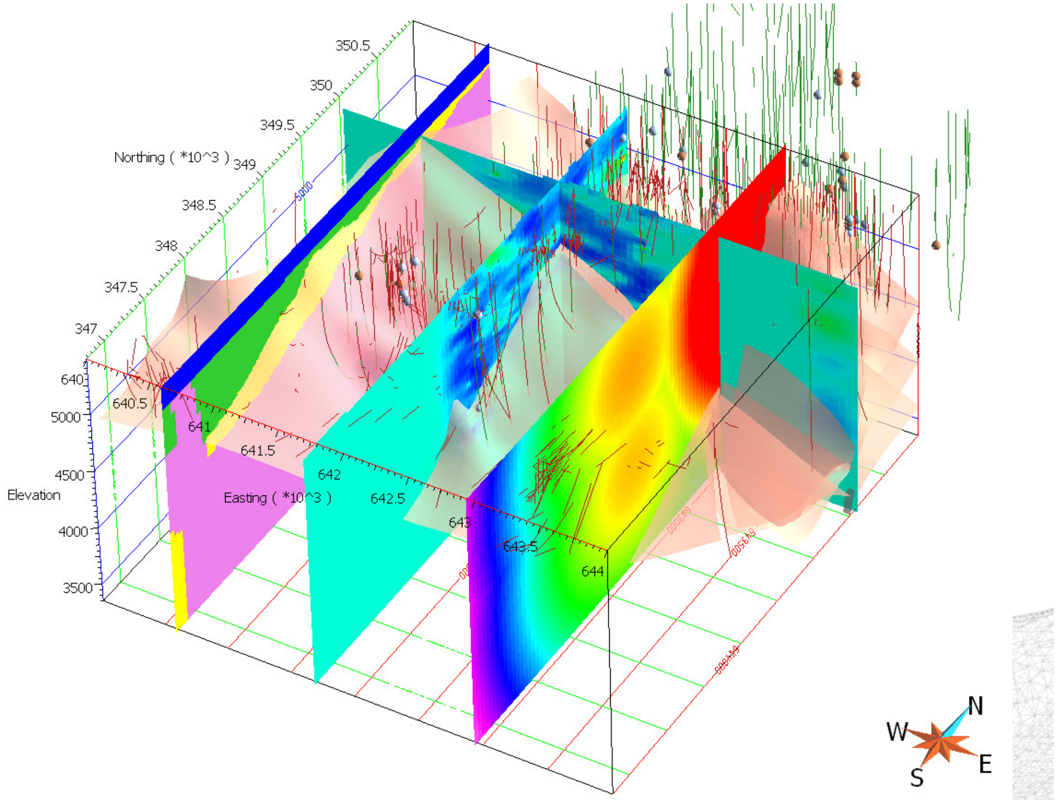
The modern exploration context

- Common Earth Model: a single, shared, consistent earth model
- a working hypothesis that can be queried, tested, modified
- ore system footprint recognition in multi-disciplinary data

- typical components:
  - lithology
  - alteration
  - structure
  - geochemistry
  - mineralisation
  - physical properties
  - spatial relationships
  - topological relationships



GlencoreXstrata, Ribago VMS district

Outline

- the modern mineral exploration context
- role of geophysical data
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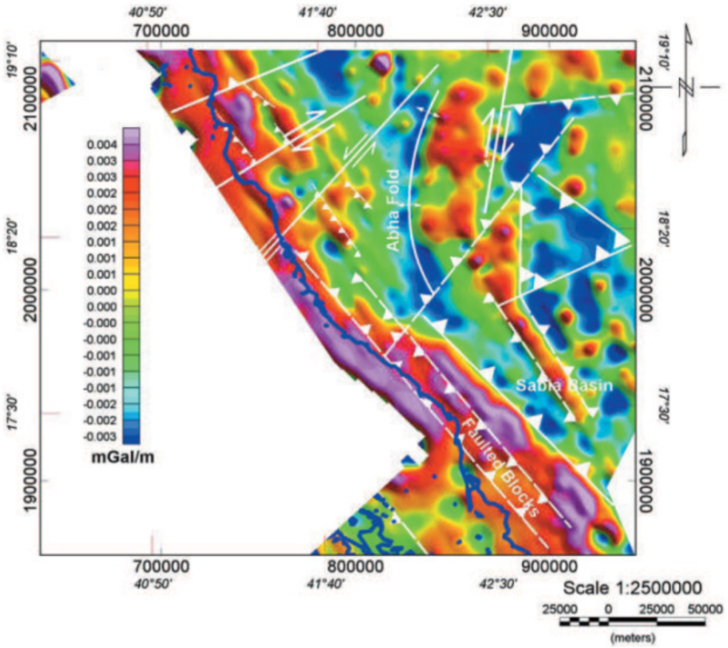
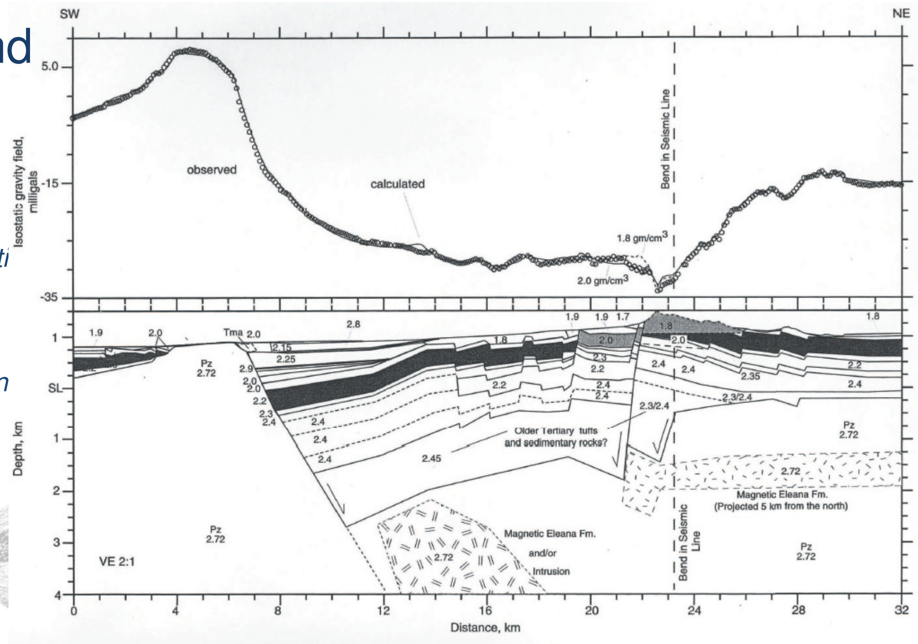
Role of geophysical data

- how can it contribute to the 3D multi-disciplinary model?
- potential field data can say a lot about:
  - geometry of structural domain boundaries
  - geometry of formational, lithological, alteration domain boundaries
  - gross mineralogical variation within domain boundaries
  - ... typically in that order of sensitivity, and always under interpretational guidance





Hinze, W., Von Frese, R., and Saad, A. (2013). *Gravity and Magnetic Explorati Principles, Practices and Applications*, Cambridge University Press , after:

Elawadi, E., Mogren, S., Ibrahim, E., Batayneh, A., and Al-Bassam, A. (2012). *Utilizing potential field data to support determination of groundwater aquifers in the southern Red Sea coast, Saudia Arabia*. Journal of Geophysics and Engineeering, v9.

Brocher, T.M., Hunter, W.C., and Langenheim, V.E. (1998). *Implications of seismic reflection and potential field geophysical data on the structural framework of the Yucca Mountain-Crater Flat region, Nevada*. Geological Society of America Bulletin, v110.

Example – Ore System footprint of Cu Au Porphyry

Criteria	Description	Data required	Model representation
direct anomalous Cu Au Mo	anomalous Cu (>124ppm), Au (>5ppb), Mo; (negative anomalies of Mn)	Soils, rock chips, MMI	Polygons interpreted of metal enrichment and metal depletion.
Heat and metal source: volume, geometry and proximity	The precursor intrusion. The geometry and structural intersections facilitate local transport and trap of the porphyry from the intrusion.	**magnetics**, **gravity, MT**, district geology maps	Wireframe of the intrusion
Porphyry pipe	Felsic intrusive directly associated with Cu Au Mo mineralisation	Mapping, rock chip and soil samples, **DC/IP, gravity**	Outcrop polygons, wireframe, chargeable volumes. Low density volume modelled from gravity inversion
chargeability of sulphides (mineralisation and pyrite halo)	Disseminated sulphides directly associated with porphyry mineralisation or porphyry alteration	**DCIP survey**	DC/IP inversion
structures	Structures are utilised as a pathway for the porphyry intrusion, local trapping site for Cu and/or Au veins	**magnetics, gravity, DCIP, MT**, district geology map, project geology map, Aster satellite data,	Fault traces and fault surfaces
Potassic alteration	Alteration domain around a porphyry system	soil geochem, ASTER, **TMI and RTP 1VD, magnetic inversions**	Polygons from geochemical signatures. 3D domains/ wireframe from magnetic inversion
Phyllic (AKA sericitic) alteration	Alteration domain around a porphyry system	soil geochem, **mag inversion and 1VD**, surface mapping-quartz, Aster	Polygons.
Propylitic alteration	Alteration domain around a porphyry system, partly magnetite destructive	soil geochem, **mag inversion and 1VD**, surface mapping-quartz,	Polygons from geochemical signatures. Possibly magnetic 'lows' as 3D wireframes / domains
Argillic alteration	Alteration domain around a porphyry system	Soil geochem, Mapping, argillic or 'clay' polygons.	Polygons from geochemical signature,

Role of geophysical data

- “Direct detection”, or components of an *ore system footprint* model
  - EM
  - DCIP
  - Seismic
  - MT
  - …..

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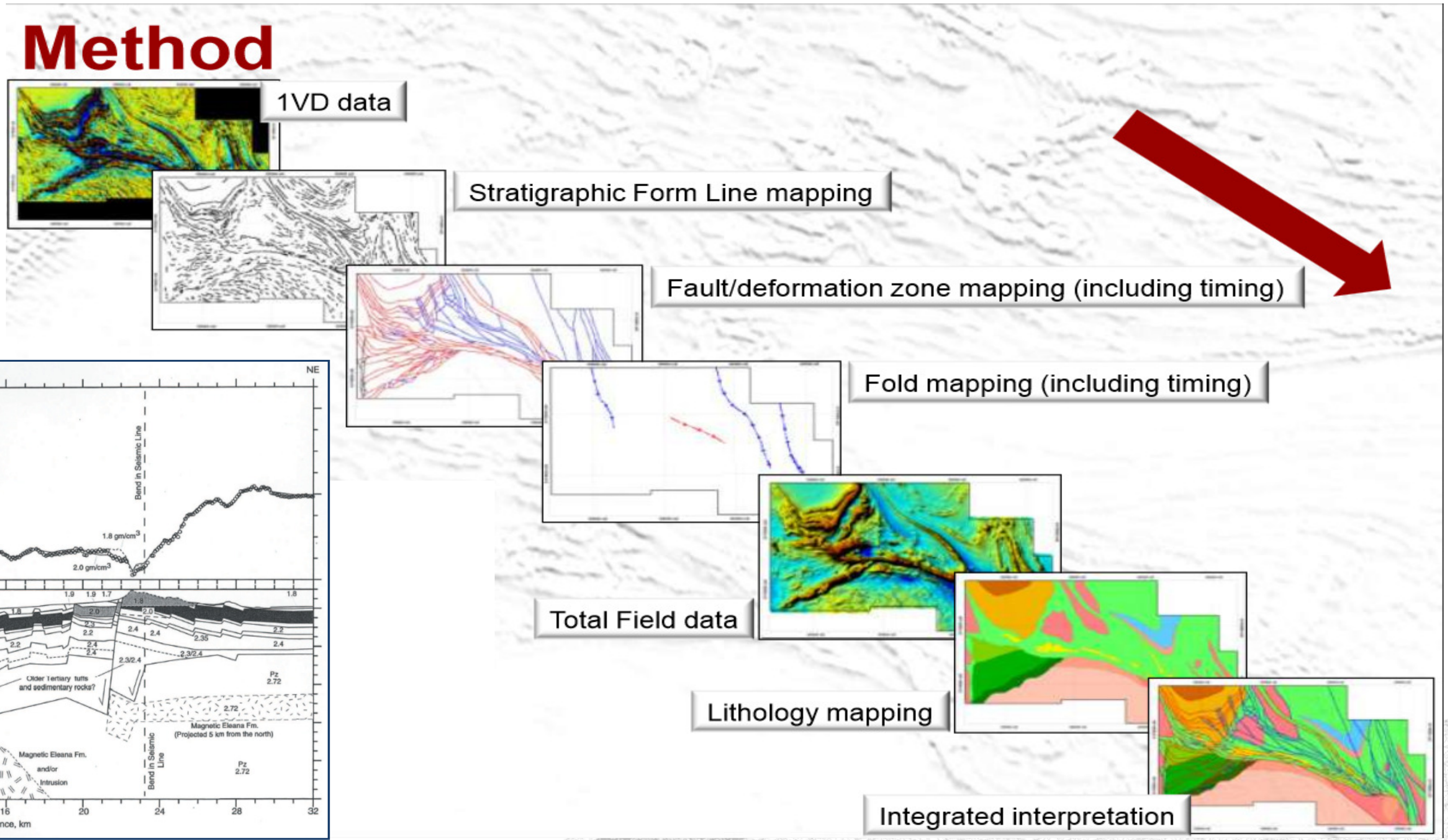
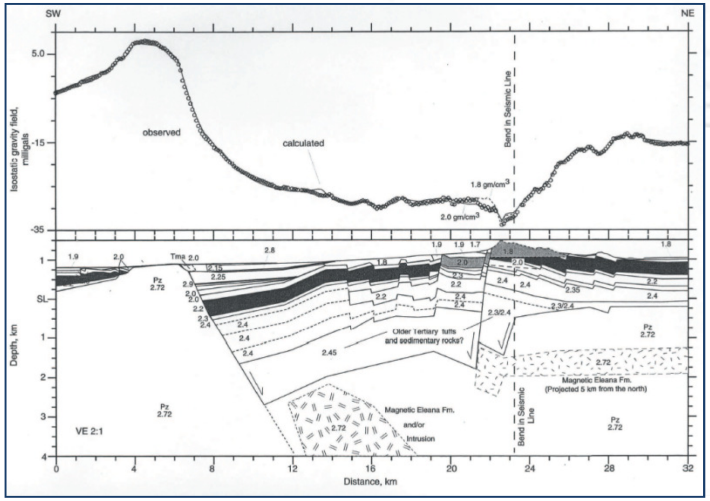
mechanics of geological interpretation

- geological models are comprised of structural and litho-stratigraphic surfaces, which divide the earth into rock type domains





Siddorn, J.P., (2010). *The geological interpretation of aeromagnetic data: A geologist's perspective.* KEGS Symposium, Toronto.

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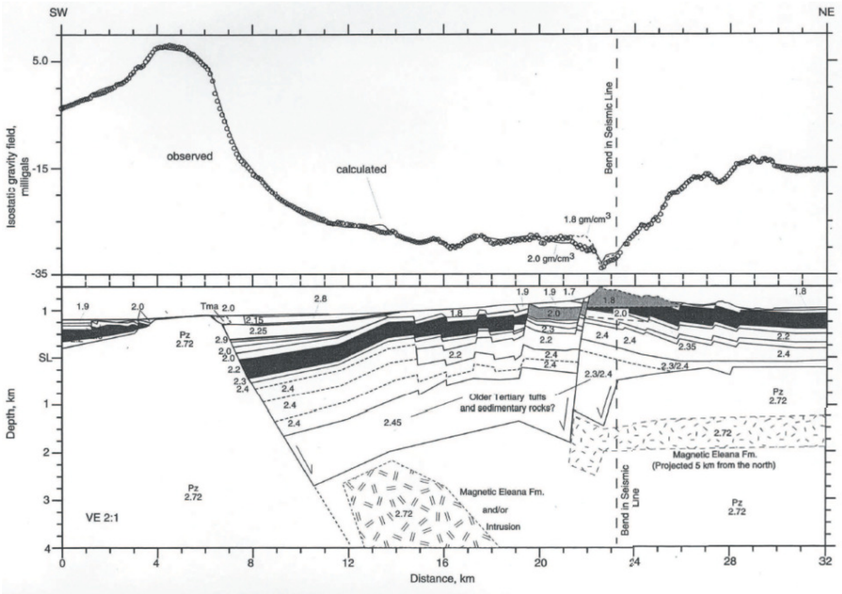
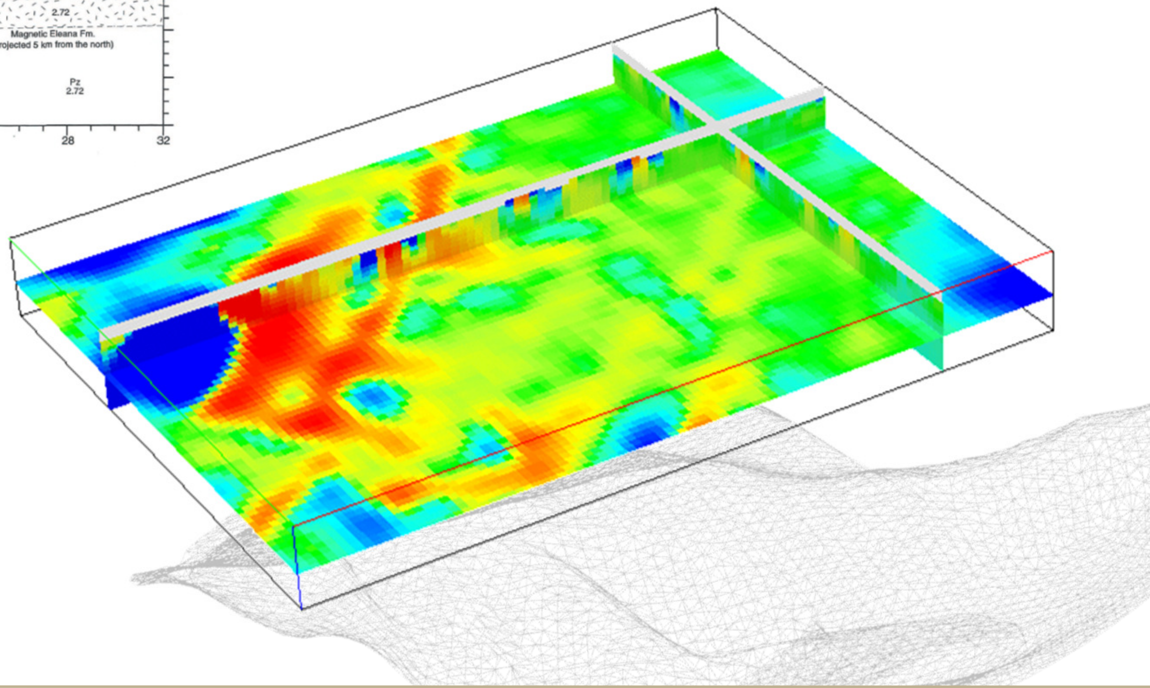
Unconstrained Inversion: one step forward, two steps back?





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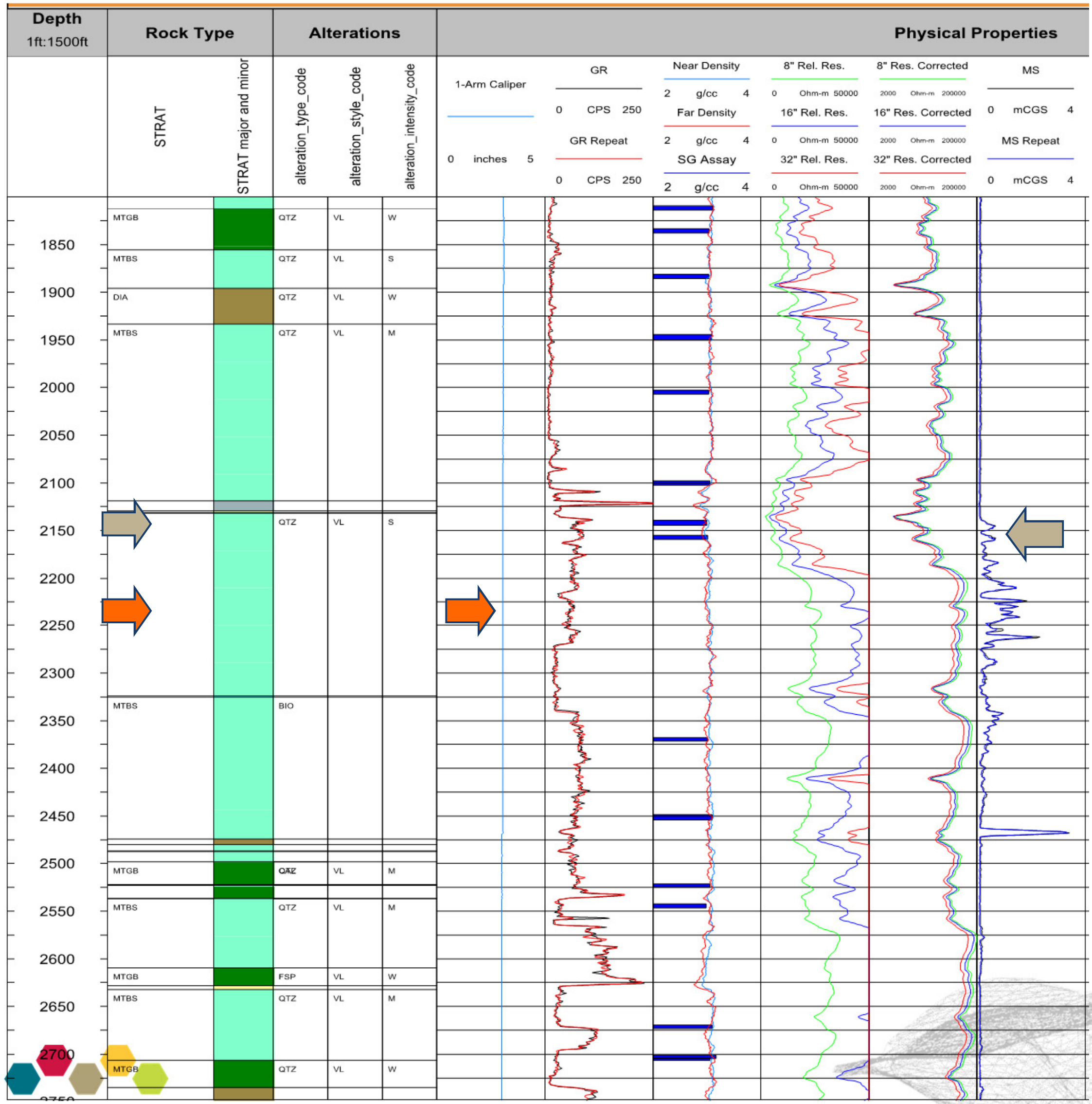
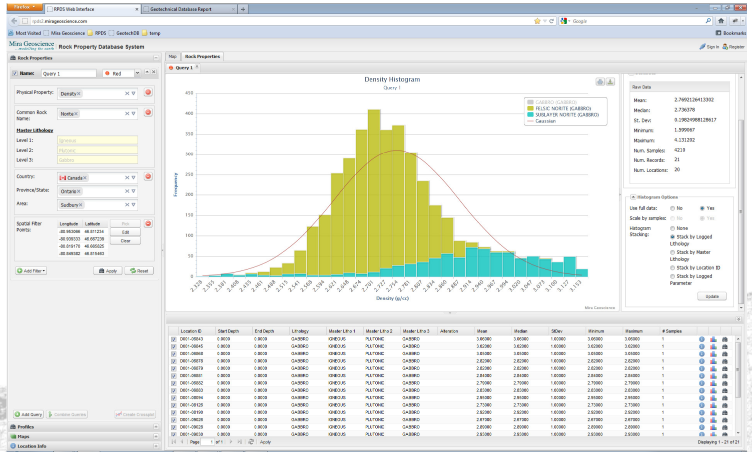
Interpreting geological meaning of rock properties





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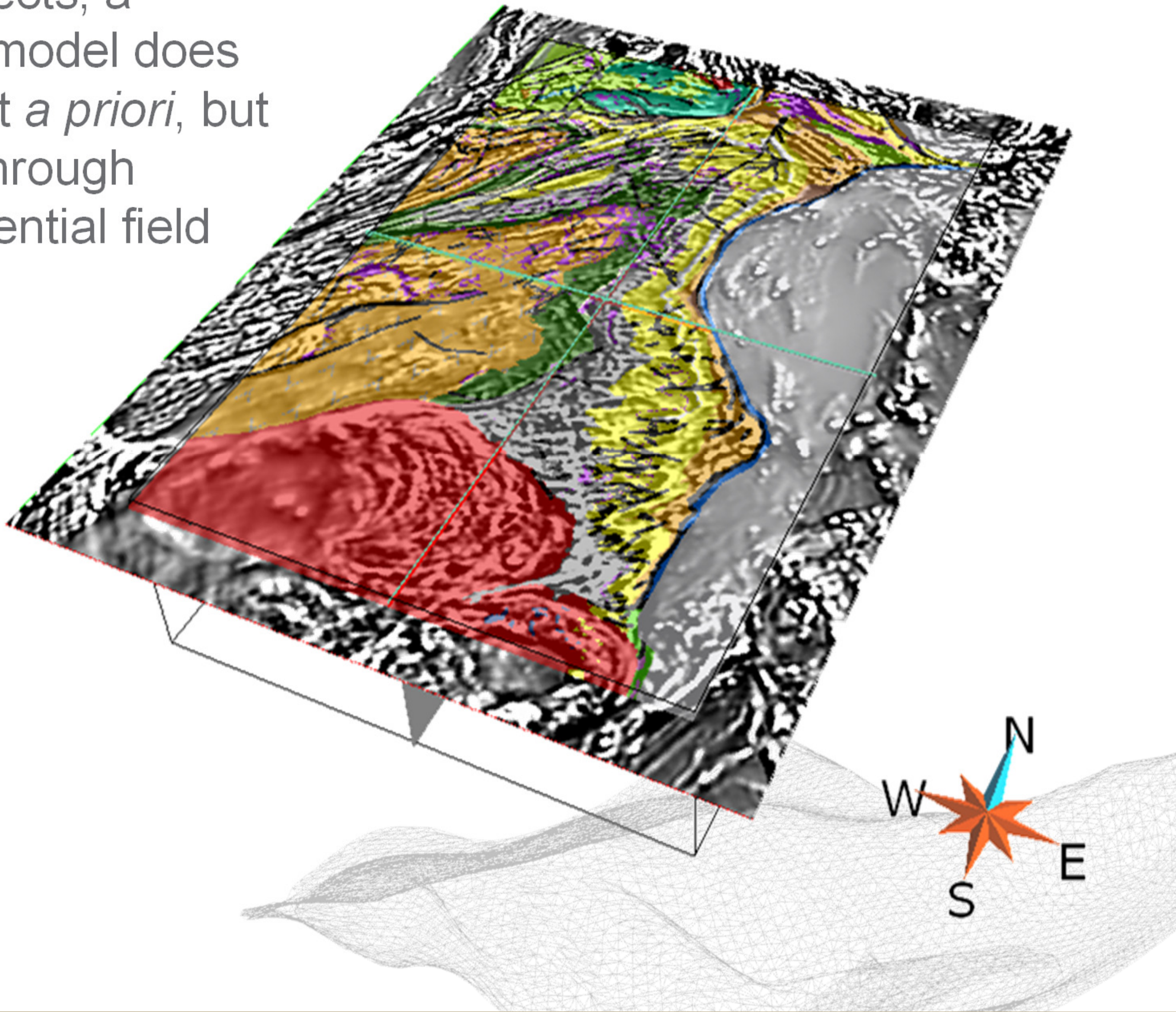
Victoria Project
KGHM International

courtesy
DGI Geoscience

Creating the starting model

- for less mature projects, a geologically based model does not necessarily exist *a priori*, but can be developed through interpretation of potential field and other data



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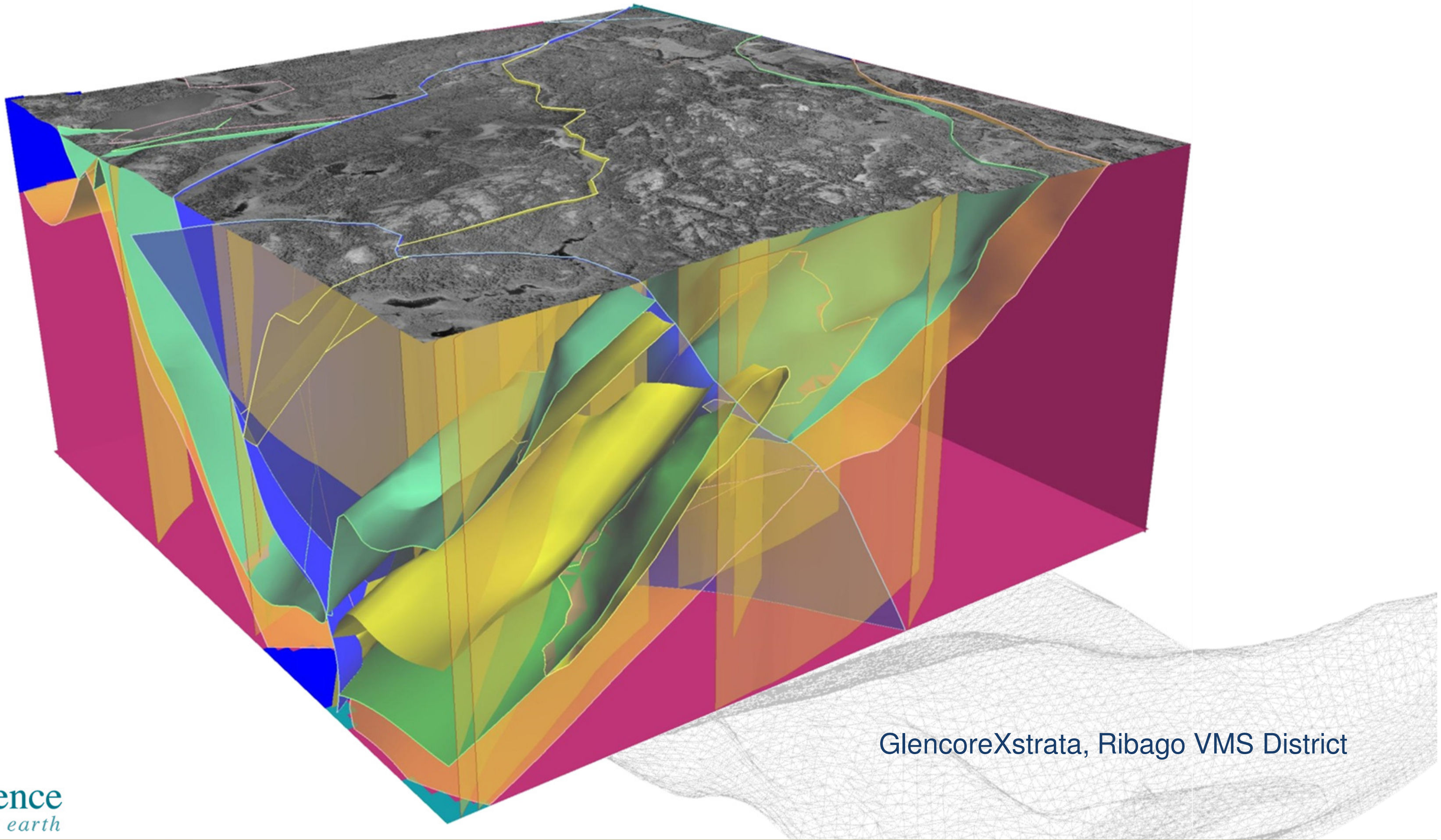
Inversion applied to geological models

- geological models are comprised of structural and litho-stratigraphic surfaces, which divide the earth into rock type domains



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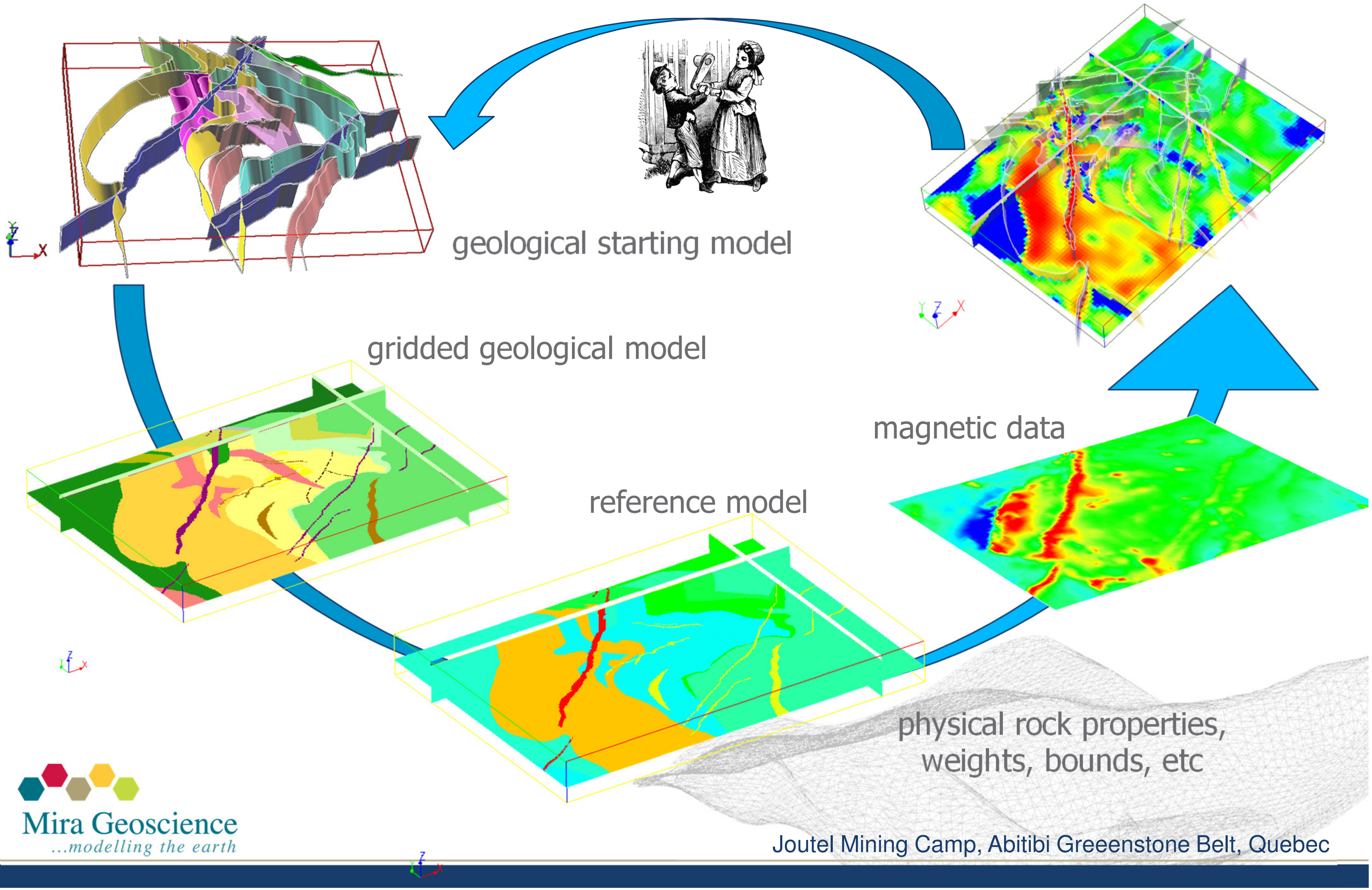
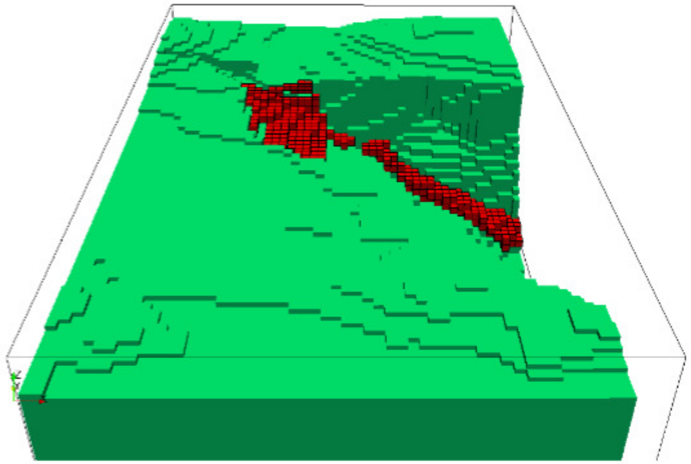
Geophysical inversion in a geological context

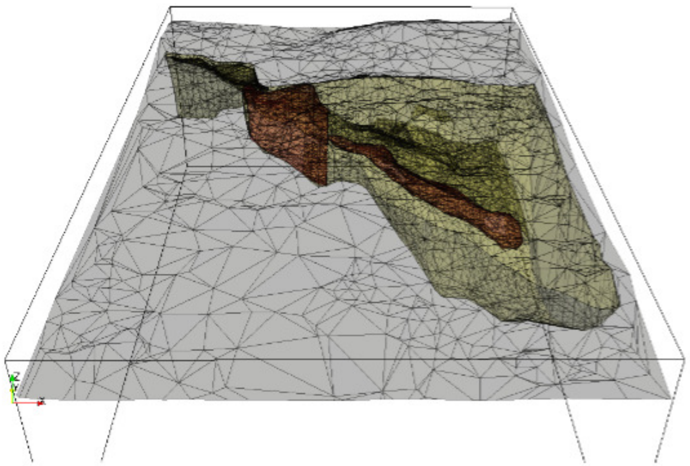


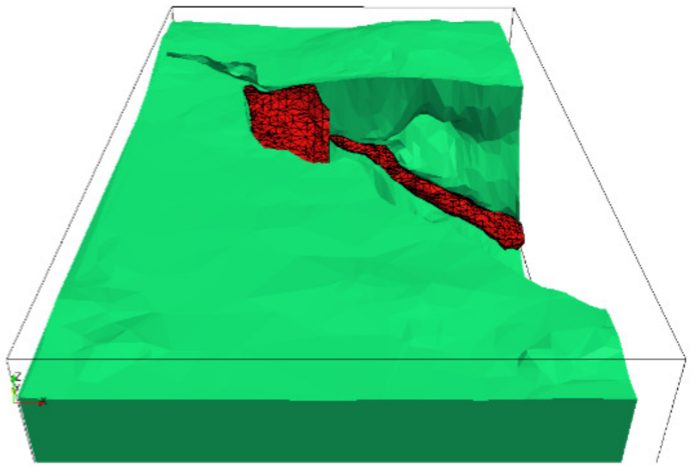
Joutel Mining Camp, Abitibi Greeenstone Belt, Quebec

Inversion applied to geological models

"geological and geophysical models can share the same modelling mesh; they can be the same model"







Voisey's Bay, Labrador

Lelièvre, P., Carter-McAuslan, A., Tycholliz, C., Farquharson, C., and Hurich, C. (2012). *Unstructured grid modelling to create 3D earth models that unify geological and geophysical information.* GAC-MAC Annual Meeting, St. John's.

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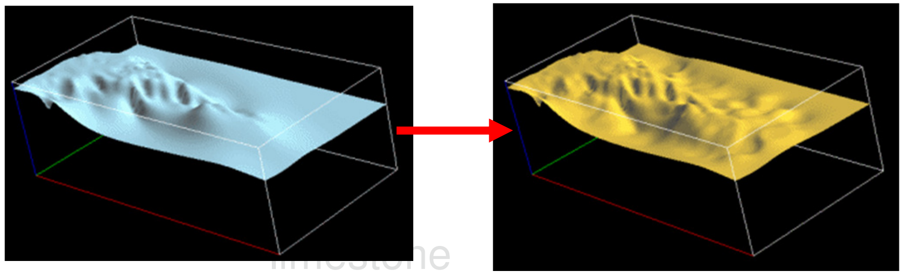
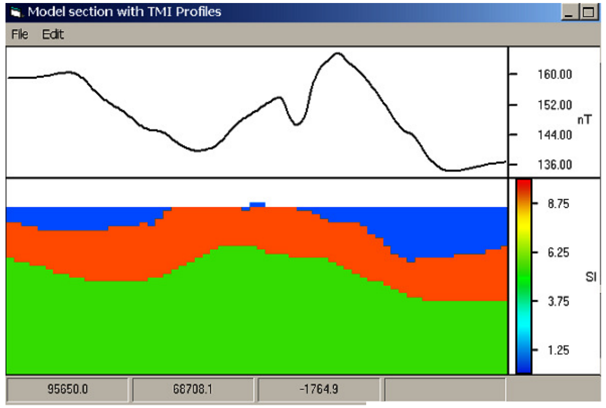
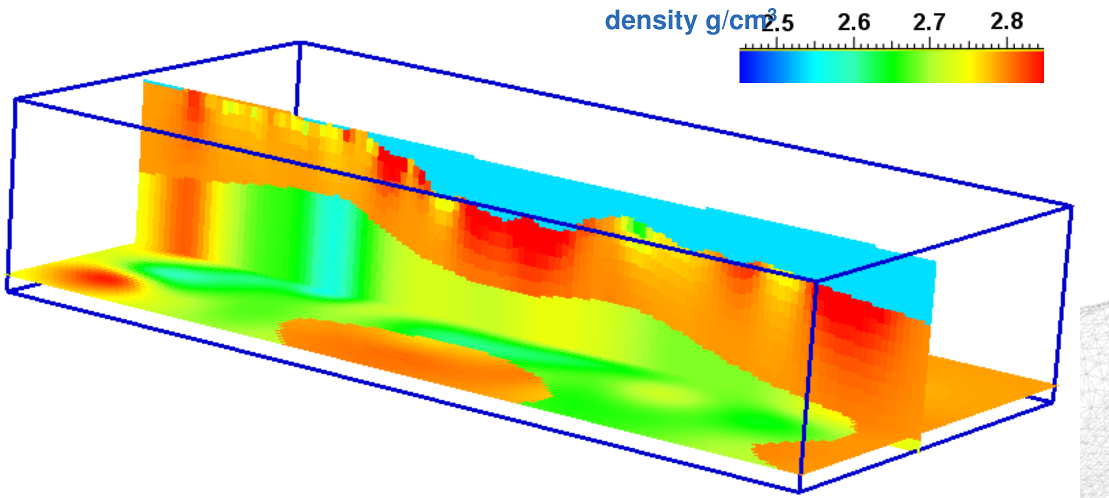
Inversion applied to geological models





VPmg framework for
geological parameterization

Pillara, Western Autralia



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Fullagar, P.K., Pears, G.A., Hutton, D., and Thompson, A. (2004). *3D Gravity and Aeromagnetic Inversion for MVT Lead-Zinc Exploration at Pillara, Western Australia*. Exploration Geophysics, 35, 142-146.

Outline

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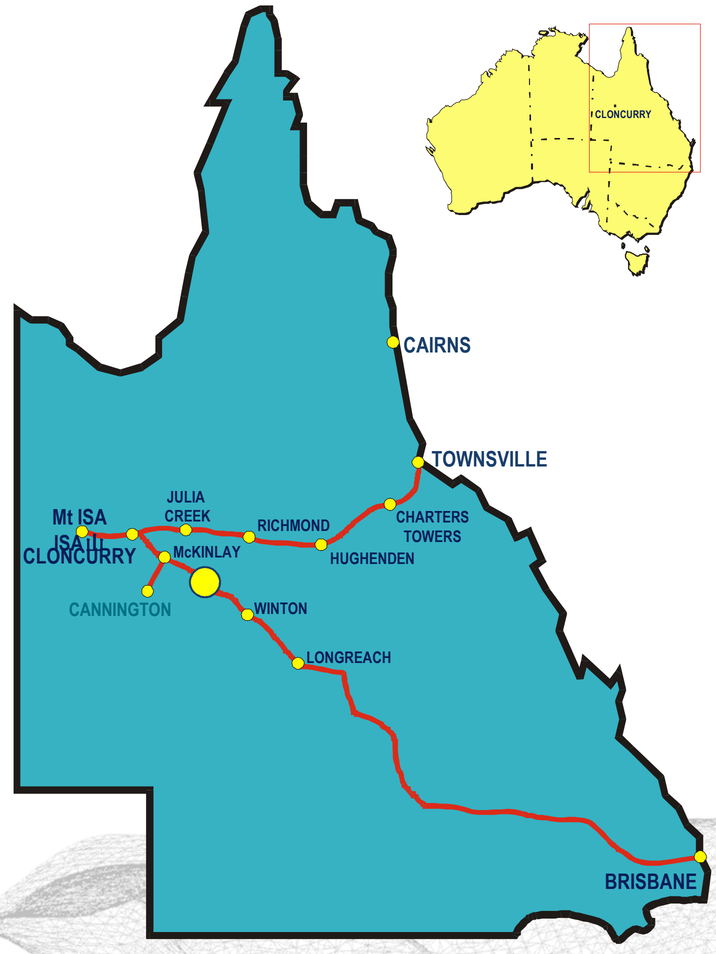
Mount Dore region 3D Mineral Potential Study

- 175km x 70km
- detailed 3D prospectivity analysis



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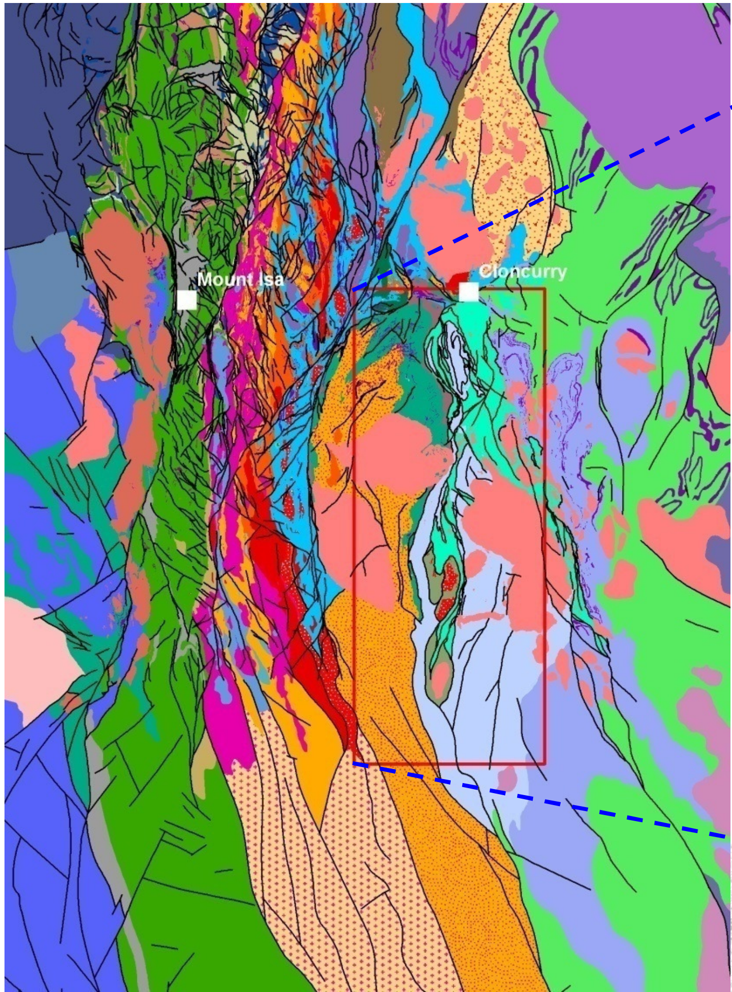
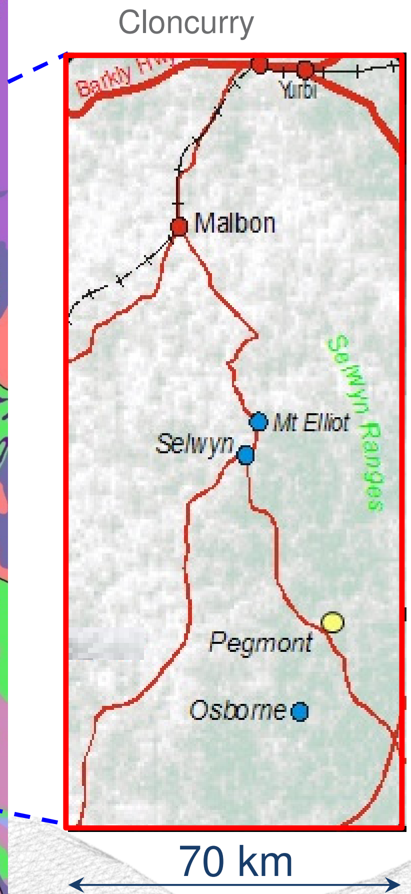
Methodology

- Geological modelling: GOCAD/SKUA
- Geophysical inversion: MAG3D, GRAV3D, VPmg, EmaxAIR
- Pseudo-lithology prediction: LogTrans
- Quantitative exploration targeting: 3D weights of evidence

The Mount Dore Project Region

- Several significant IOGC deposits
- rich company and public domain data
- high discovery potential





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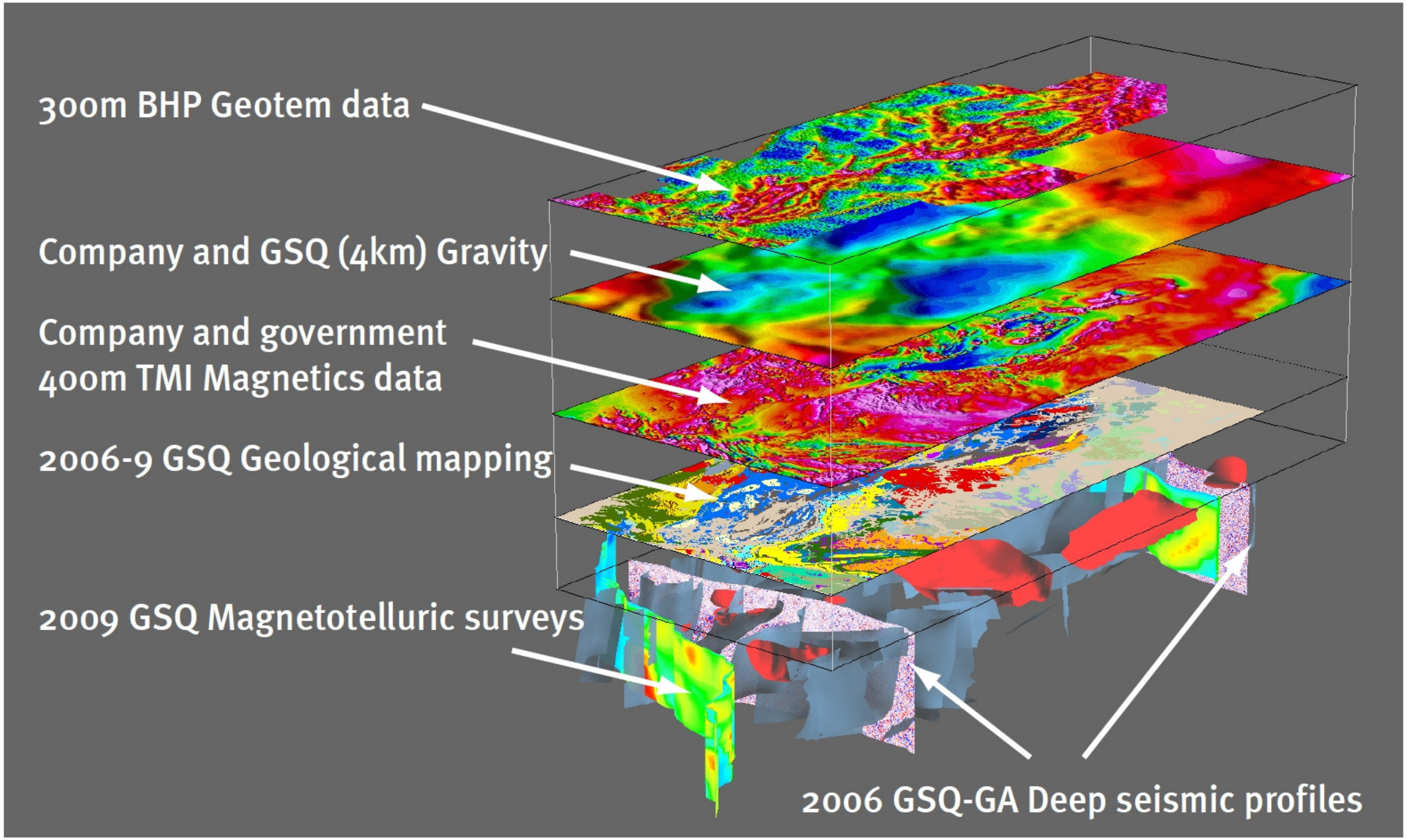
Mount Dore Project – geophysical datasets



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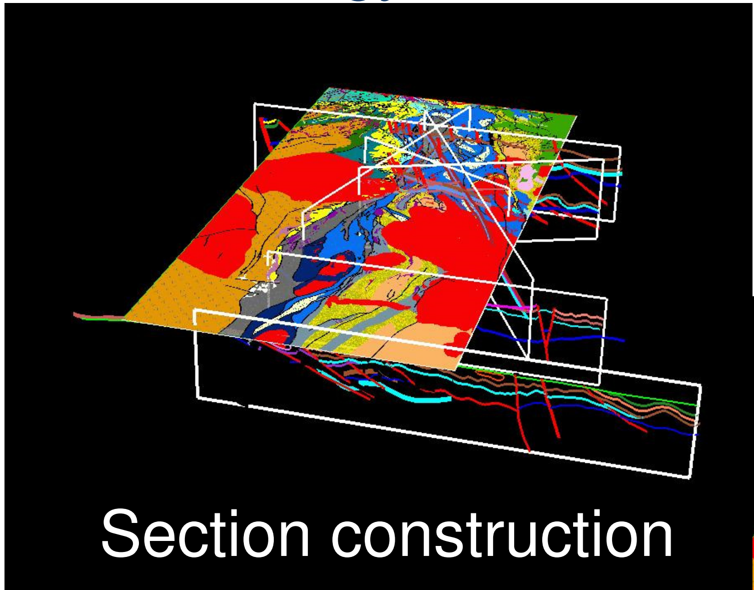
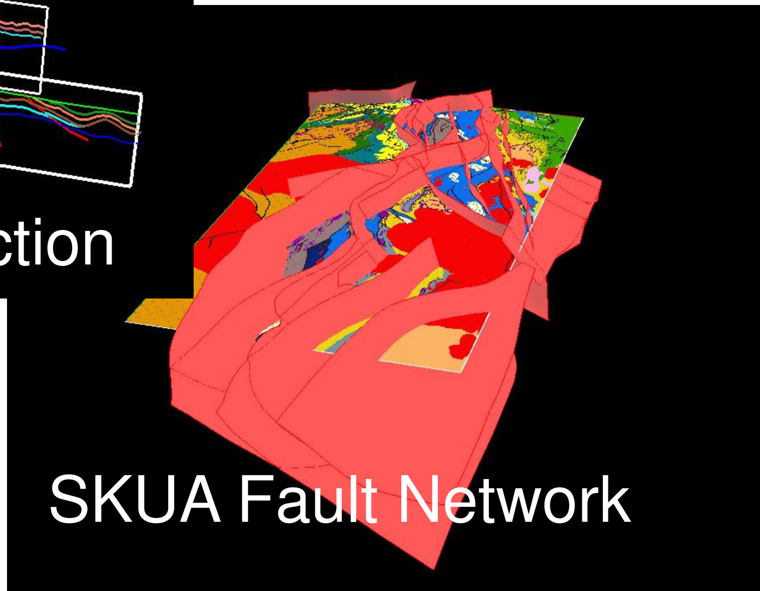
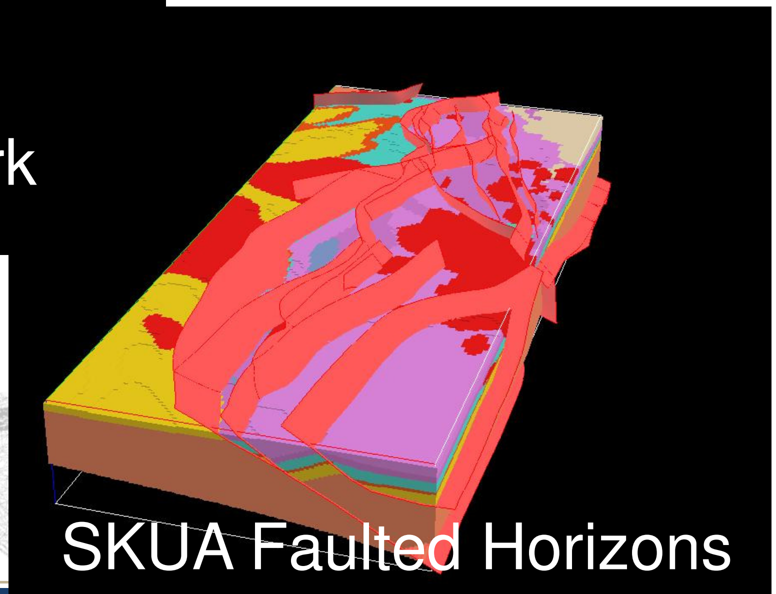
Geology model construction





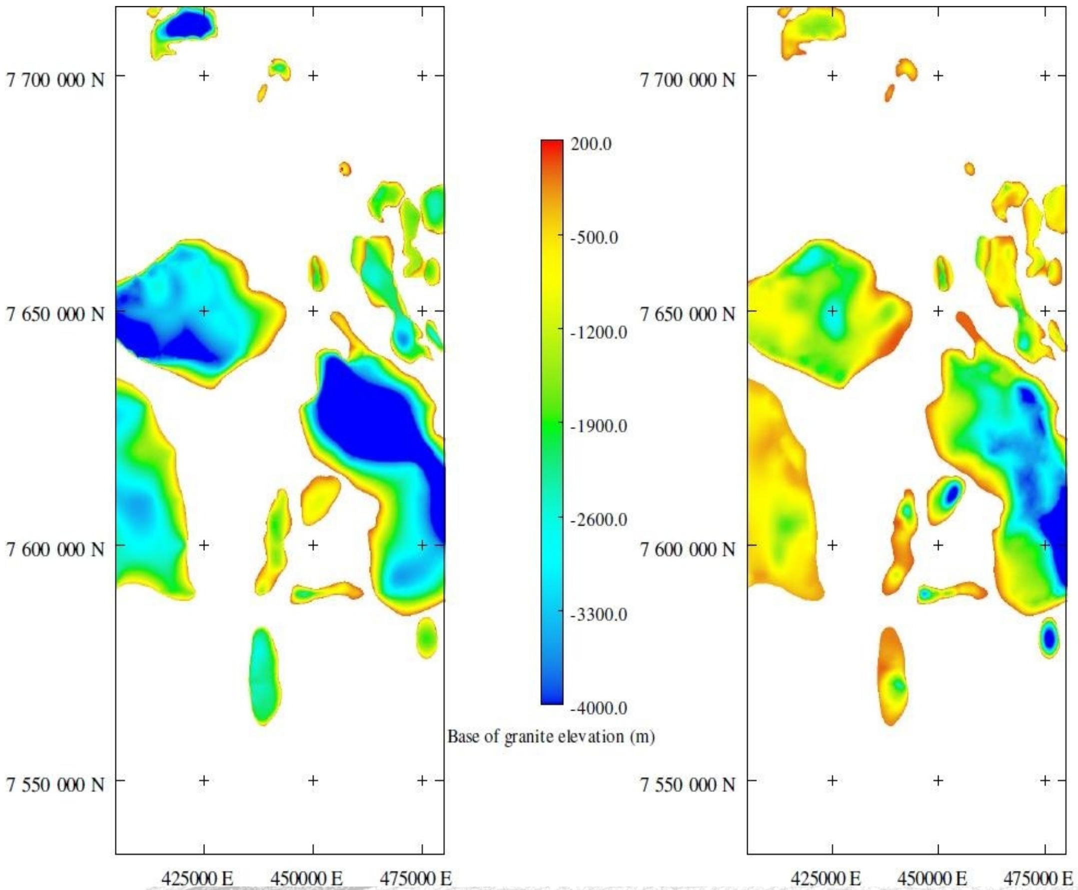


Geometry inversion as geological modelling tool

•Granite body starting depths estimated on cross sections and modelled in 3D

•Gravity inversion used to change the depth of the granites.

• **EQUALS:** Geophysics doing geological modelling



Base of granite elevation before (left) and after inversion (right).

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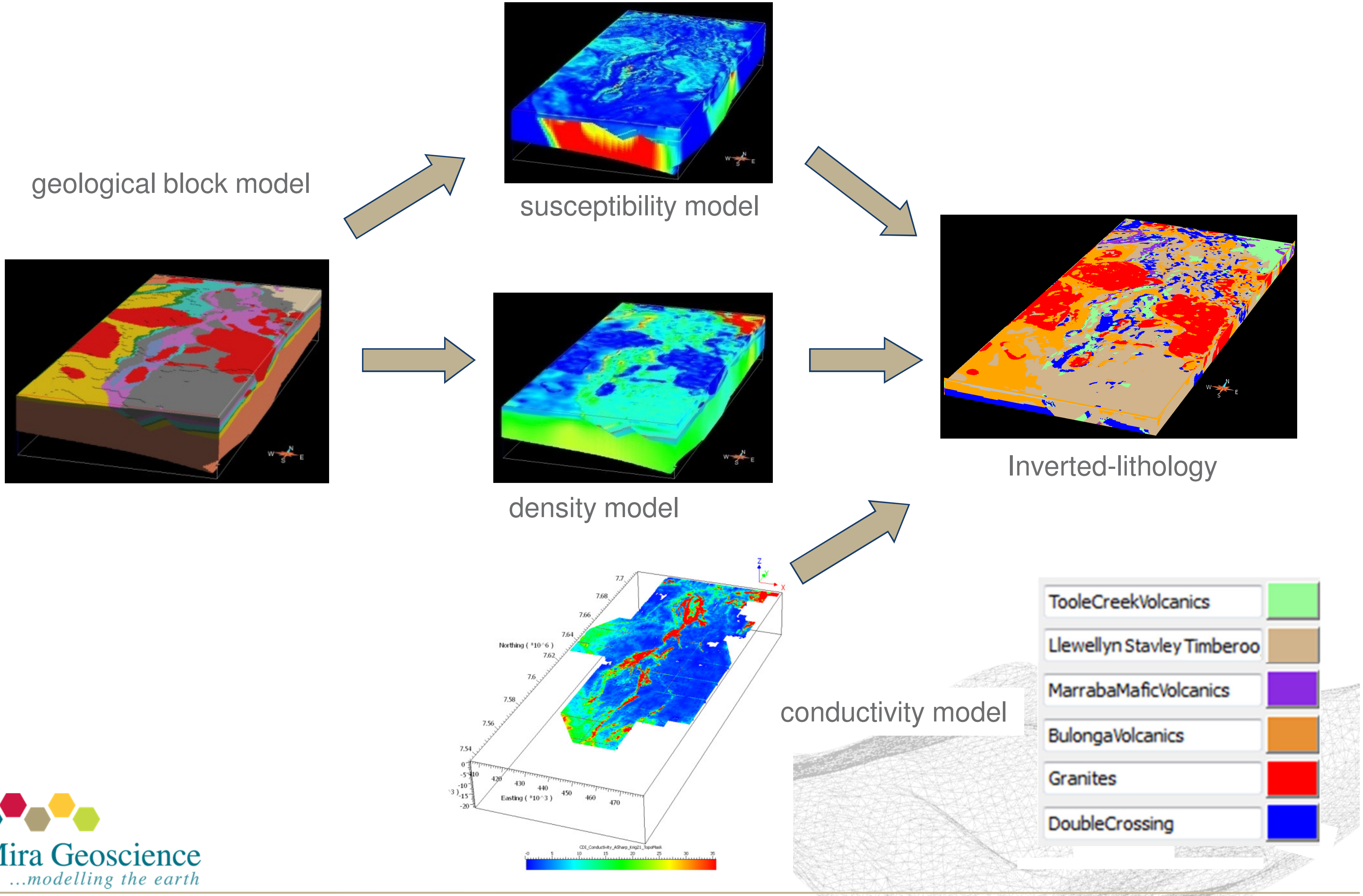
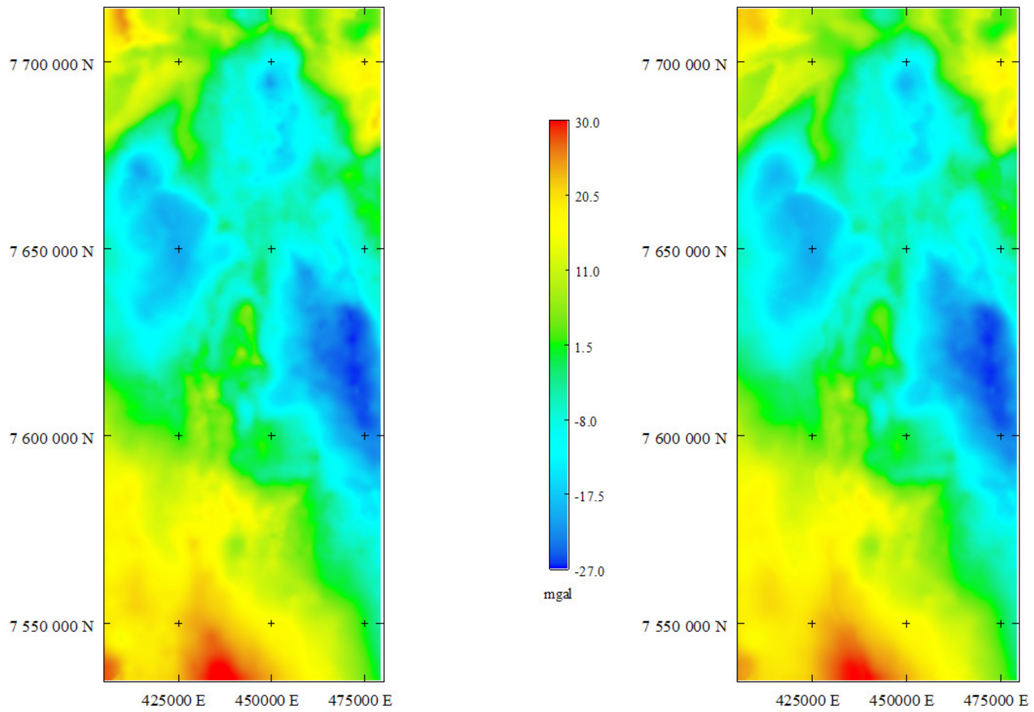
Mount Dore Project – inversion and pseudo-lithology workflow

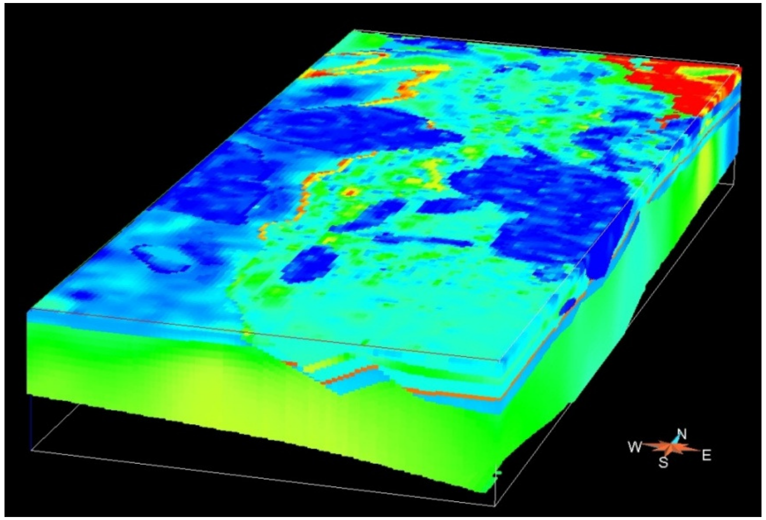


Regional gravity inversion (900m cells)

- Initial homogenous unit gravity inversion
- Heterogenous unit inversion: cells 500m vertical, increasing with depth

Observed Calculated





3D regional density model

900m X 900m cells

RMS misfit = 0.4mgal

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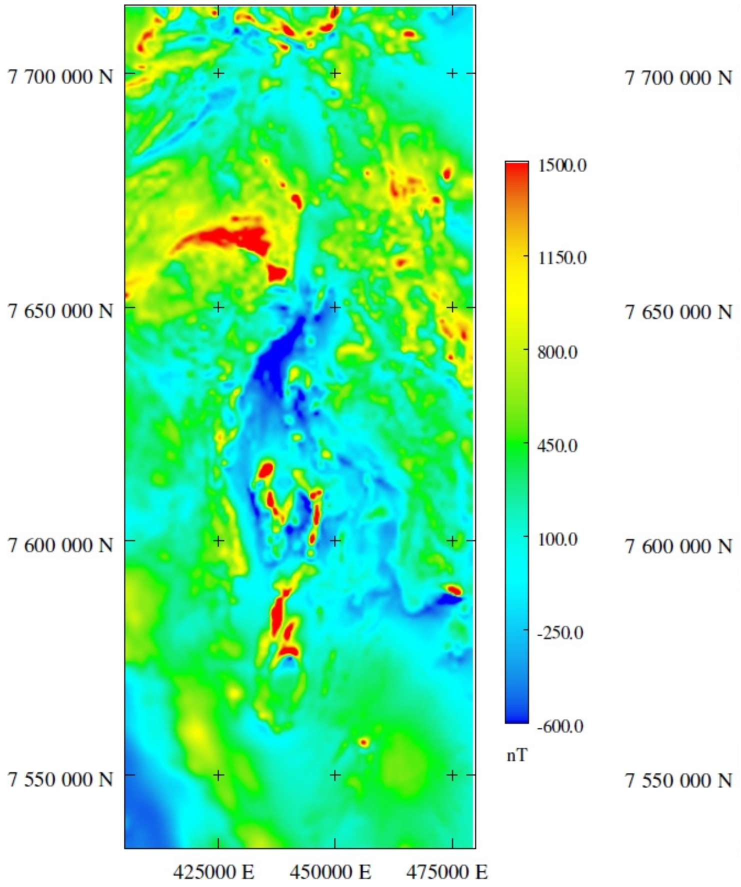
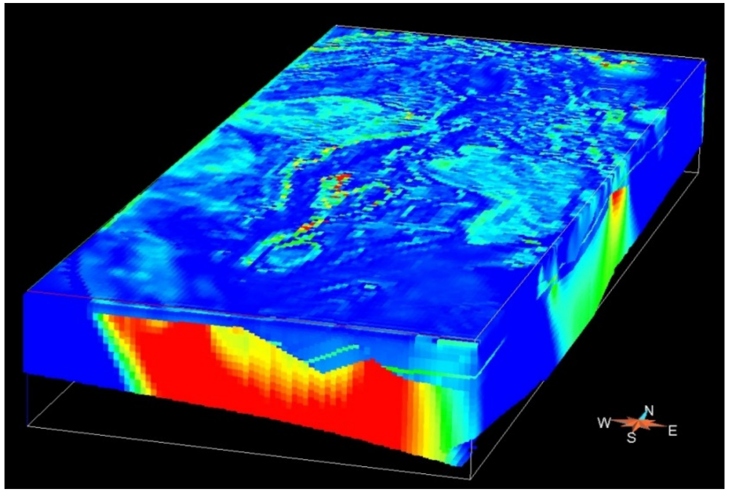
Heterogeneous unit magnetic inversion

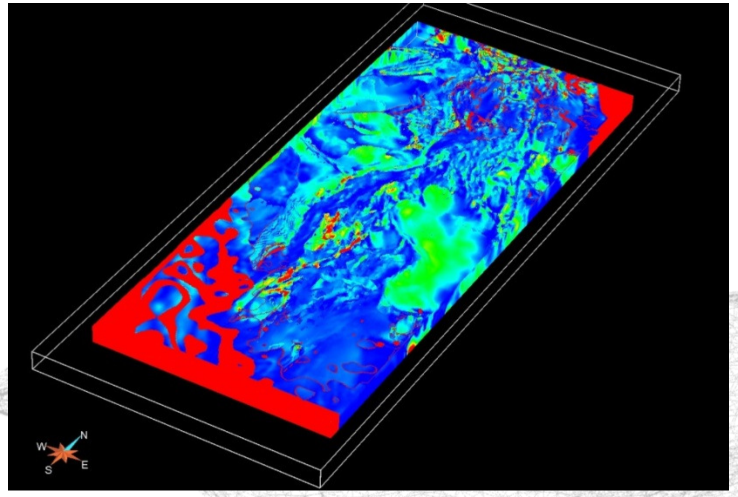
observed TMI



900m cell susceptibility model (VPmg)

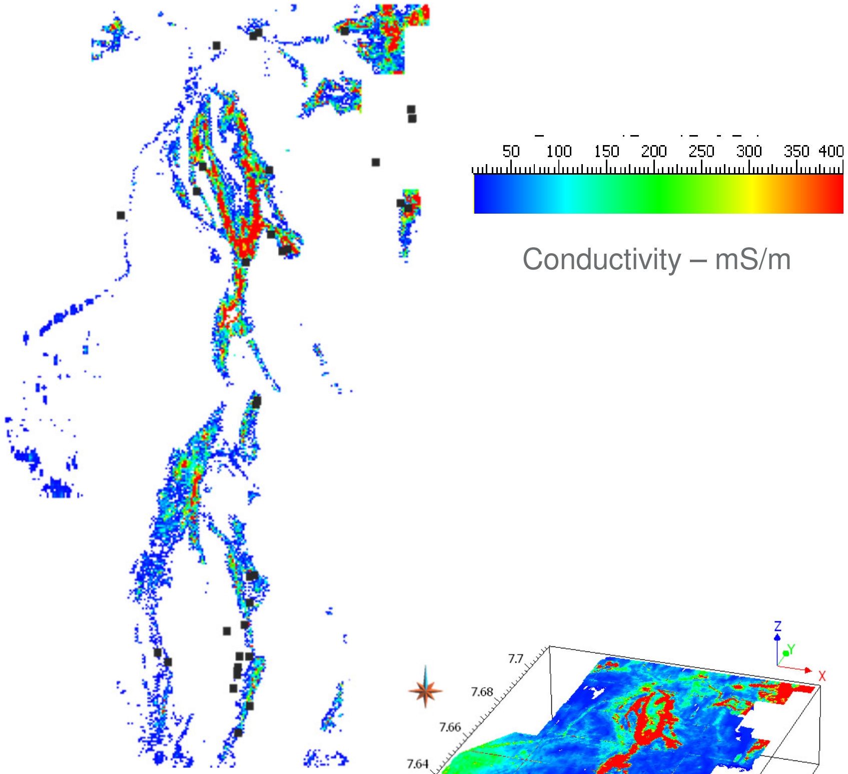


300m cell susceptibility model (MAG3D)



A detailed look at the AEM at Mt Dore

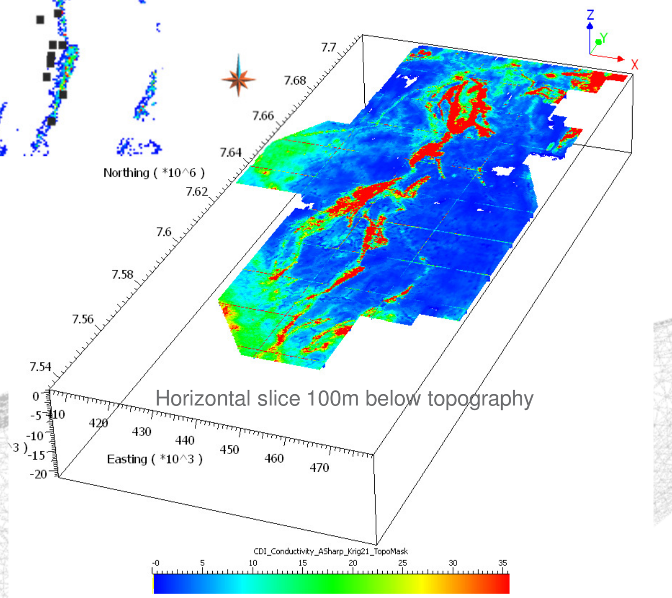
- 1998 Geotem data
- CDI (image to right) shows strong coupling between early to late time channels with shale units
- Not a definitive test for identifying massive sulphides
- Unlikely to create 'direct detection' drill targets



Processing:

- Conductivity-depth sections produced with EmaxAIR

- CDI sections interpolated into 3D grid

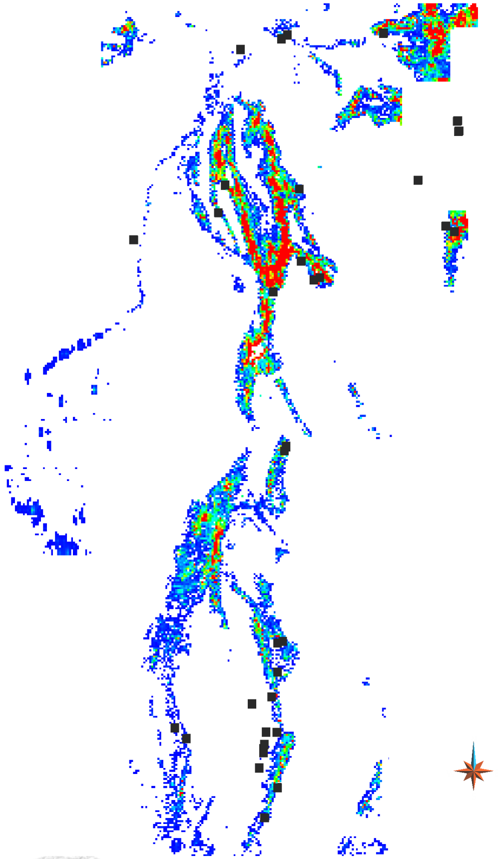


How useful was AEM for quantitative targeting

- Useful for improving the geology model
- Useful for assigning ‘inverted lithology’ units

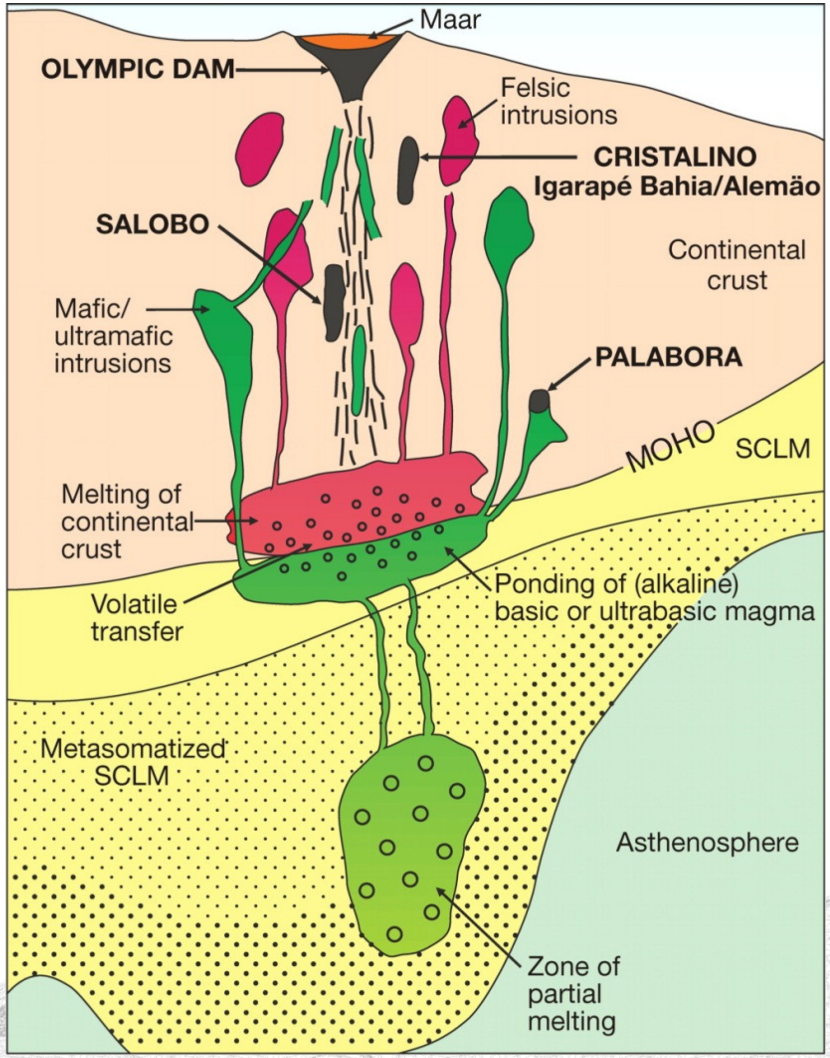
- AEM has the highest statistical correlation with known IOCG after ‘surface geochemistry’ samples over sub-cropping deposits

- BUT HOW ?– we saw that AEM was largely responding to geology – not identifying massive sulphides directly



Exploration criteria – regional and local scales

- Anomalous surface geochemistry
- Crustal plumbing system
- Close to Mafic Intrusives
- Plumbing system intersecting intrusives
- Dilational zones on the Fault Network
- Geological contacts between shale and other rock types
- Surface Uranium anomalism



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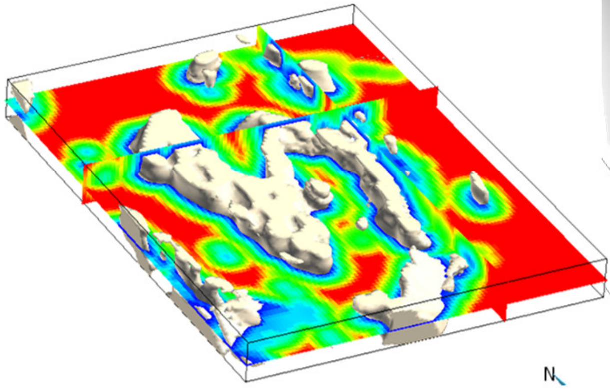
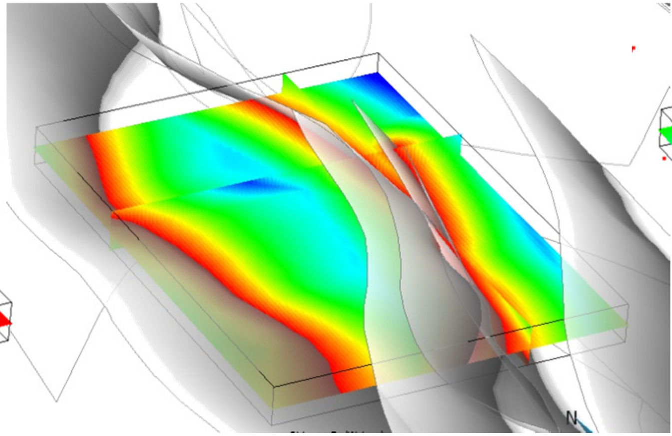
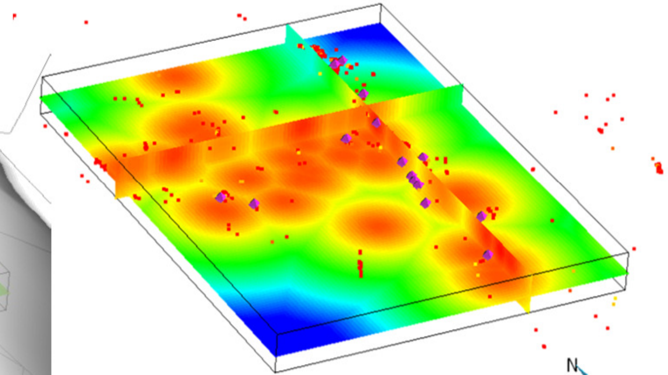
Regional targeting – targeting criteria



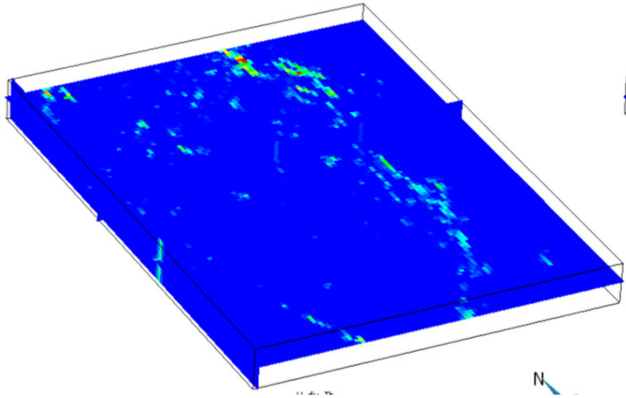
Distance to mafic volcanics



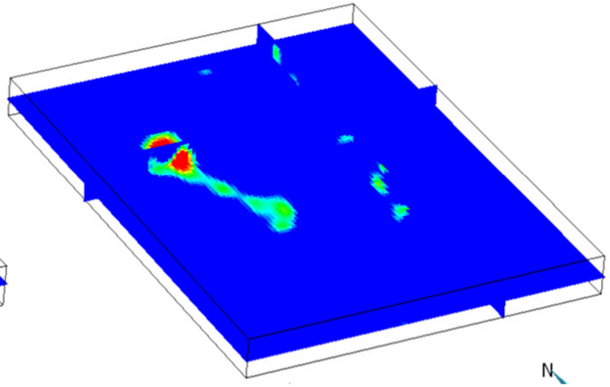
Distance to crustal faults



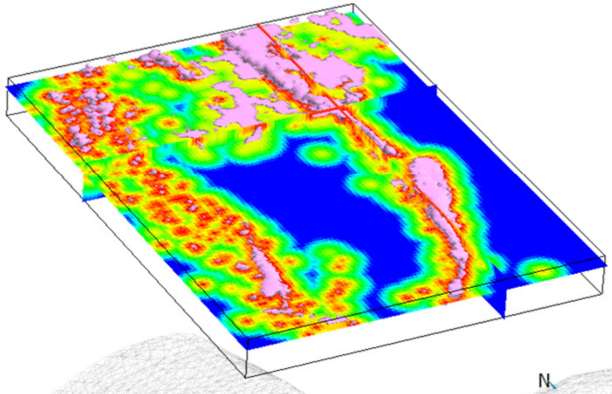
Near anomalous Au



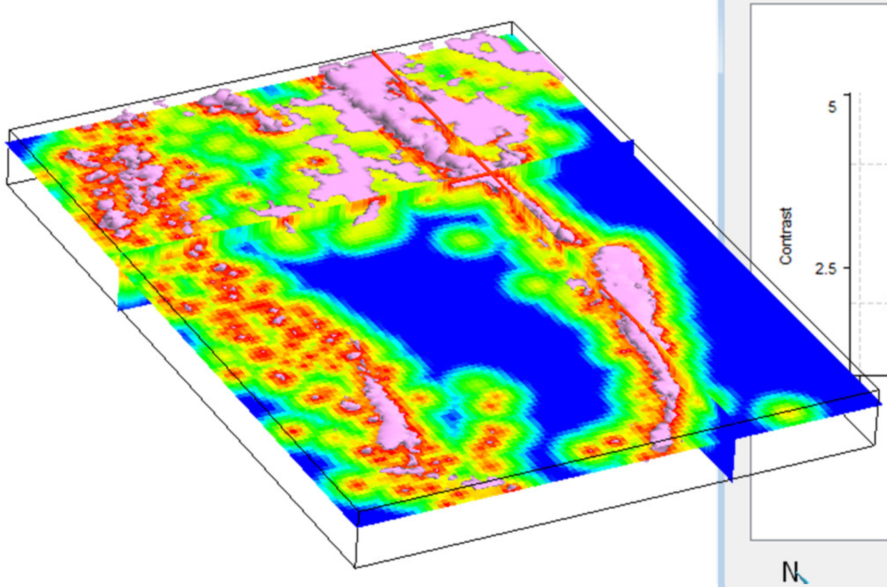
Uranium anomalism (U/Th)

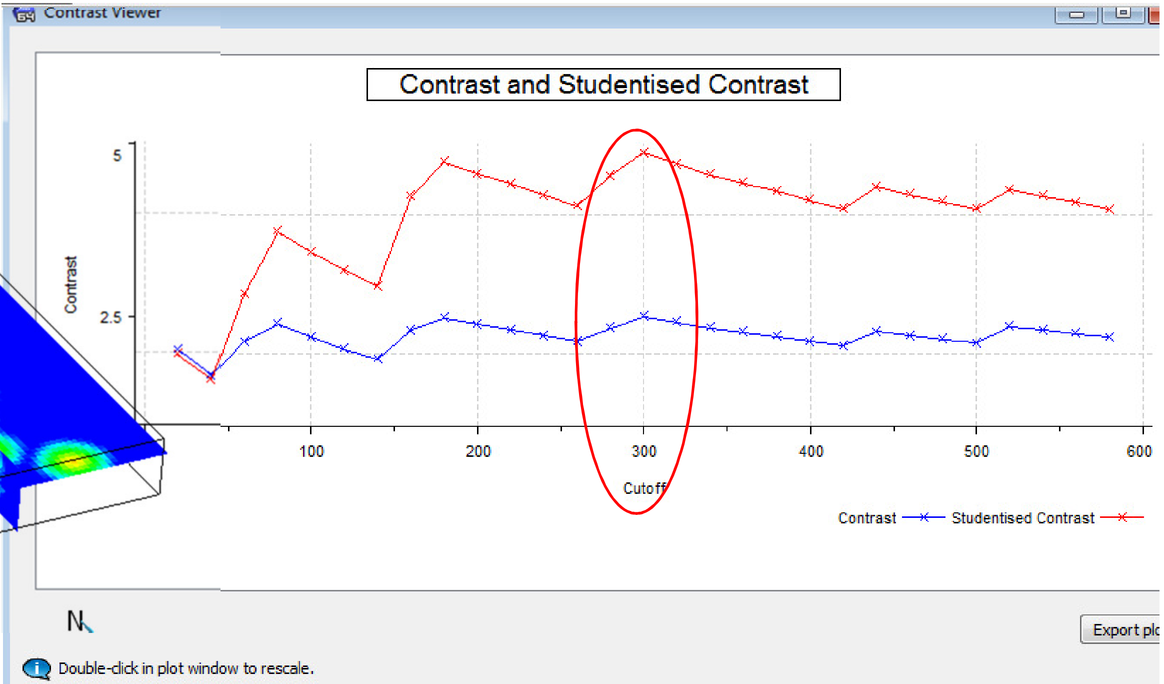


Dense and magnetic rocks



AEM – but what?





	IntervalStart	IntervalEnd	Wplus	Wminus	Contrast	StudContrast	PercDeposits	NumDeposi
4	0	80	2.22778	-0.201354	2.42914	3.76226	20	3
5	0	100	2.03589	-0.196684	2.23257	3.45797	20	3
6	0	120	1.87467	-0.191982	2.06665	3.20108	20	3
7	0	140	1.73001	-0.187043	1.91705	2.96943	20	3
8	0	160	1.97946	-0.358323	2.33778	4.26747	33.3333	5
9	0	180	2.05052	-0.457987	2.50851	4.75878	40	6
10	0	200	1.9669	-0.453243	2.42014	4.5912	40	6
11	0	220	1.89148	-0.448589	2.34007	4.43936	40	6
12	0	240	1.81281	-0.44332	2.25613	4.28016	40	6
13	0	260	1.73844	-0.437913	2.17635	4.12884	40	6
14	0	280	1.81579	-0.54964	2.36543	4.56991	46.6667	7
15	0	300	1.85666	-0.675161	2.53182	4.89141	53.3333	8
16	0	320	1.77883	-0.667779	2.44661	4.72682	53.3333	8
17	0	340	1.70923	-0.660621	2.36985	4.57855	53.3333	8
18	0	360	1.65258	-0.654373	2.30695	4.45706	53.3333	8
19	0	380	1.5975	-0.647909	2.24541	4.33817	53.3333	8
20	0	400	1.53861	-0.640542	2.17915	4.21017	53.3333	8
21	0	420	1.47975	-0.632673	2.11243	4.08128	53.3333	8

Export tab

Distance to conductive edges

Related to rheological geological boundaries – a local structural trap for IOCG mineralisation

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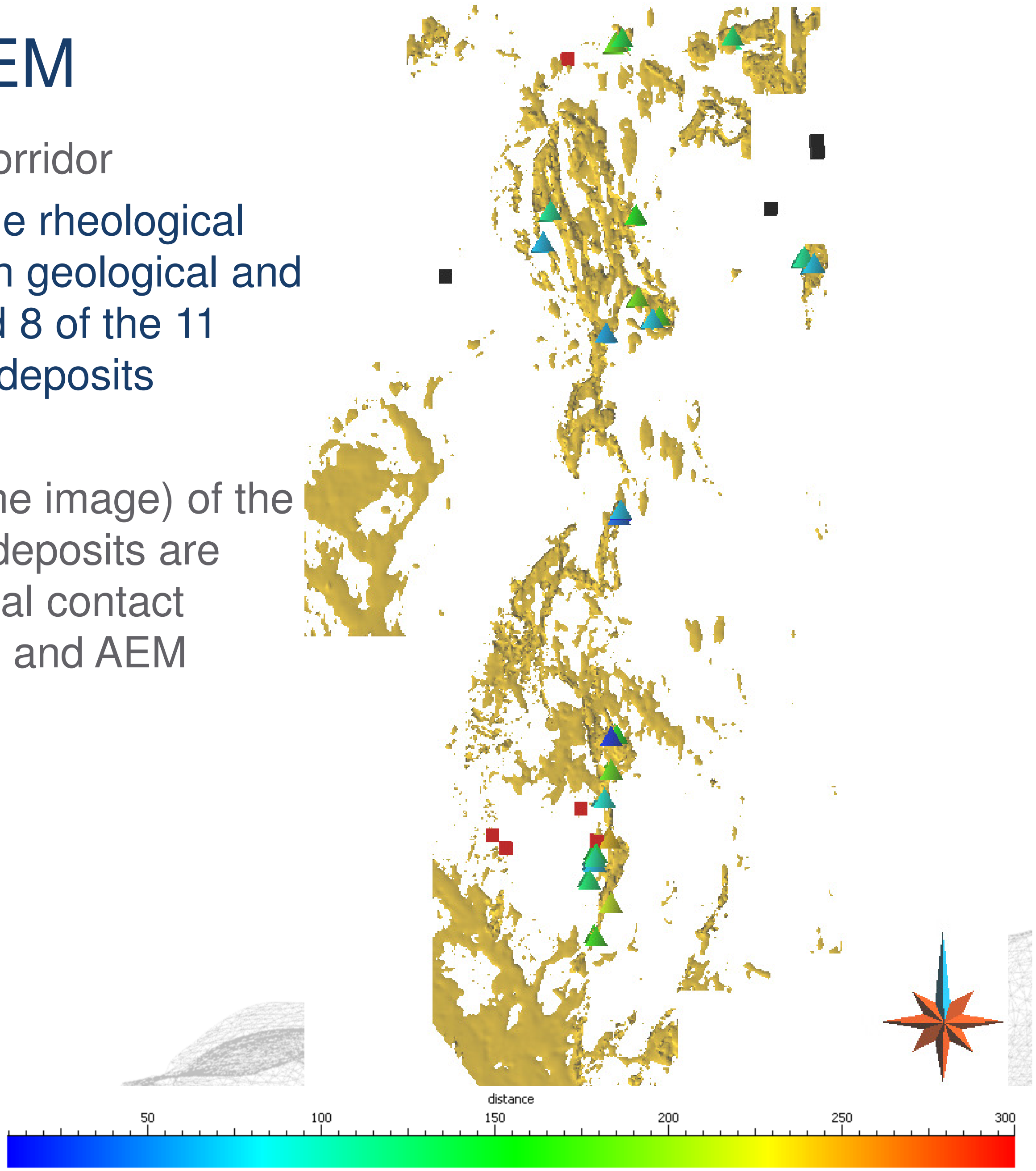
The success of AEM

- In the main mineralisation corridor
  - A zone within 300m of the rheological contact identified through geological and AEM modelling identified 8 of the 11 known significant IOCG deposits

- Regionally 26 (triangles in the image) of the 36 known significant IOCG deposits are within 300m of the rheological contact identified through geological and AEM modelling



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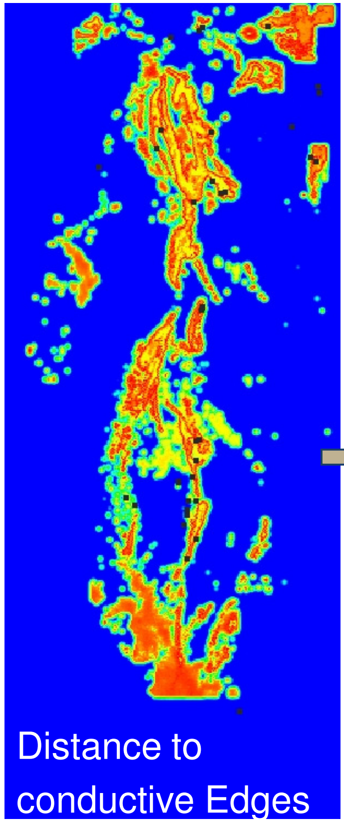
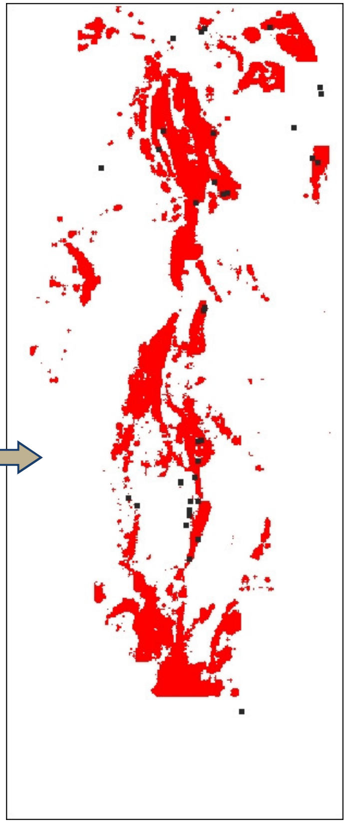
3D Weights of Evidence (WoE) Targeting

- Of the 22 proposed exploration criteria,
- only 11 had significant correlation with mineralisation in the Mount Dore area.





Exploration Criteria	Weight +	Weight -	Contrast	Stud. Contrast	Favourable Range - Start	Favourable Range - End
Coincident Gravity High-Magnetic High	2.29	-0.2	2.49	5.9	0.81	0.246
Distance C-Sharp Filter ISO <35	2.88	-0.91	3.79	11.09	0m	300m
Distance to Crustal faults	0.74	-0.32	1.06	3.12	0m	964m
Distance to faults intersecting mafics	1.12	-0.29	1.41	4	0m	921m
Fault Roughness	2.79	-0.17	2.96	6.63	0	0.00015
Geological Complexity	1.8	-0.35	2.15	6.09	0.107	0.0198
Normalised Susceptibility	3.25	-0.14	3.39	7.03	0.372	0.0884
Regional Density Model	3	-0.08	3.08	5.11	0.426	0.32
Uranium divided by Thorium	2.12	-0.58	2.7	8.1	1.289	0.274
Distance to Gold Anomaly <150	5.16	-0.29	5.45	14.15	0m	304m
Distance to Copper Anomaly <2000	5.72	-0.75	6.47	19.35	0m	250.7m

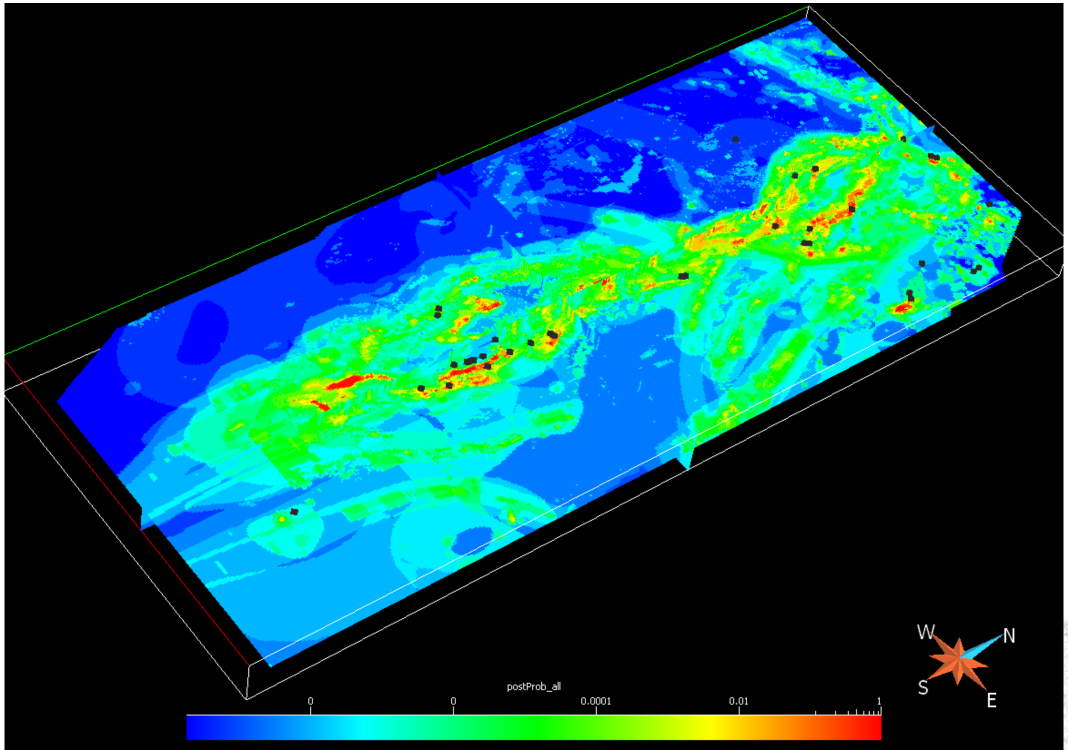
Variables with the highest studentised contrast values (C/stdevC) are the most significant contributors to the mineral potential model.

Mineral Potential Index

- The Binary evidential properties and their associated weights are combined to create a Mineral Potential Index.
- ◦

- Final result is model-driven 3D mineral prospectivity potential volume

Mt Dore
Mineral Potential Index



training cells (black dots)

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Conclusions

- Geophysics can act as a key ingredient to exploration methods based around Ore System Footprints – not designing drill holes in data space
- integrated interpretation requires a single, shared earth model
- geophysical responses are usually dominated by the 3D geometry of geological boundaries
- inversion is most usefully deployed to modify geological domain geometry and bounded physical property distributions
- key technologies:
  - 3D geological modelling
  - physical property analysis
  - rapid, iterative geologically-based forward modelling and inversion

interpretational effectiveness demands interactive, iterative geological and geophysical modelling by a multi-disciplinary team