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Geological Modelling of Geophysical Data:

Alternatives to the 3D Inversion Black Box v2.0

TGDG
Sept 11, 2012

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Disclaimer

None

The statements to be made in this presentation will indeed contain very forward looking statements…beware!

Part of this talk was given at KEGS Symposium last March 2012, with co-authors Stephen Reford (PGW) and Bill Morris (McMaster).

(Therefore the v2.0 on the title…)

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Contents

- Motivation / Introduction
- Quick review of "old" modelling/interpretation techniques
- The approach: bring geology into the equation
- Three case studies:
  - Bathurst, NB (regional modelling)
  - Caribou deposit (prospect scale)
  - NWT Iron Ore exploration
- Topographic effects on magnetic data
- Conclusions/Final remarks

Motivation (/Rant)

- The constant request for "give me a drilling target"…
  - Out of airborne data (i.e., sufficient resolution and physical property contrast?)
  - Or when the mineralization is non-magnetic (e.g. alteration zones➔*to the side* of the big magnetic "blob"!)
- The usual "interpretation" of geophysical data with a number of blocky polygons totally disconnected from the geology of the area
- The constant request/advertising for fancy 3D inversions that look great, but…do they follow any geological principles? (in other words, are they of any use??)

Back to basics: 2D modelling

- A simple model can provide with good information on physical properties and some ideas on geometry
- However, we must keep in mind:
  - models are non-unique
  - Resolving power of different geophysical techniques (i.e. how deep can we go? Can we "see" (define) the base of bodies, or just the top?
  - Physical property contrast (i.e. can we distinguish host rock from target/mineralized unit?)

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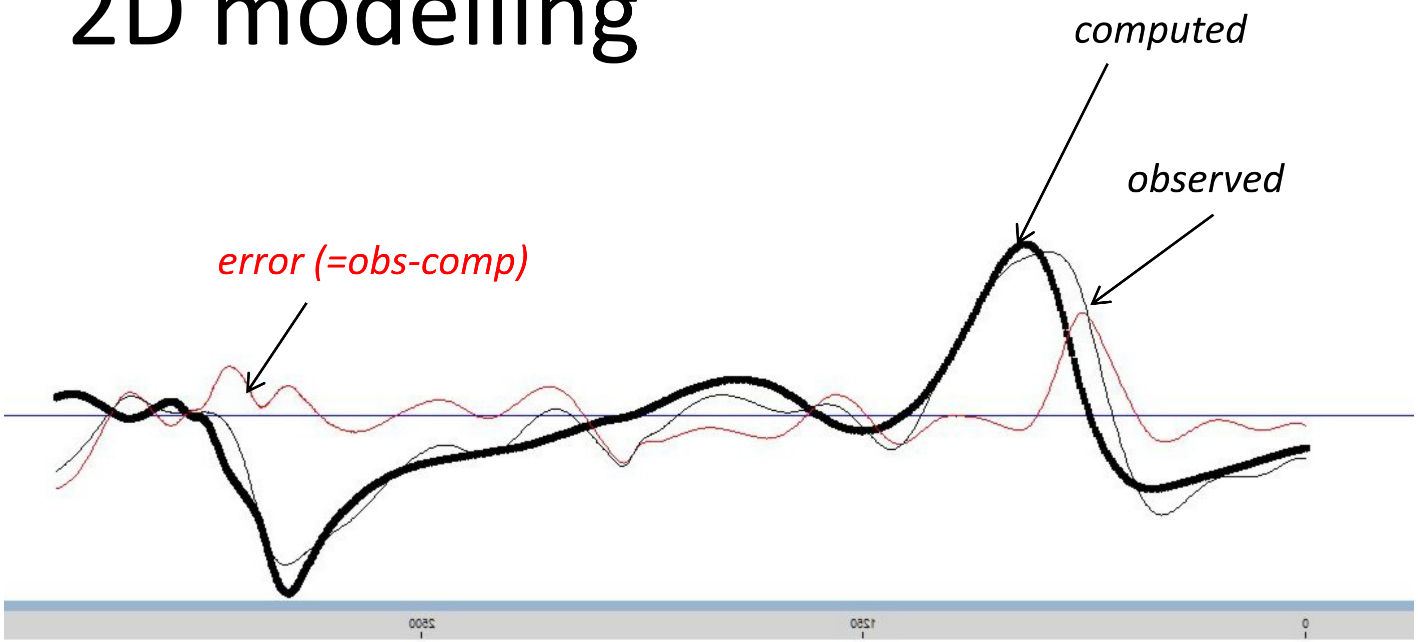
Back to basics:
2D modelling



Simple case:

- Mag data
- Inclination: 80 deg; Declination: 24.1

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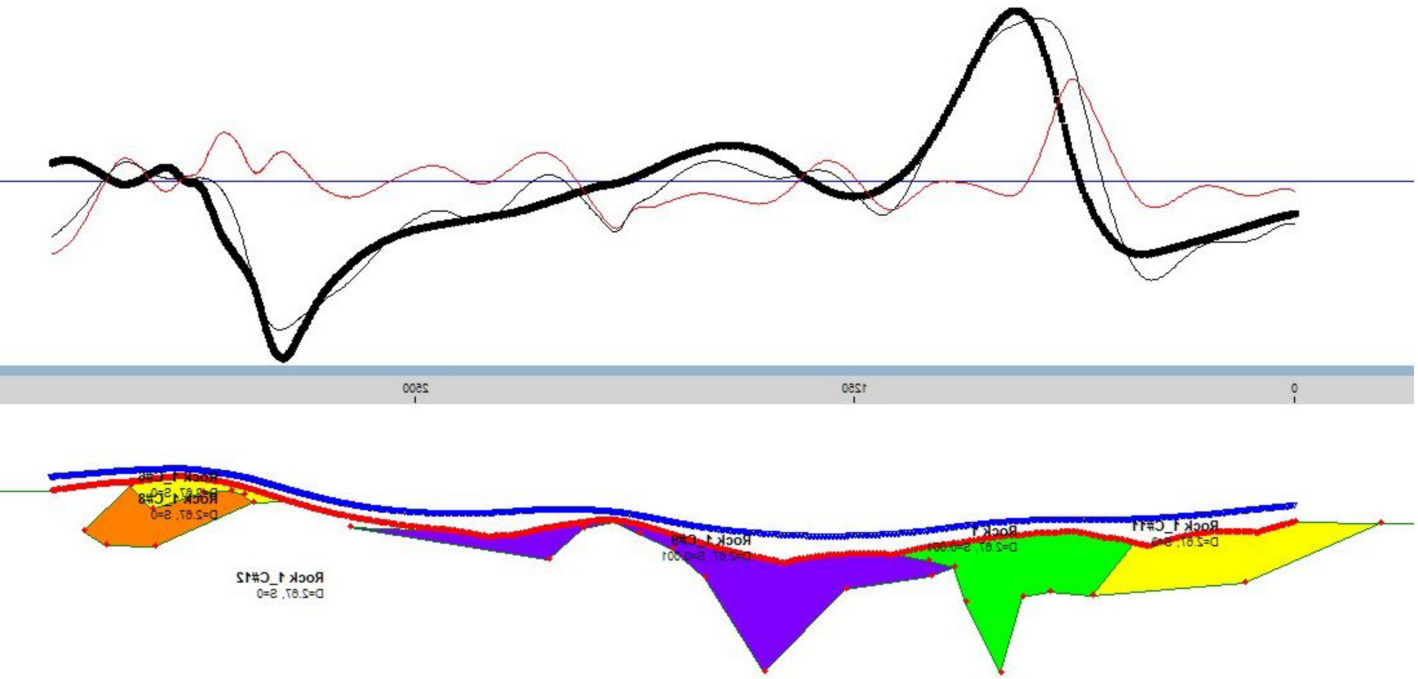
Back to basics:
2D modelling



Model 1:

- 5 bodies with “awkward” geometries and susceptibilities ~0-0.0008 cgs
- We are able to reproduce the observed signal…but does this make any geological sense??

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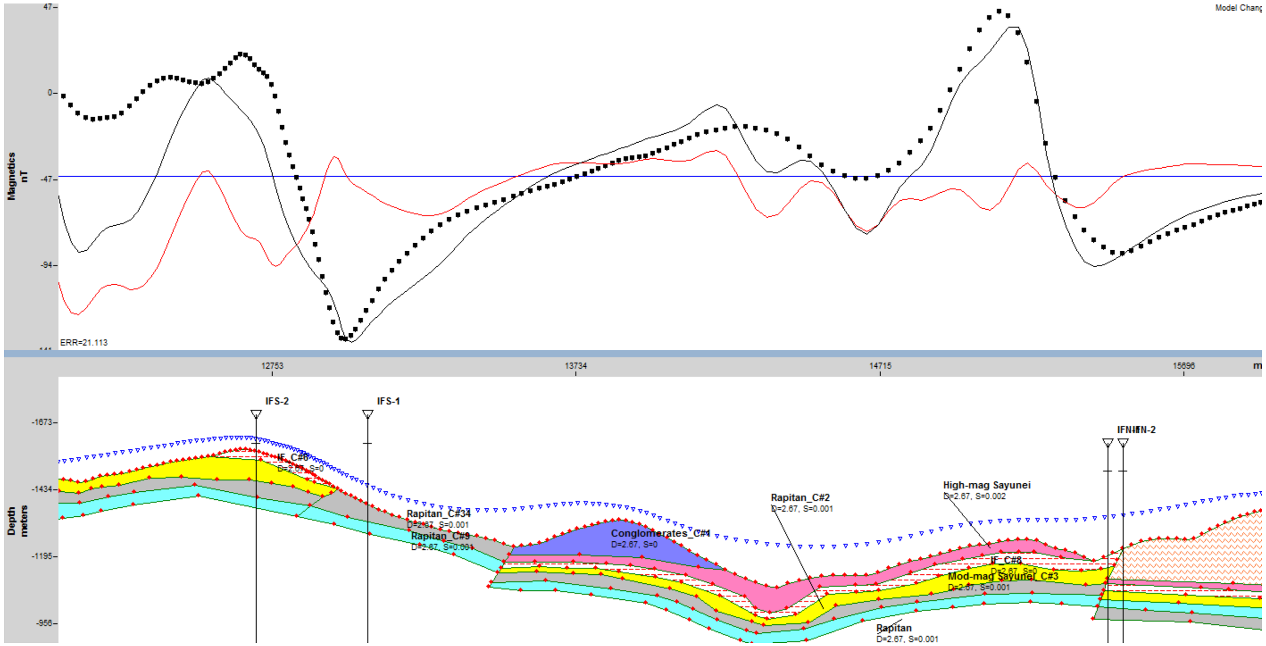
Back to basics: 2D modelling



Model 2:

- A series of sub-horizontal bodies
- Folds and faults
- *However: this requires a priori knowledge of the structure/geology*

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Hold it!!

…….Geology???

- What do we need:
  - Structure (strike/dip, faults, folding)
  - Lithology (rock type, and more than that, physical properties)
- Normally we have a few scarce strike/dip points and no susceptibility at all
- We must obtain these constraints from somewhere else

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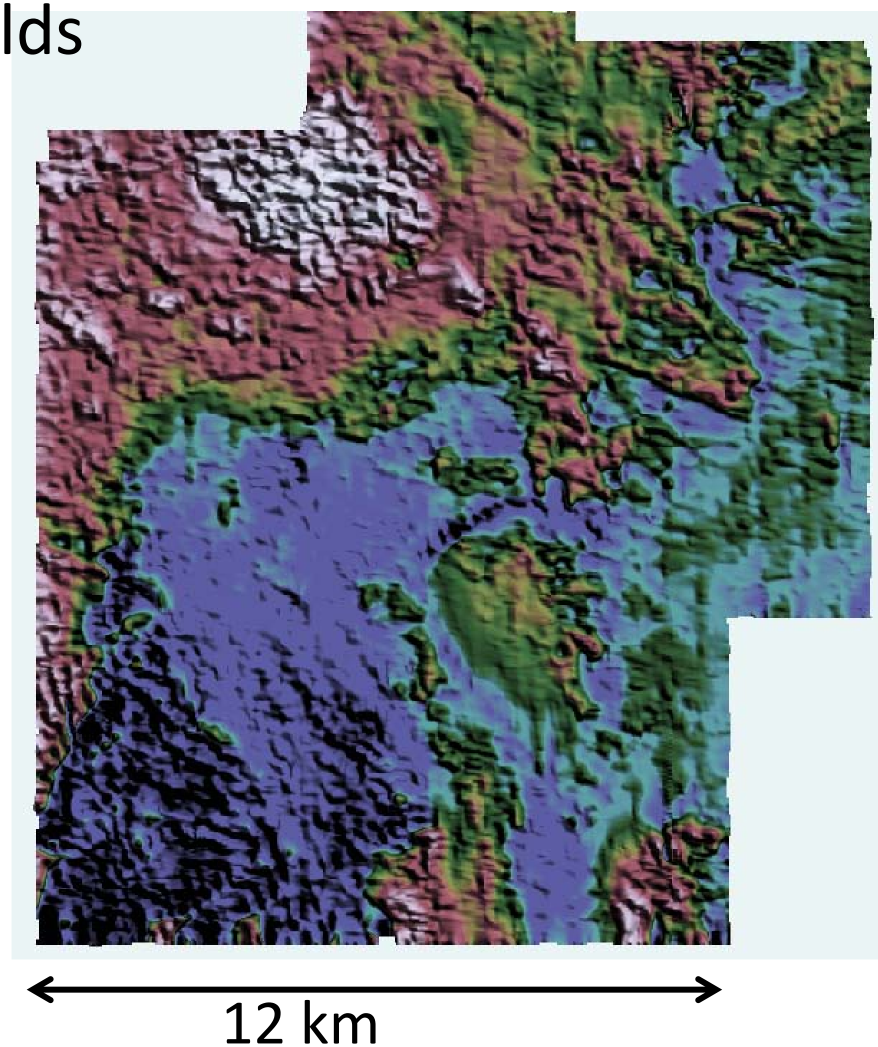
Faults

A first pass interpreting the data (qualitative) can give information on faults, contact locations, folds

RTP Magnetic data



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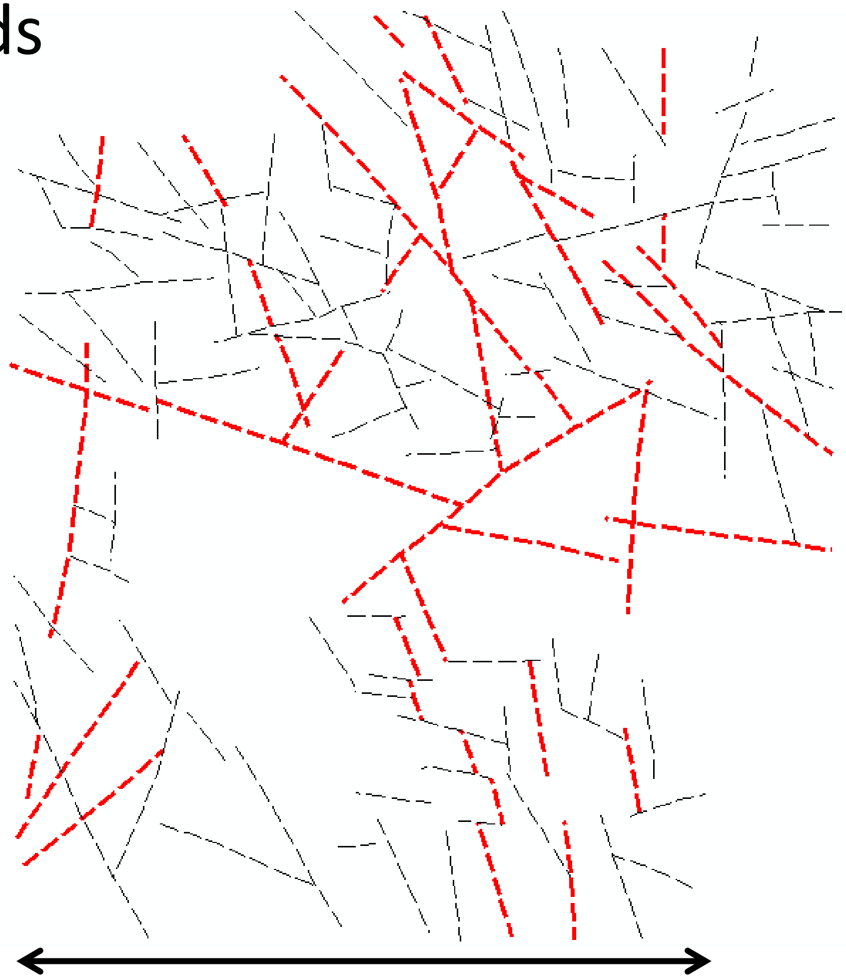
Faults

A first pass interpreting the data (qualitative) can give information on faults, contact locations, folds

As is…these are just lines, but tied up to known geology we can differentiate contacts & faults



12 km

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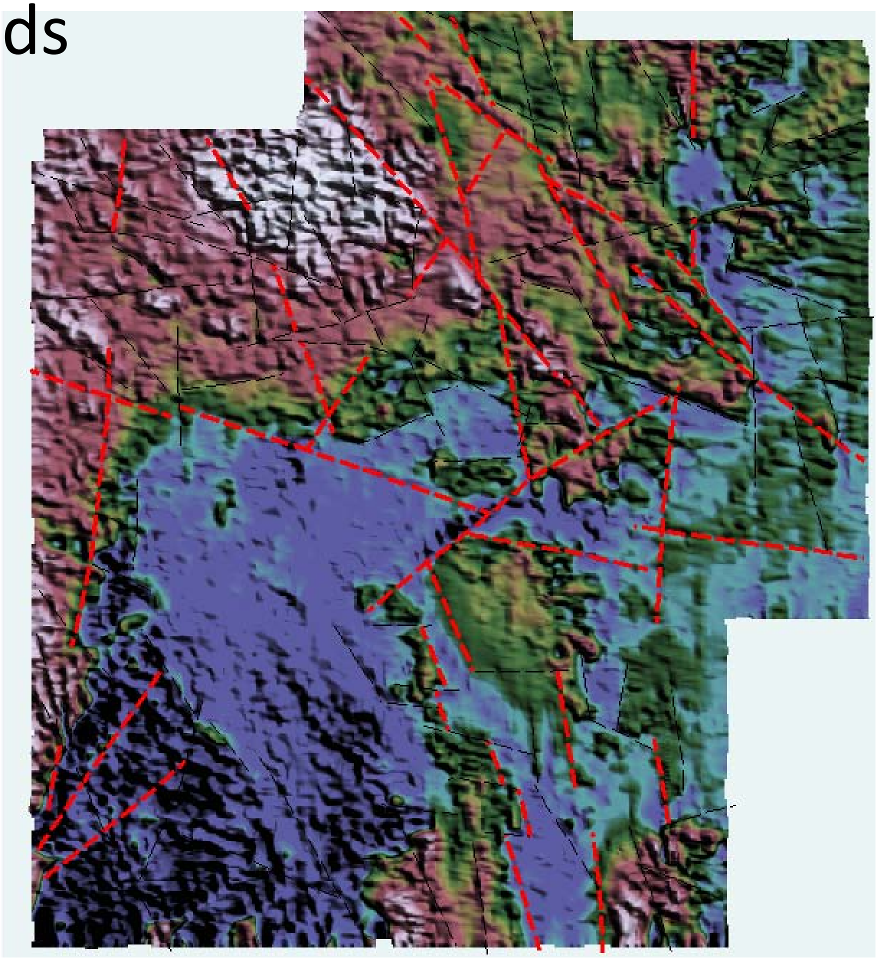
Faults

A first pass interpreting the data (qualitative) can give information on faults, contact locations, folds



12 km

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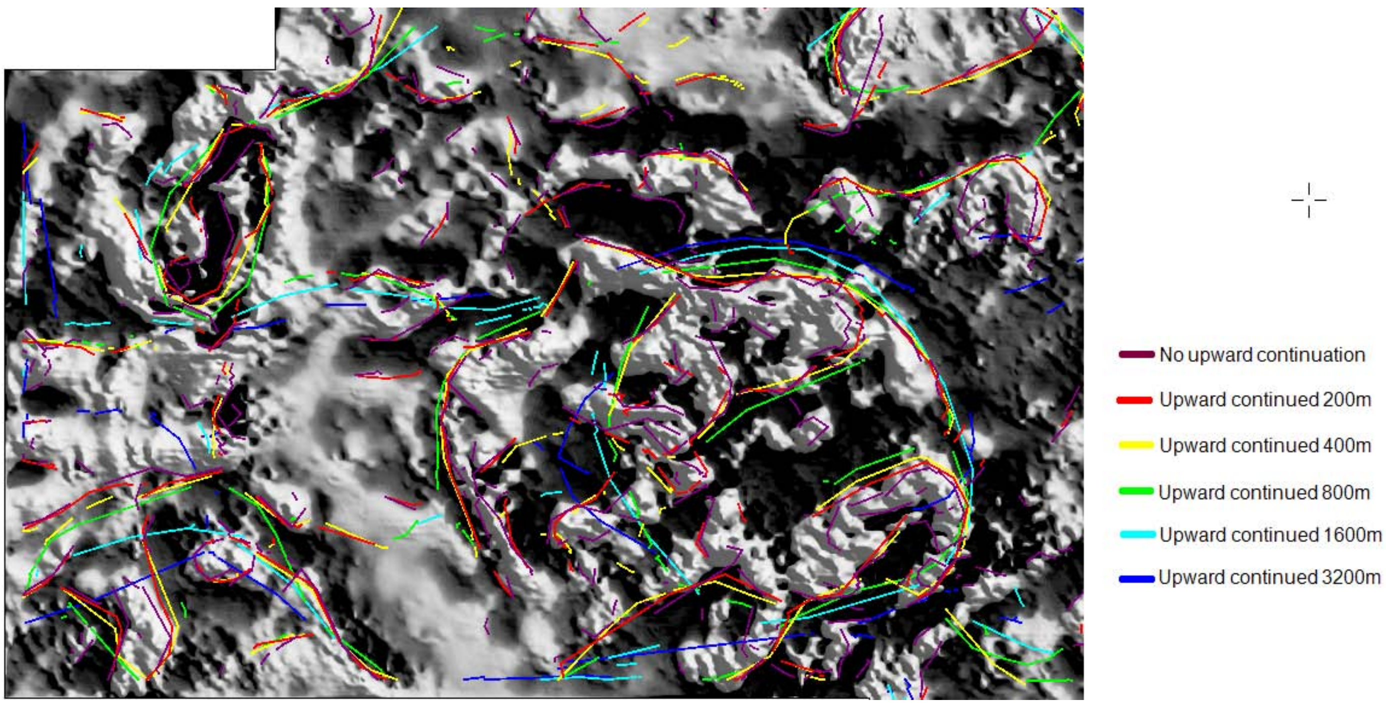
Strike and Dip

Worms: used to determine relative dip direction



12 km

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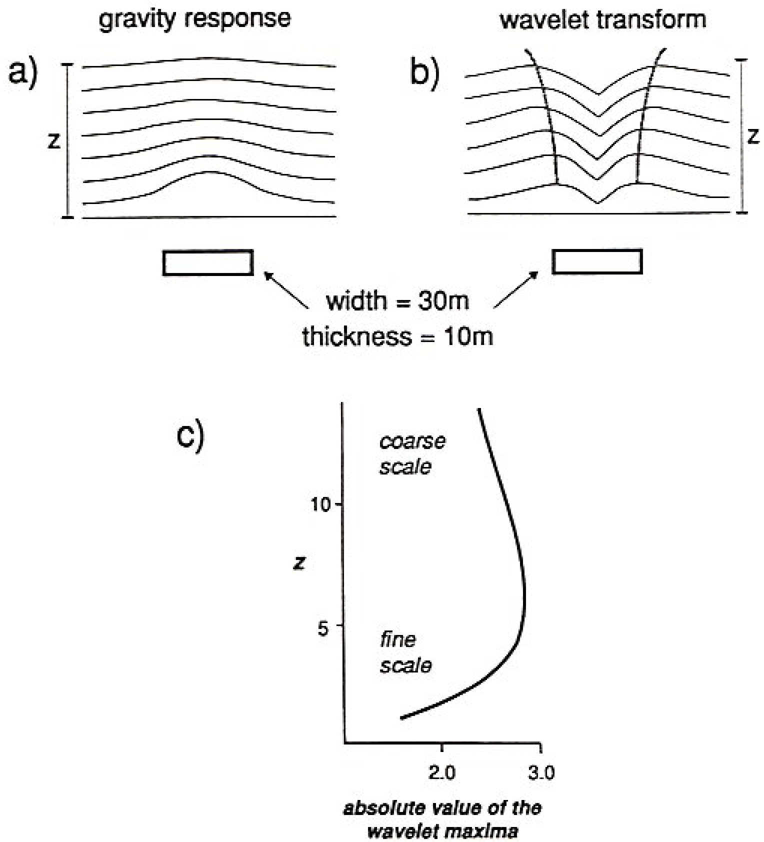
Strike and Dip

Worms: used to determine relative dip direction



From Archibald et. al., 1999

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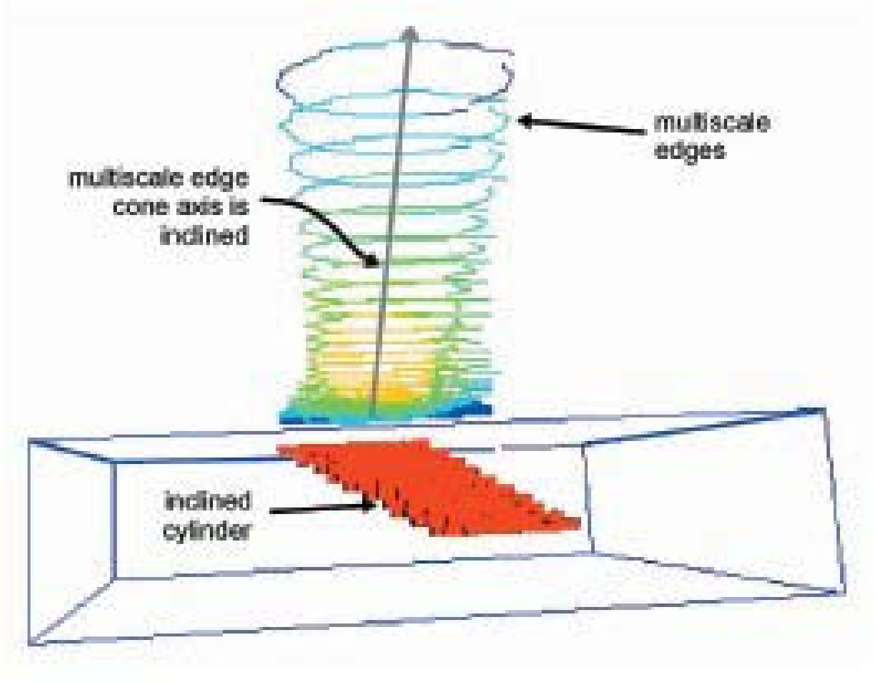
Strike and Dip

Worms: used to determine relative dip direction



From Archibald et. al., 1999

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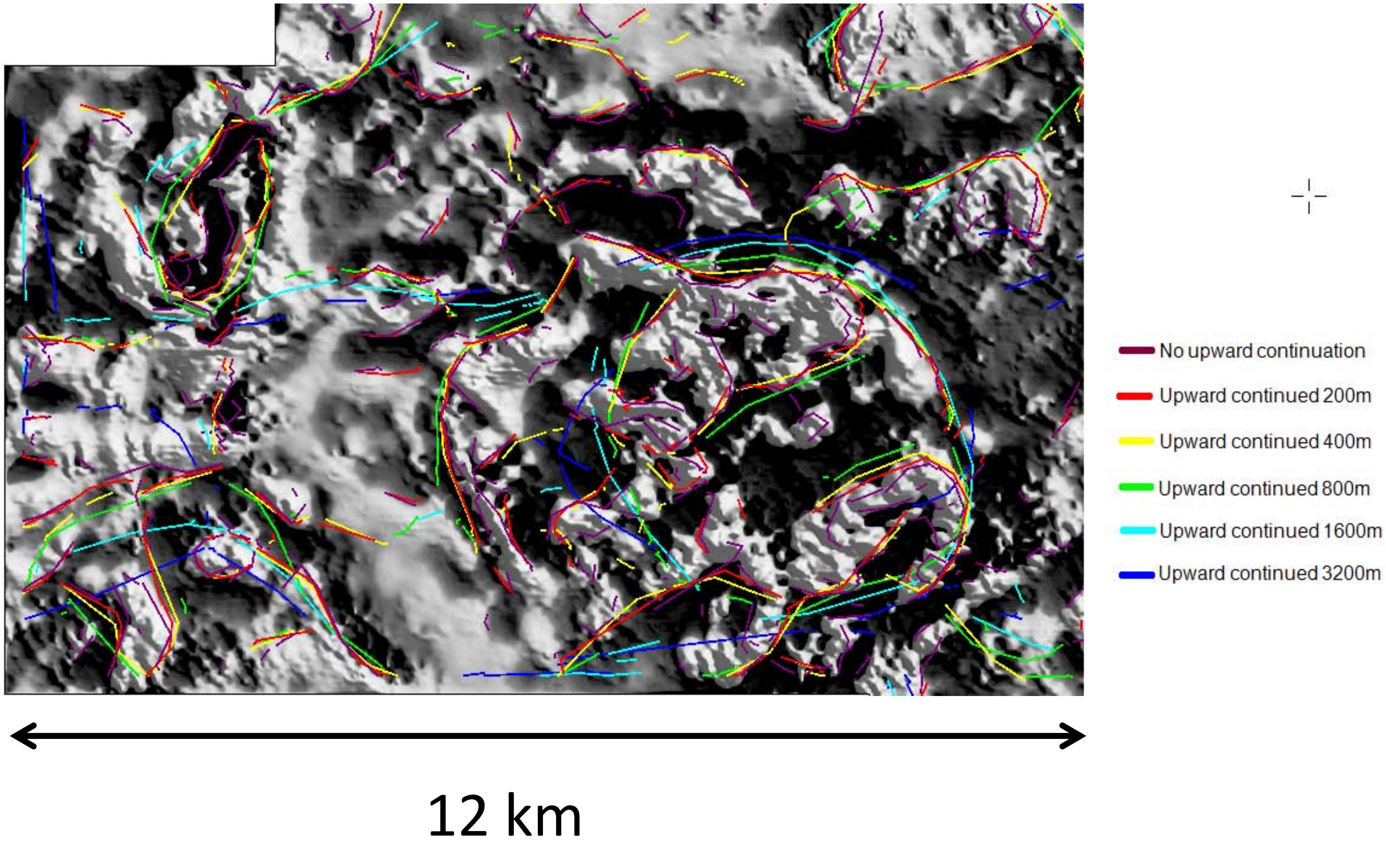
Strike and Dip

Worms: used to determine relative dip direction:

upward continuation implementation



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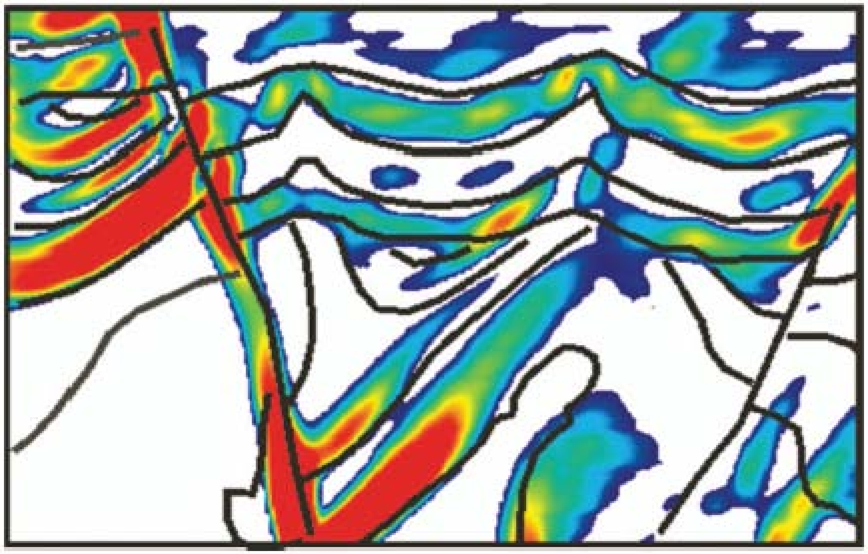
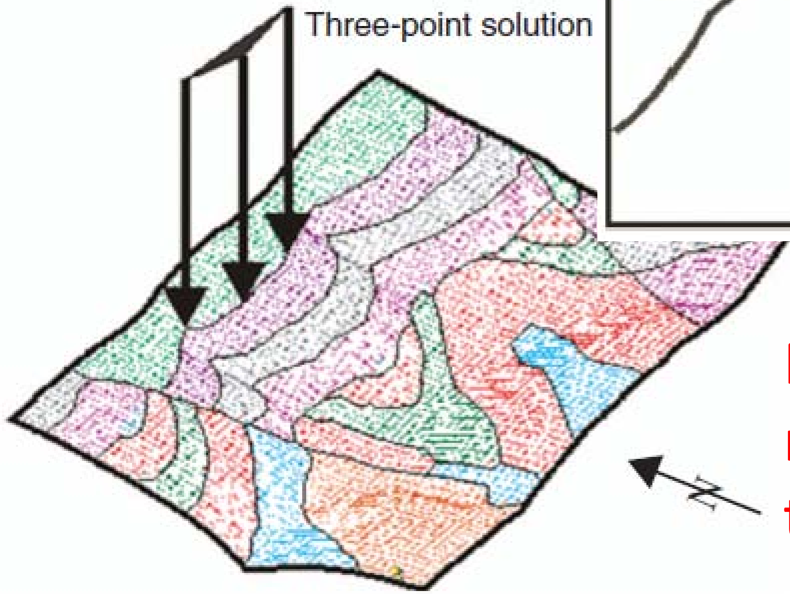
Strike and Dip

Three point solutions: if we know the location of a contact on 3 (X,Y,Z) points, we can solve for the equation of a plane➔strike, dip





Requires topographic relief and confidence on the location of contacts

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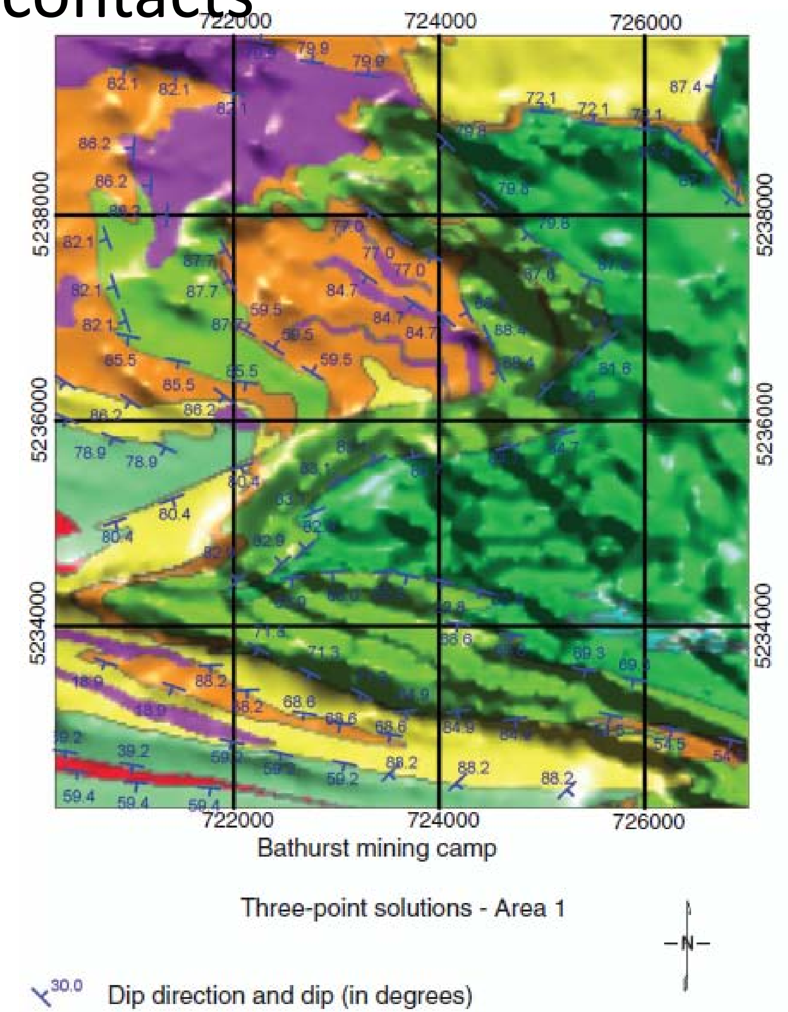
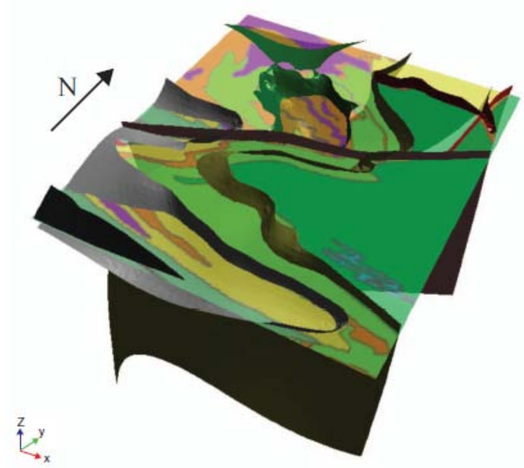
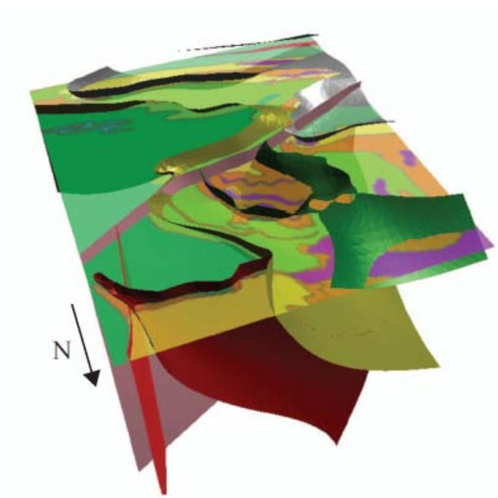
Strike and Dip

Three point solutions: require topographic relief and confidence on the location of contacts







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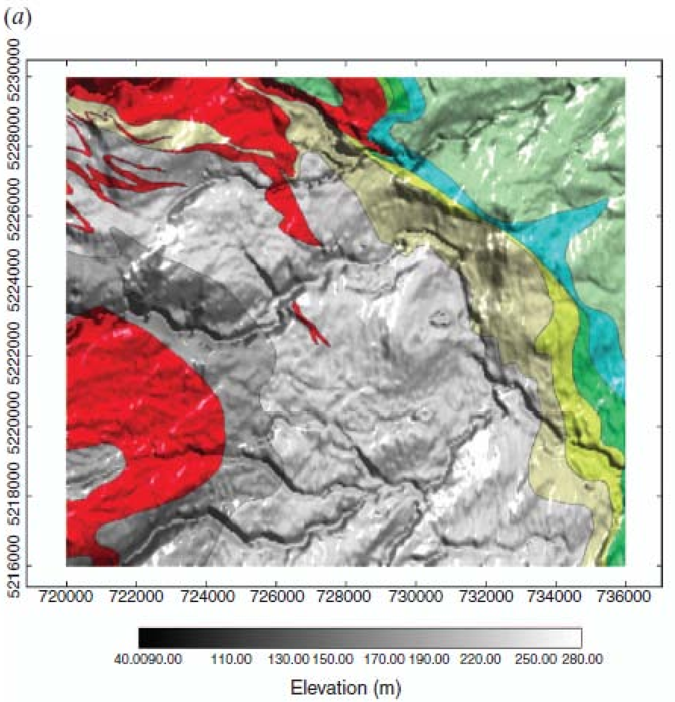
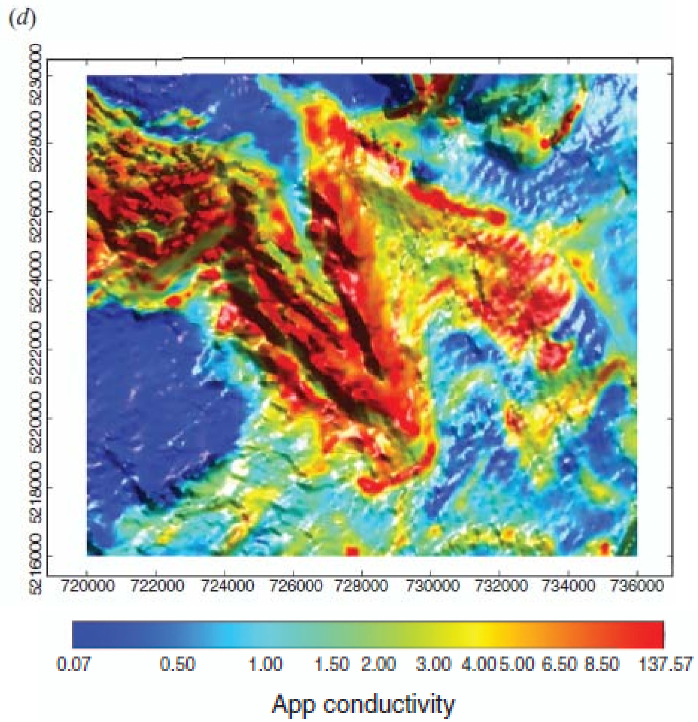
Strike and Dip

Three point solutions: a case where geophysics and topography could make a difference



Geology & Topography



EM data

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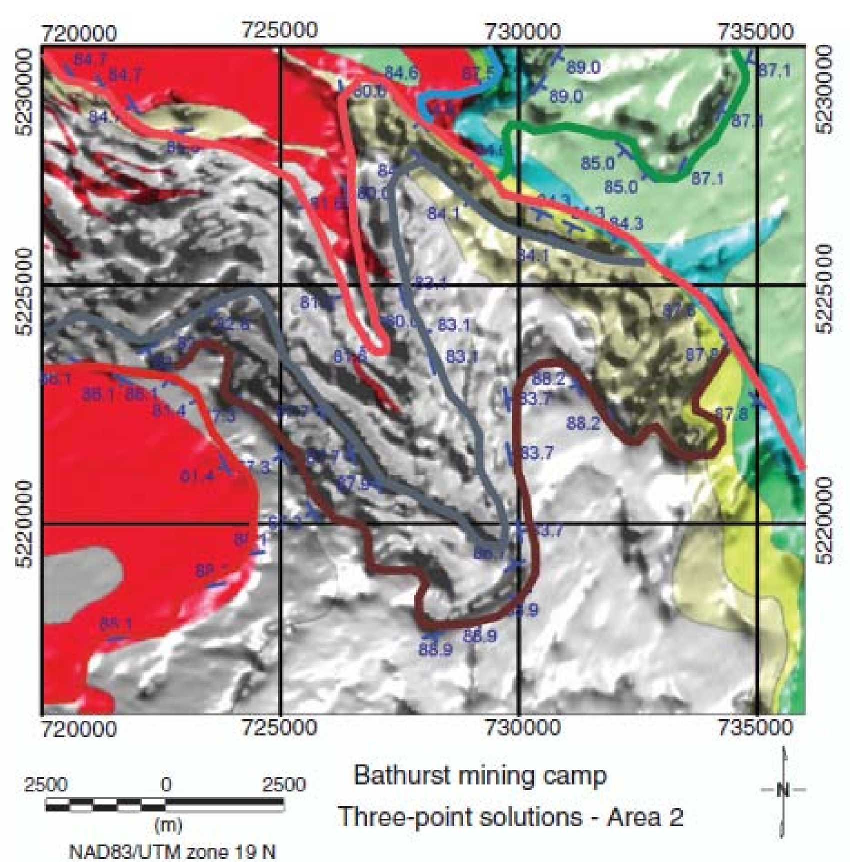
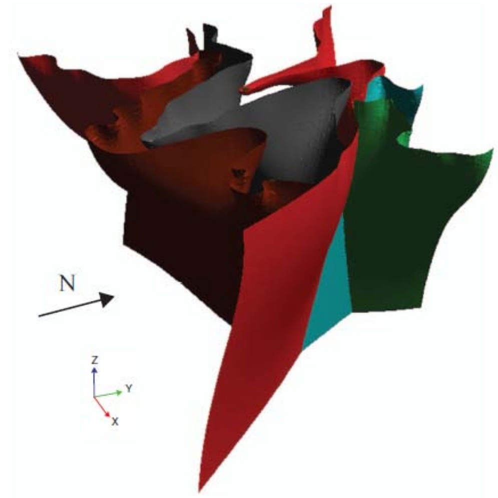
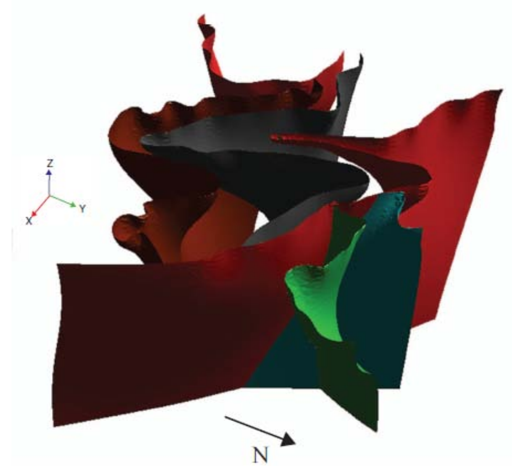
Strike and Dip

Three point solutions: a case where geophysics and topography could make a difference







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Hold it!!
…….Geology???

- What do we need:
  - Structure (strike/dip, faults, folding)
  - Lithology (rock type, and more than that, physical properties)
- Normally we have a few scarce strike/dip points and no susceptibility at all
- We must obtain these constraints from somewhere else
- Or…we use 2.5D modelling to test geological hypothesis

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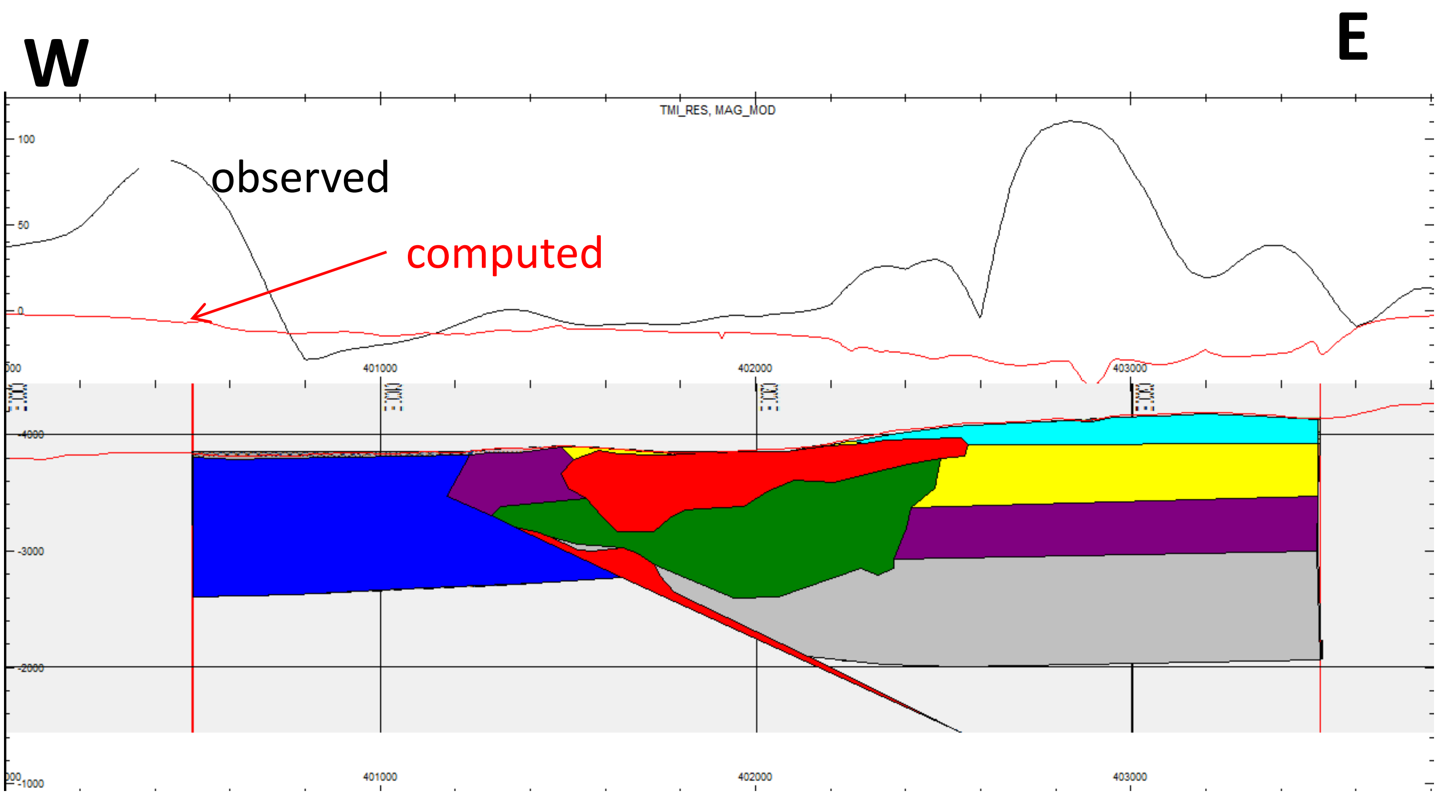
Testing geological hypothesis (2D Modelling)



Geologist provided 2D section + physical properties + ground mag survey. We then plug it into modelling software and see whether the model holds…

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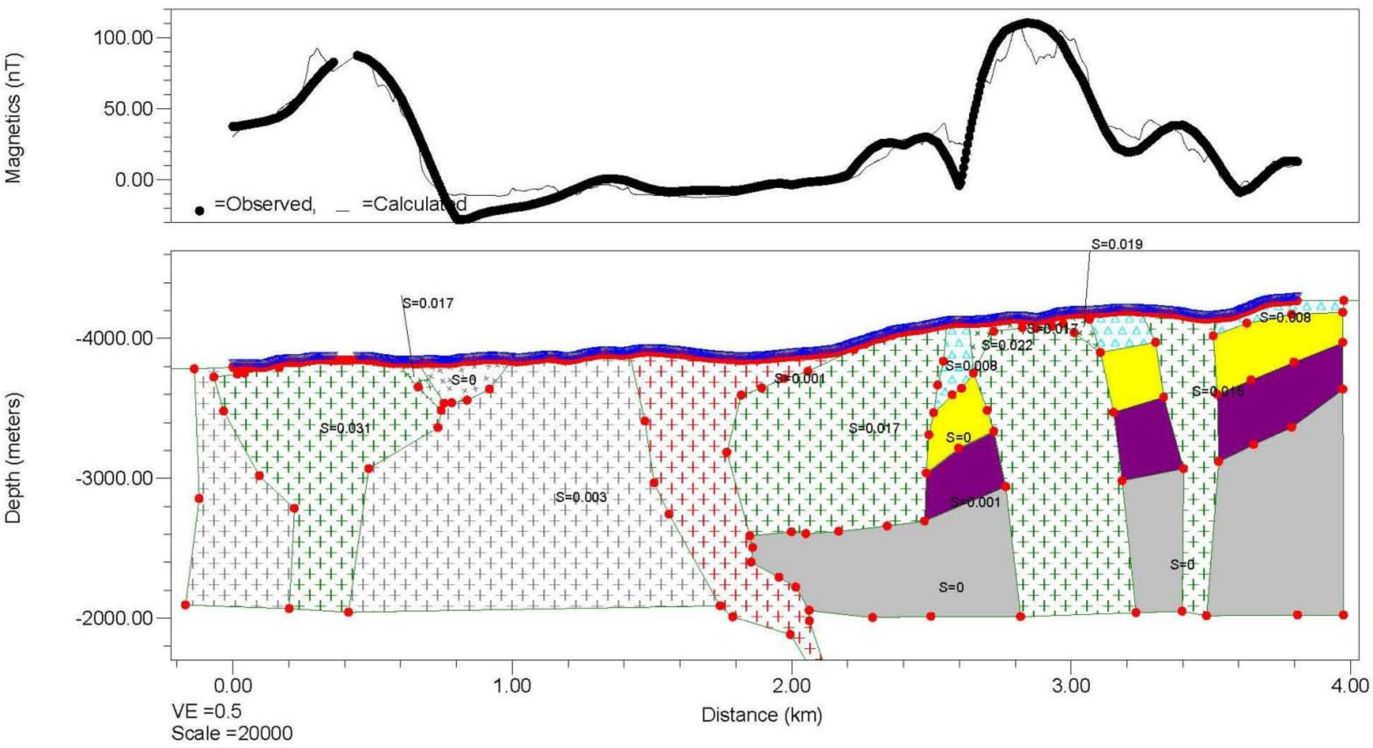
Testing geological hypothesis (2D Modelling)

W **E**



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Case studies: Integrated 2.5D modelling

Now we want to put everything on a coherent picture

- Case 1: Bathurst, NB
- Case 2: Caribou deposit, NB
- Case 3: Iron ore exploration project, NWT

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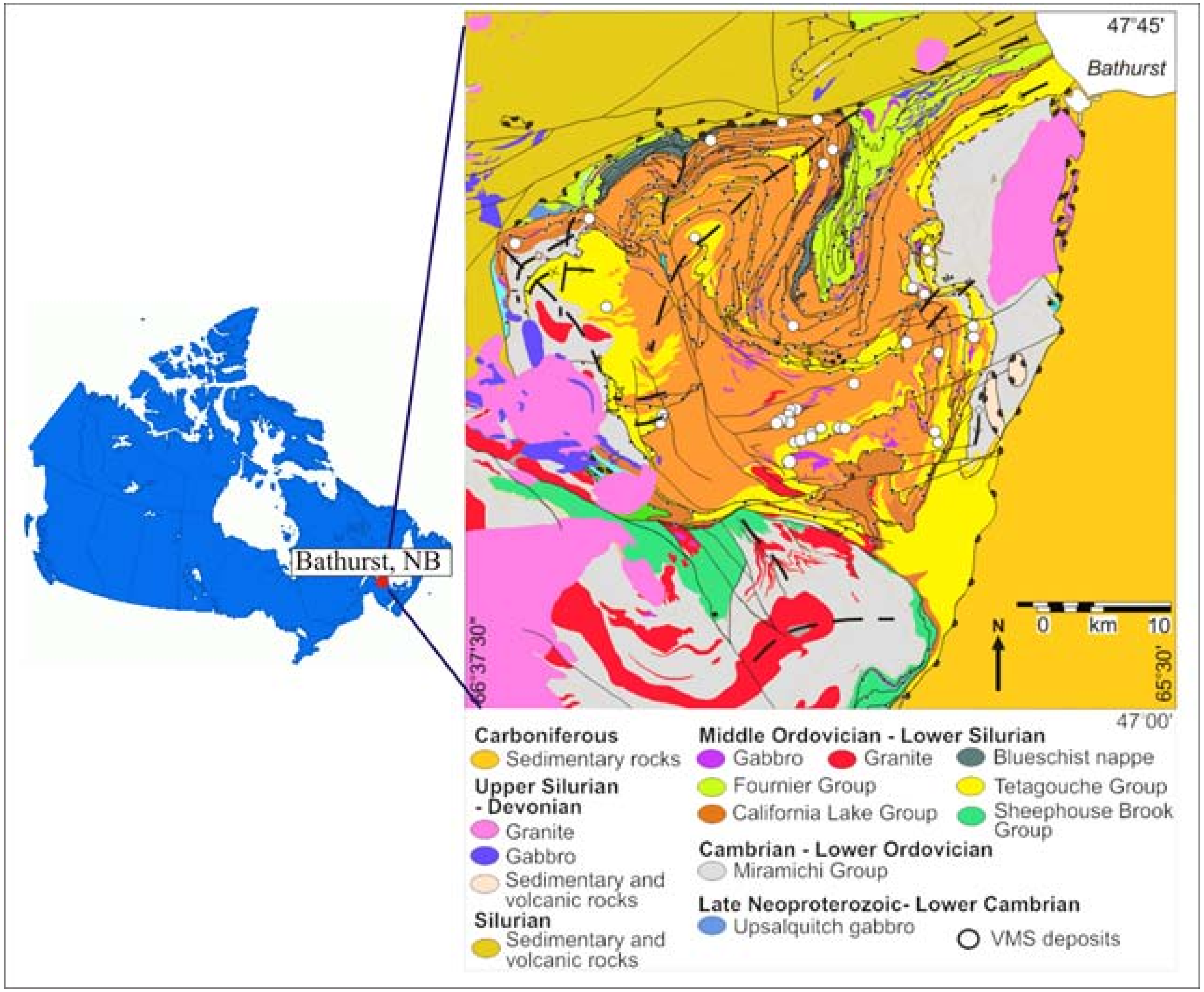
Case 1:
Bathurst Mining Camp

- One of Canada's oldest mining districts for VMS deposits
- Host to 25 massive sulfide deposits with resources > 1Mt
- Approximately 70% of those were discovered in the 1950s using a combination of geology and geophysics

Bathurst Mining Camp



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Bathurst Mining Camp

- EXTECH II a big step forward. Not the final word on the geology of the camp.
- EXTECH II identified the mineralized horizons, but only found the non-economic Camelback deposit.
- Real potential exists in the extension of known mineralized horizons at depth.
- ➔ TGI-3
- Integrated modelling of mag & grav data, with good structural control (Cees van Staal, GSC)

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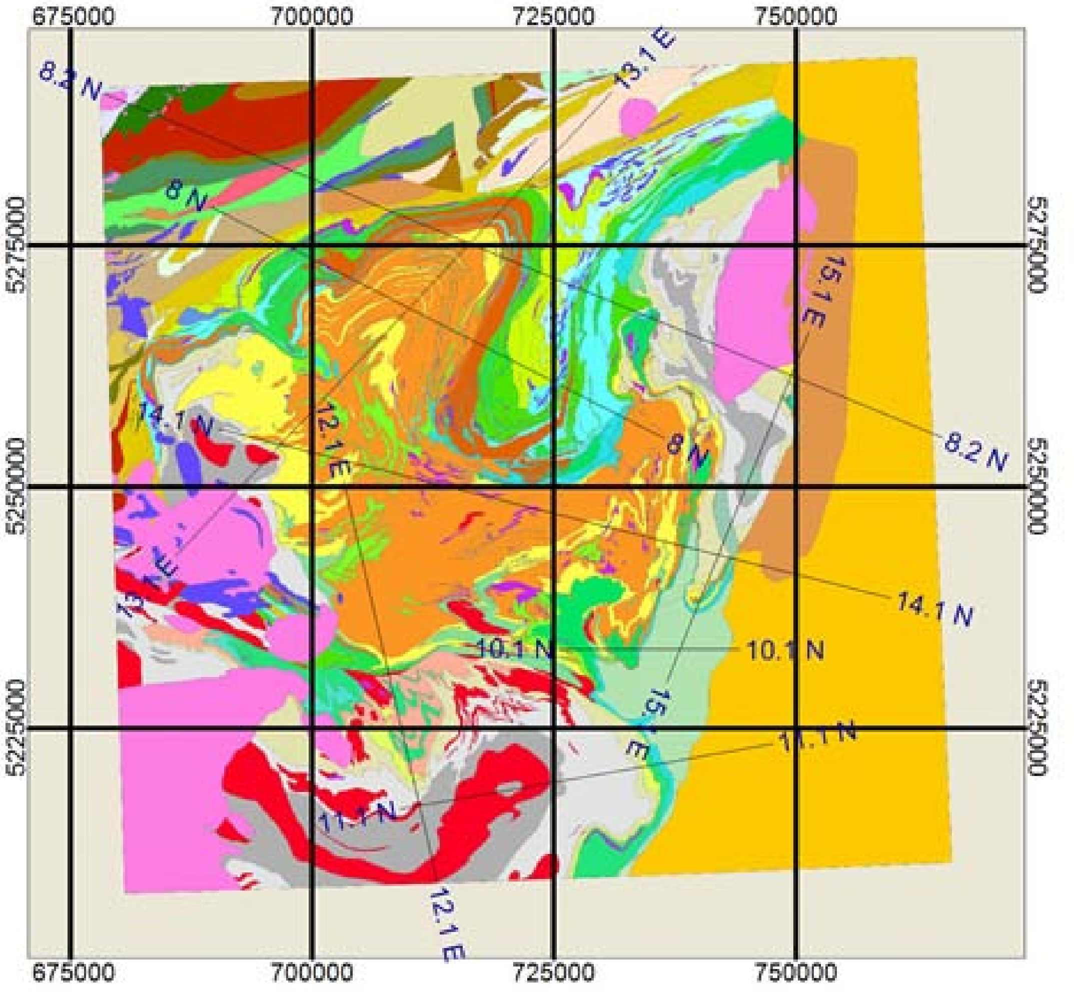
Bathurst Mining Camp



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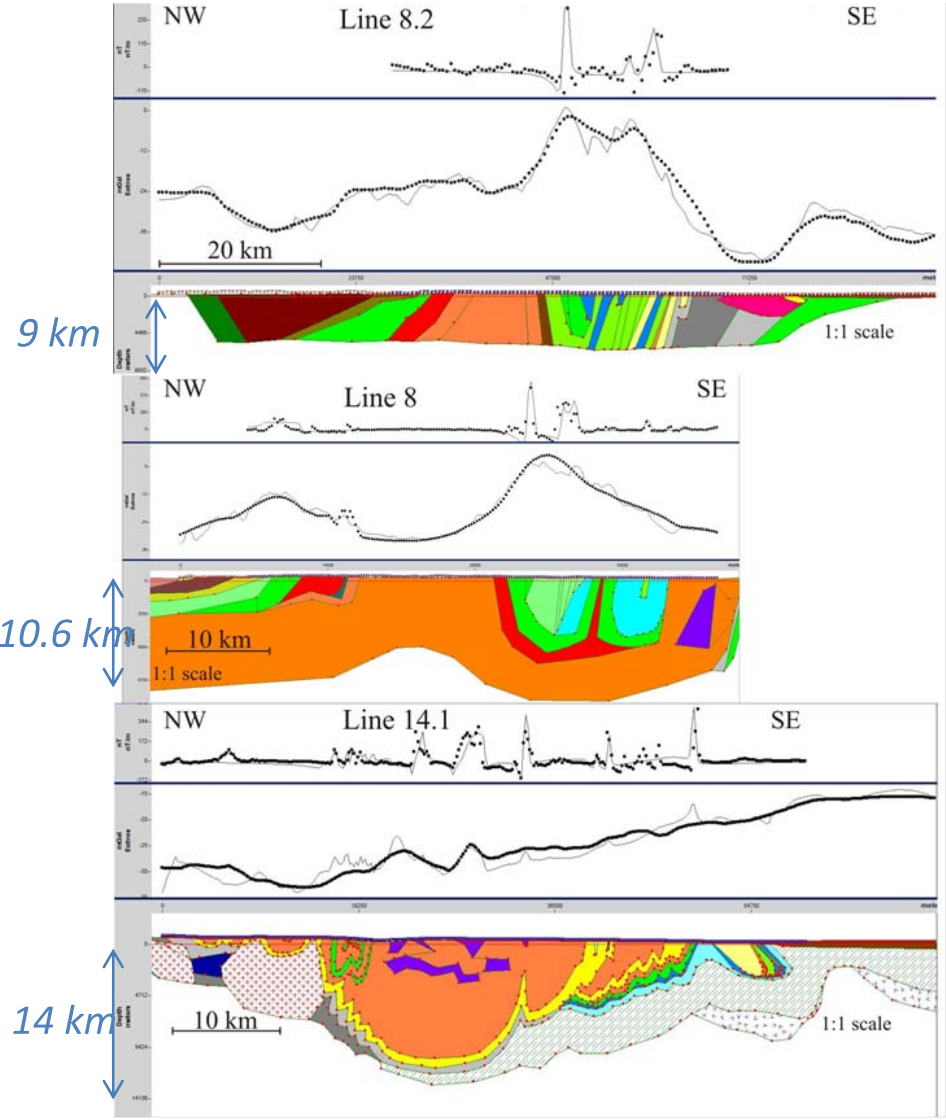
Bathurst Mining Camp



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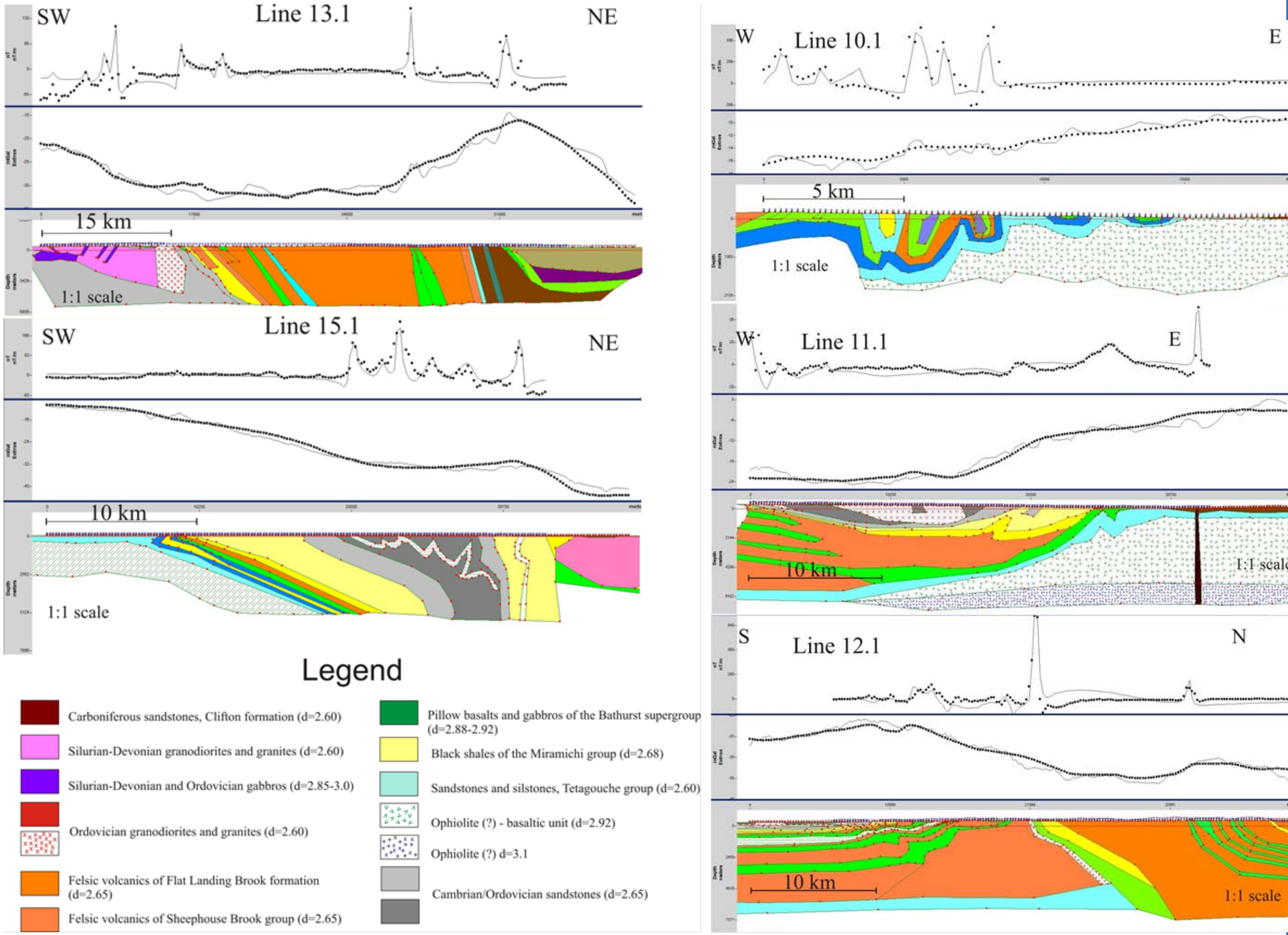
Bathurst Mining Camp



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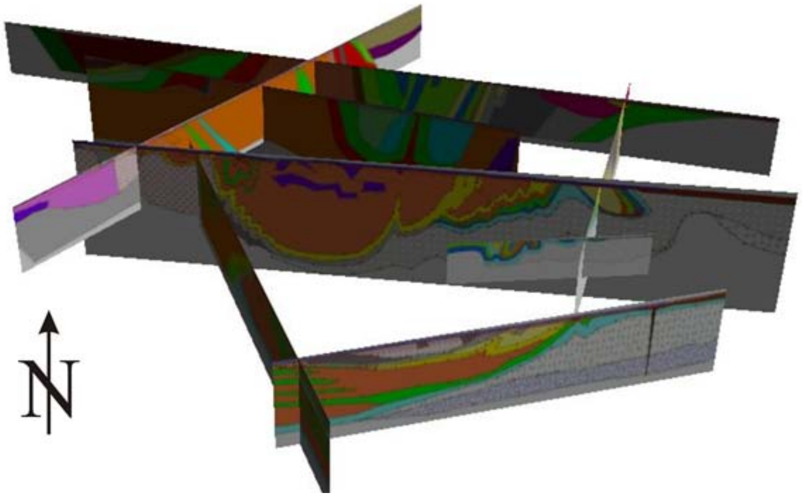
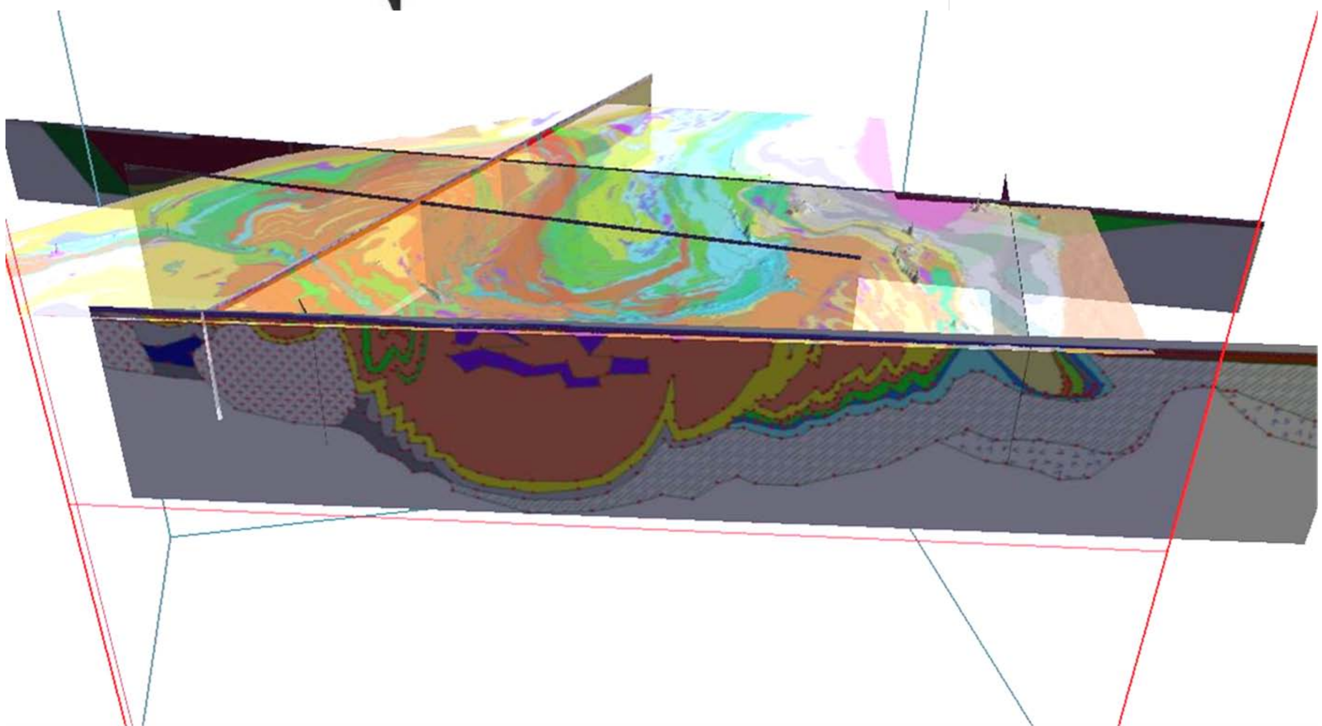
Bathurst Mining Camp





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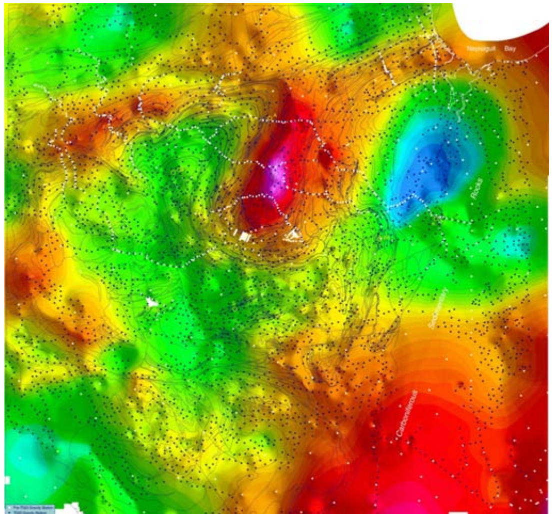
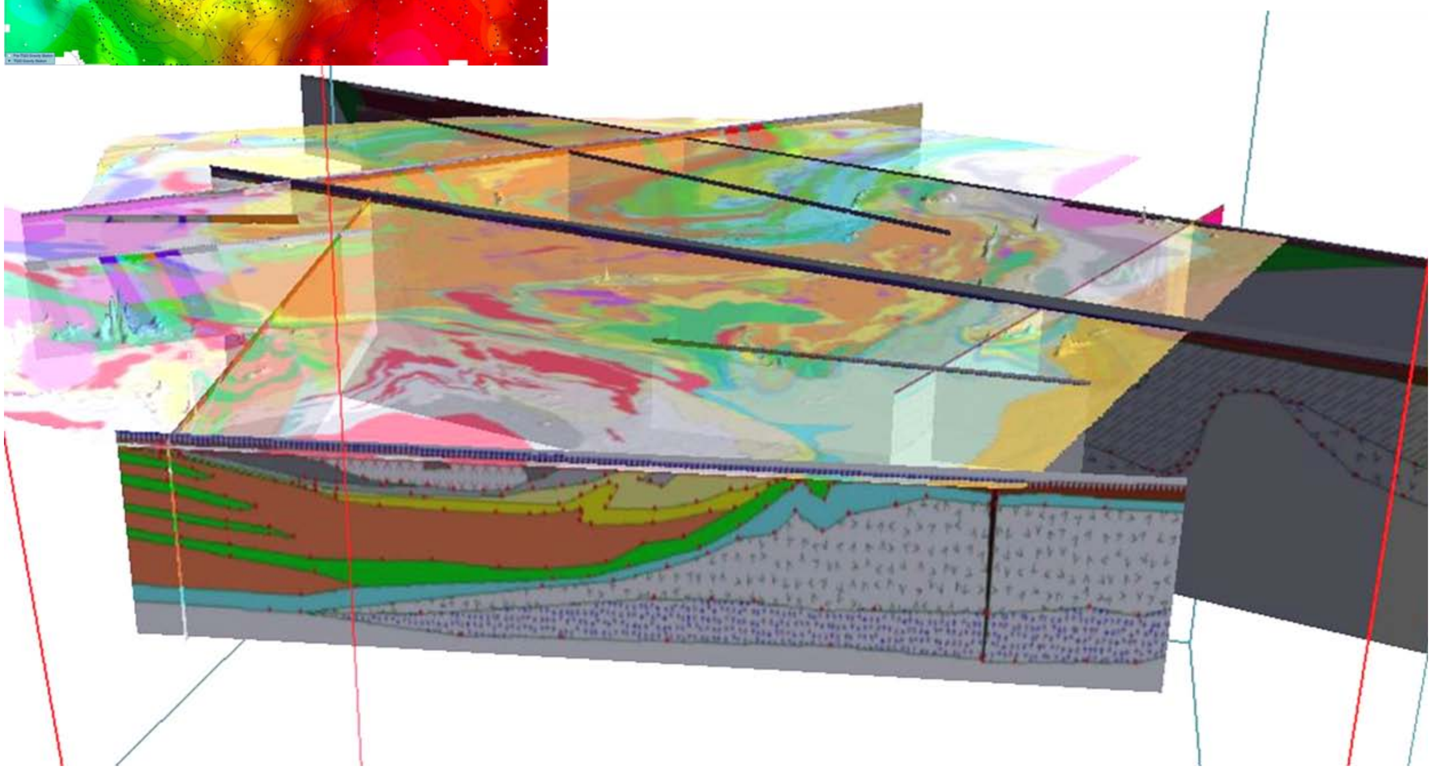
Bathurst Mining Camp





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Bathurst Mining Camp

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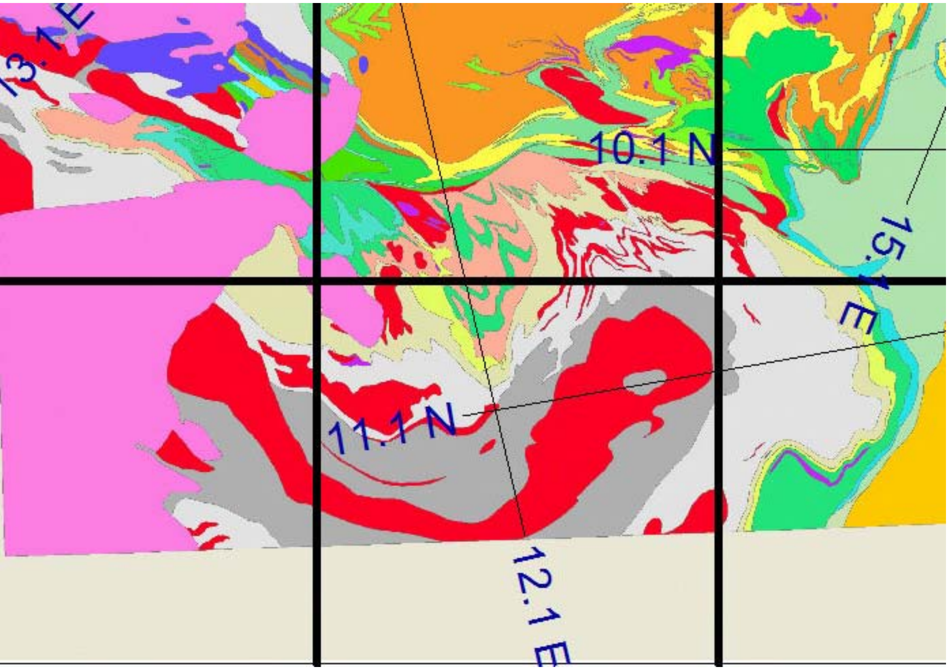
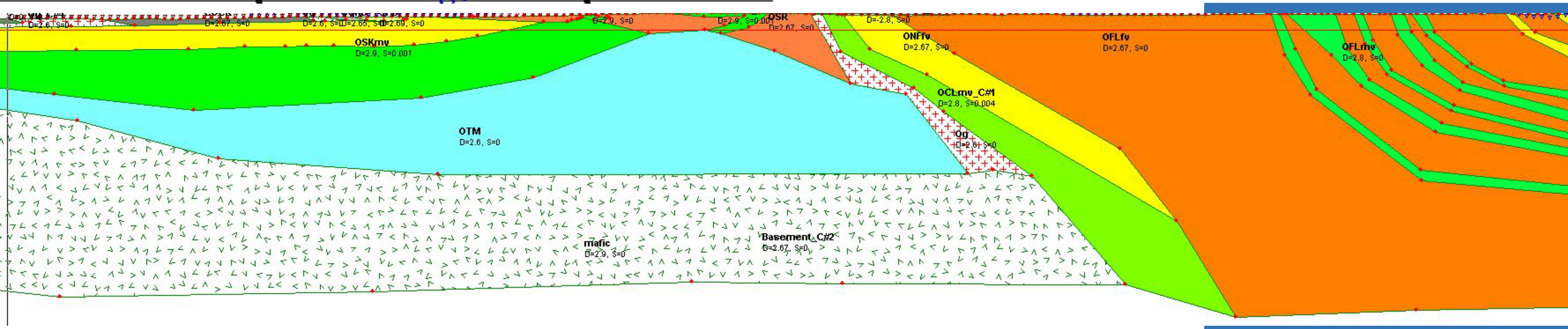


Modelling implies that the Miramichi and Mullin Stream Granite form a thin skin over the Clearwater Stream Formation that hosts the Chester deposit



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Summary of this exercise

- Geological modelling of mag & grav data combined with structural control provided a good definition of depth and geometry of volcanic units
- Mag data defined the geometry at surface; gravity data defined the depth of the different units
- Although the scale is large and outcrop is <10%, petrophysical database helped to constrain unknowns

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Case 1.5:
Caribou deposit, Bathurst, NB

- VMS deposit (Pb-Zn-Cu-Ag) located about 50 km west of Bathurst
- Dominated by the Caribou synform, which plunges steeply to the NE

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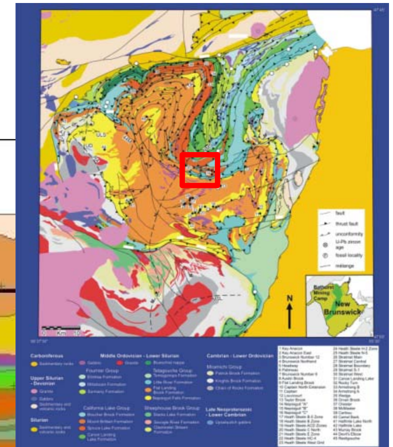
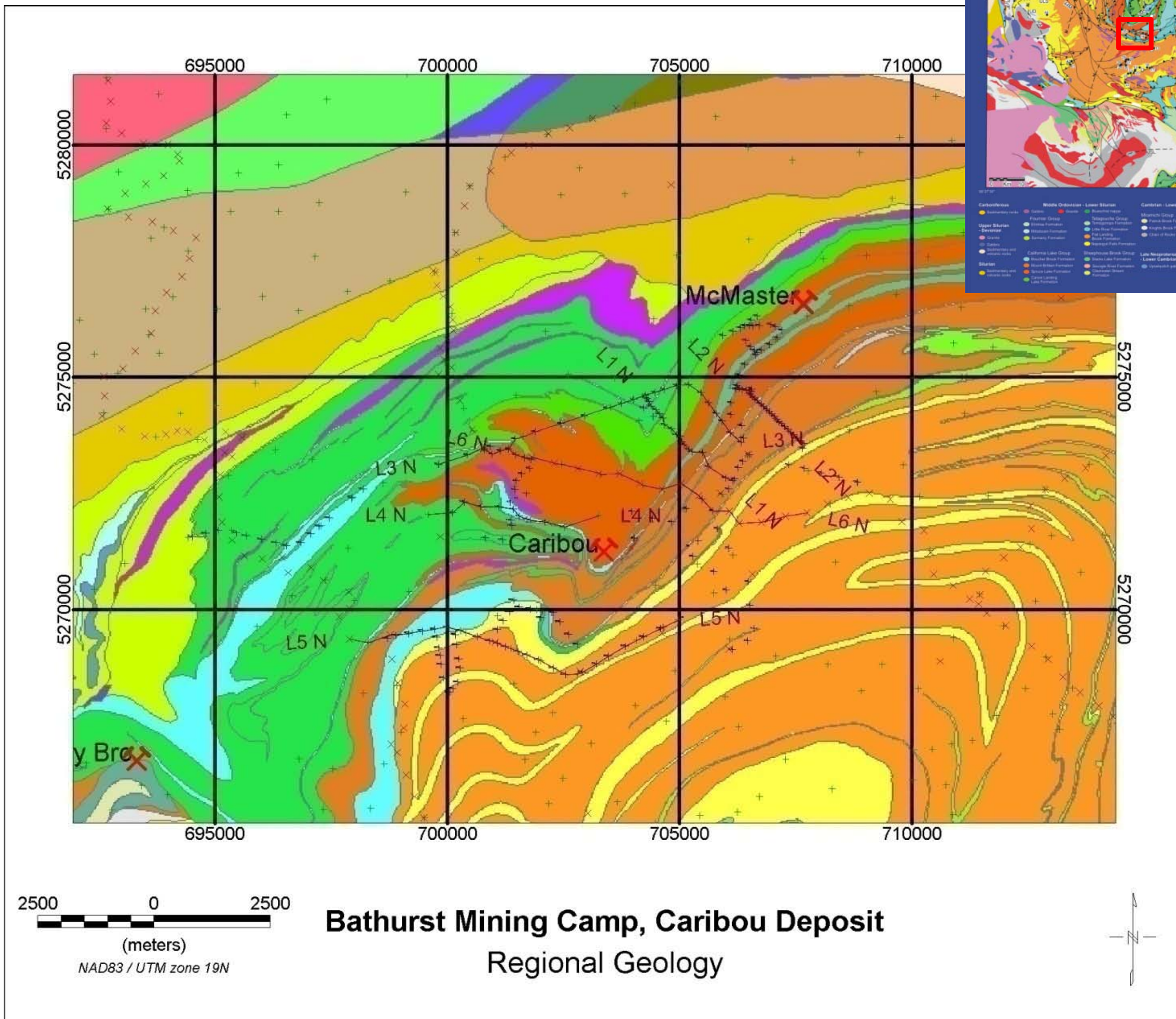
Caribou deposit: regional geology





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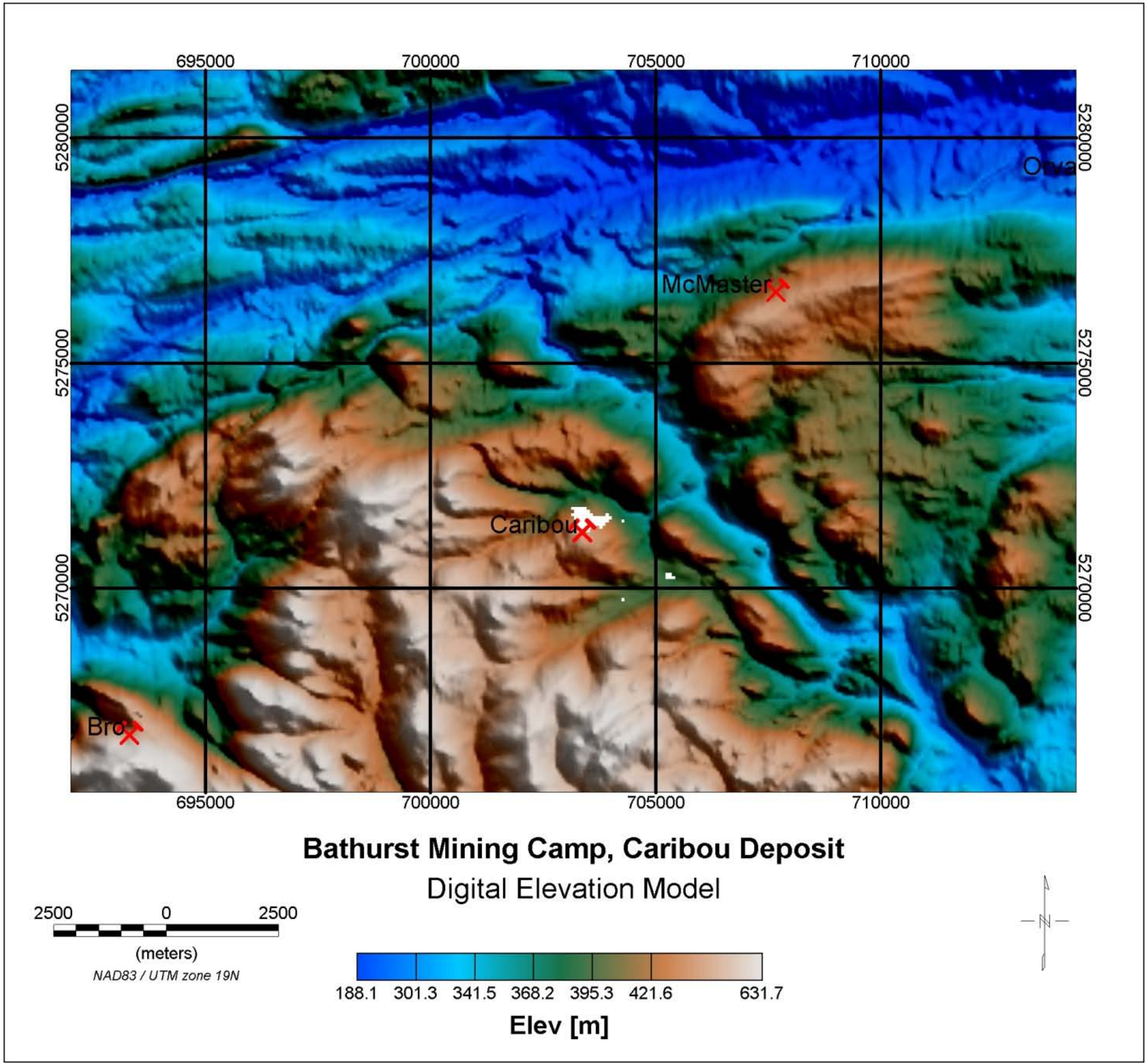
Caribou deposit: topography



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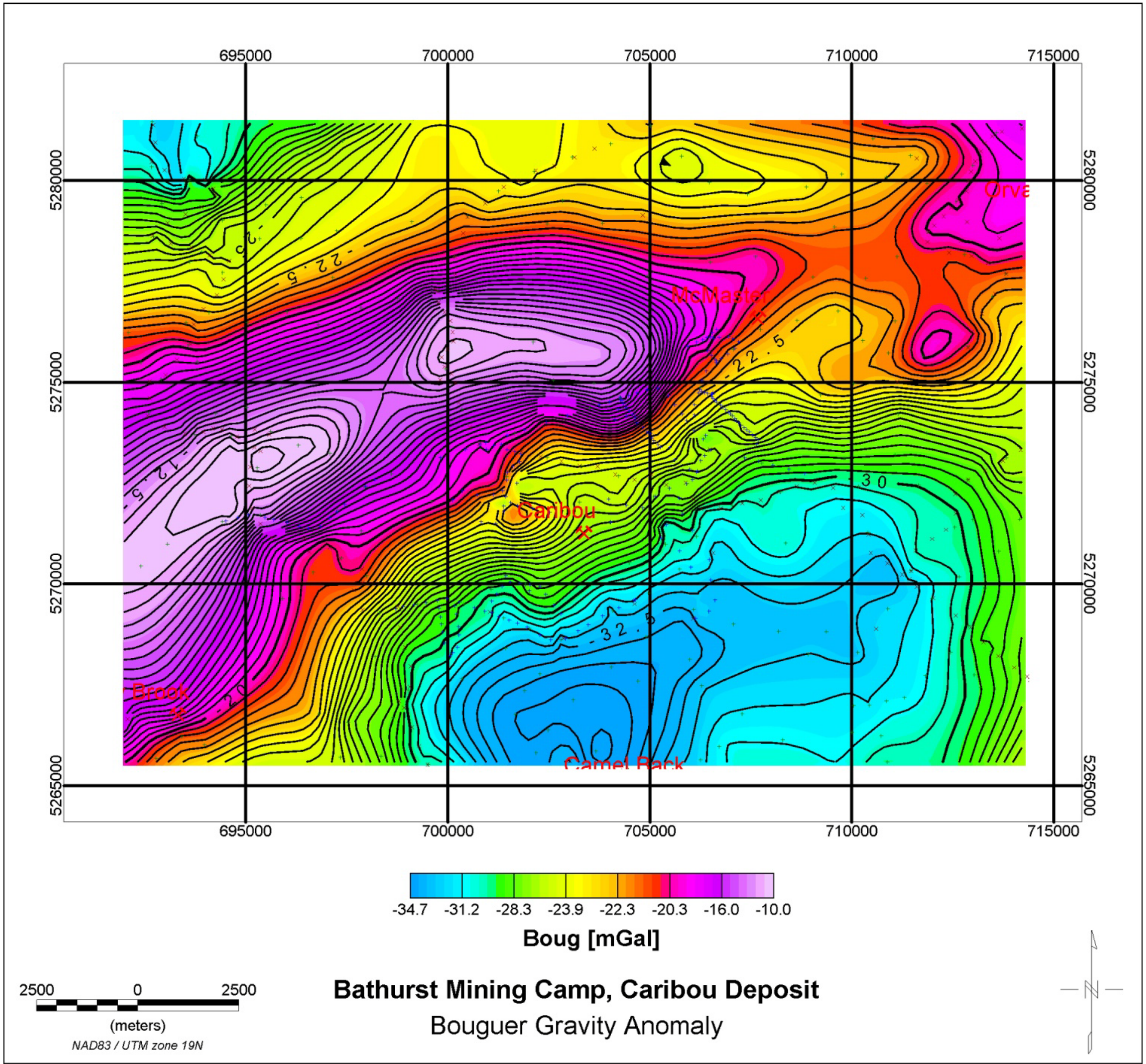
Caribou deposit: Bouguer grav



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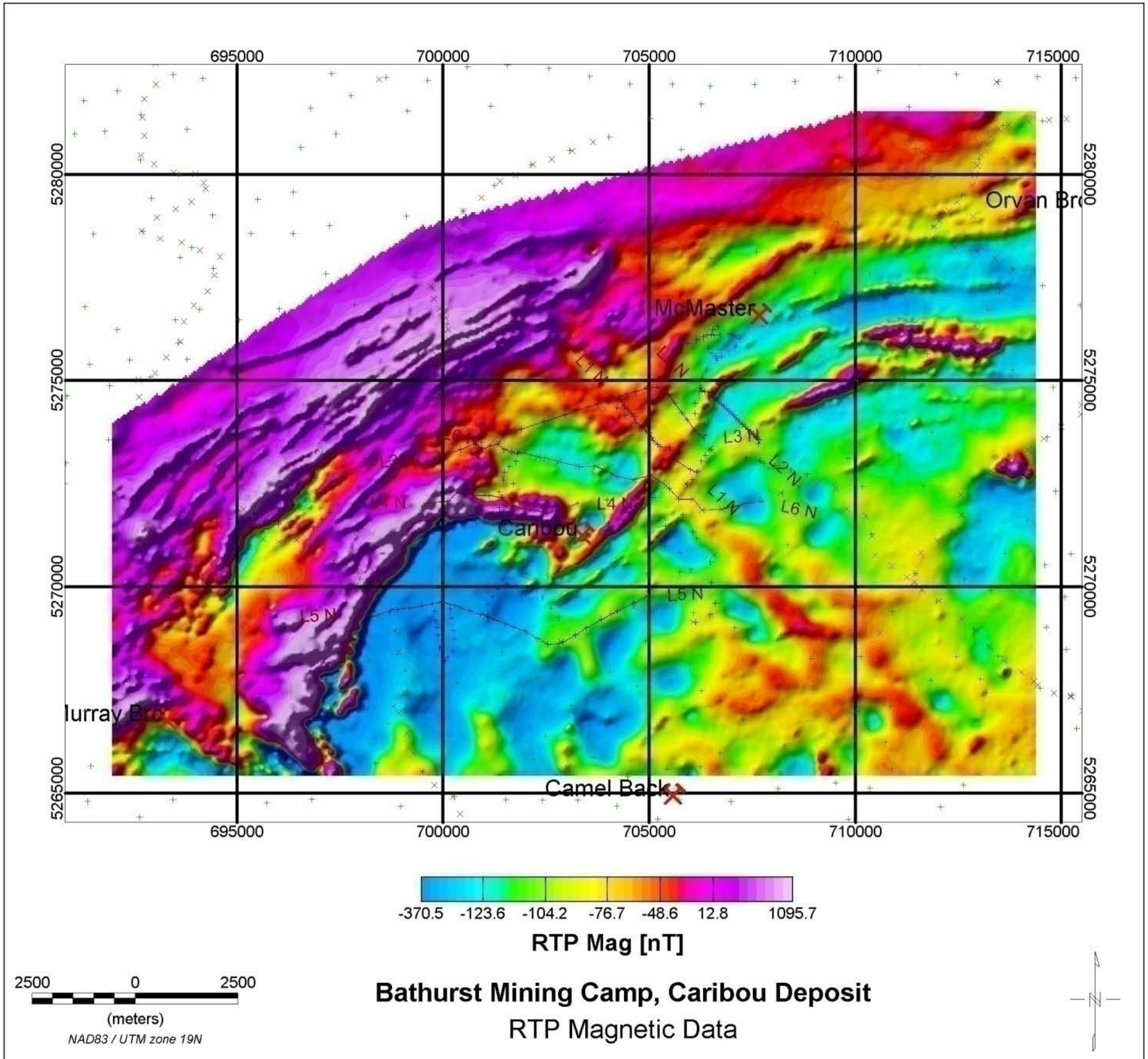
Caribou deposit: RTP mag



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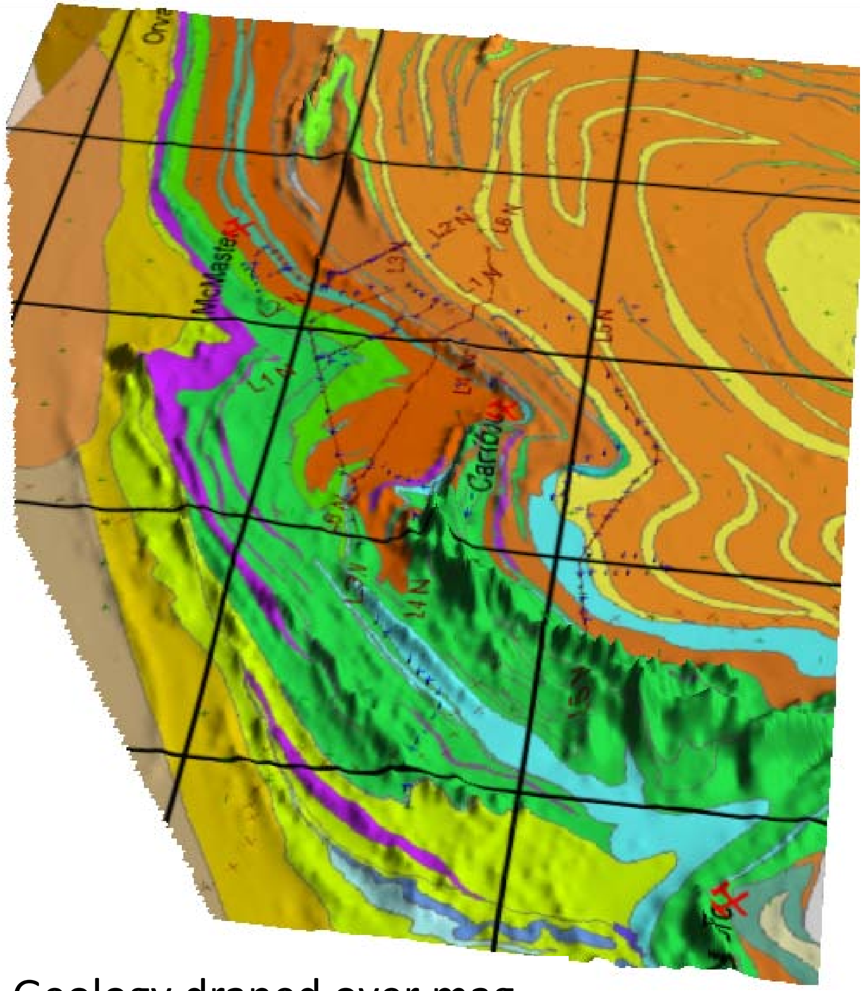
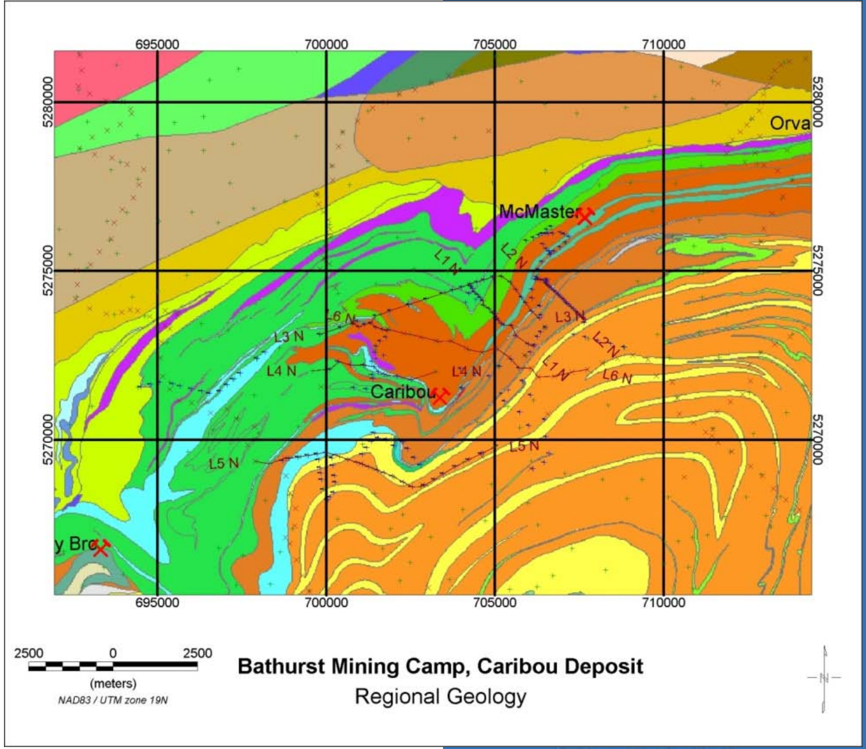
Caribou deposit: mag & geology



Geology draped over mag, looking from West



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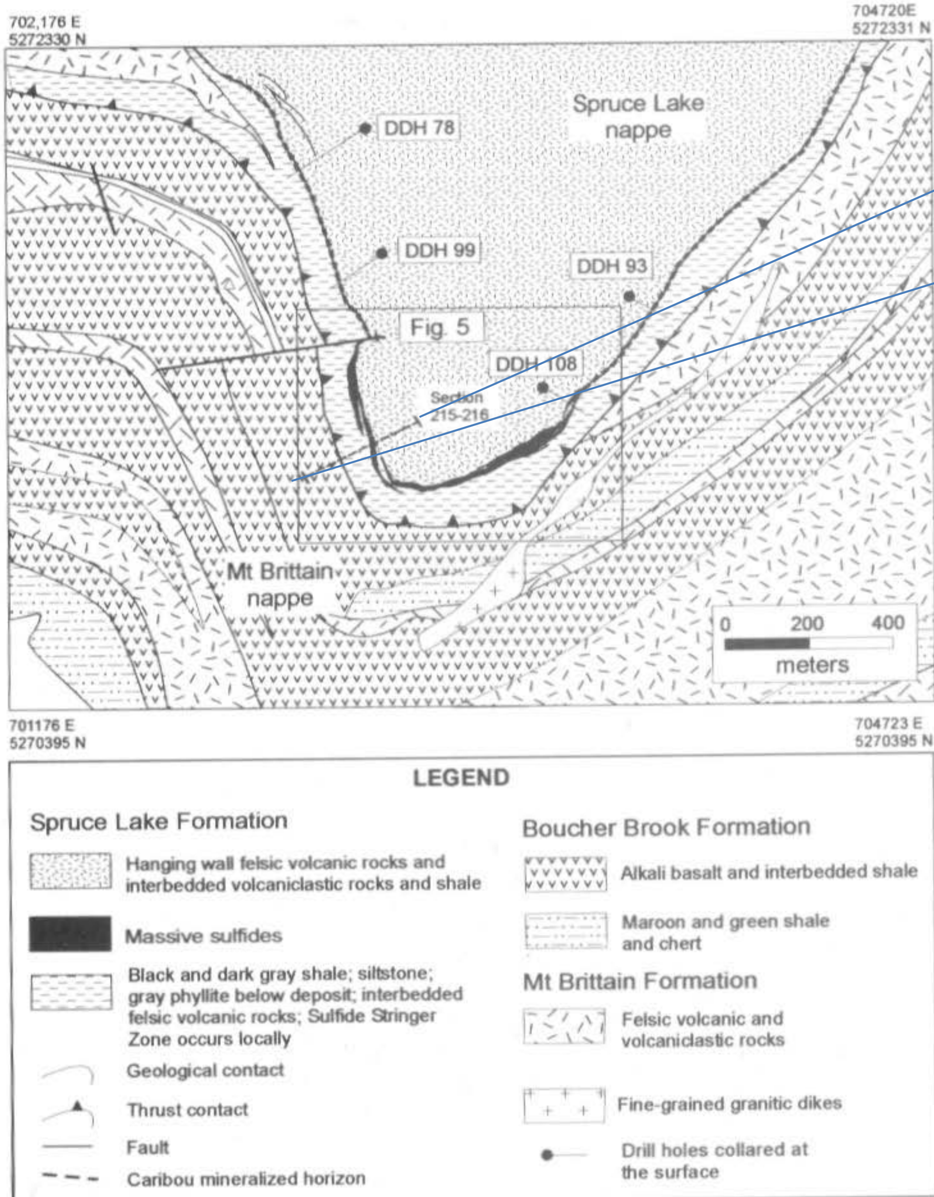
Conceptual model



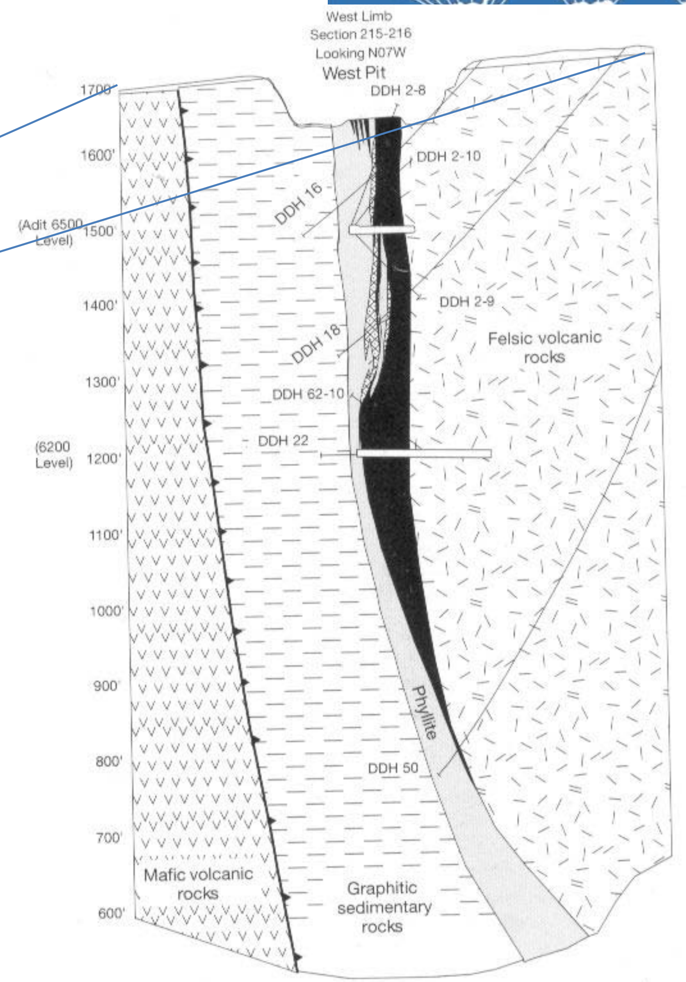
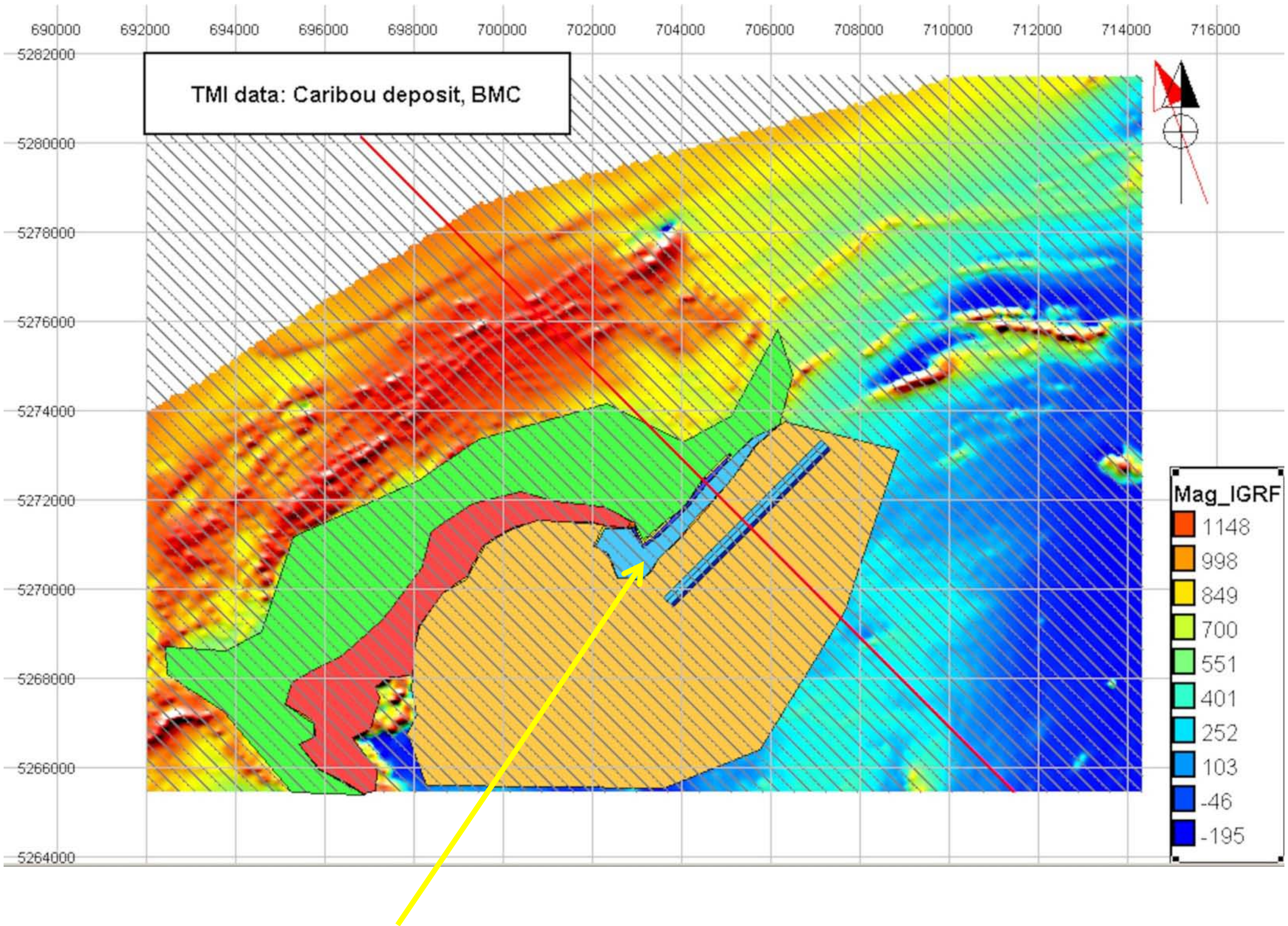


FIG. 2. Geologic cross section 215-216 of the west limb of the Caribou deposit, looking 7° west of north (modified from Cavelero, 1993). Geologic units and symbols are the same as those in Figures 1 and 5. Cross section is located on Figure 1.

(Goodfellow, 2003)

Mag model



Yellow: MS body
~ 10 m wide

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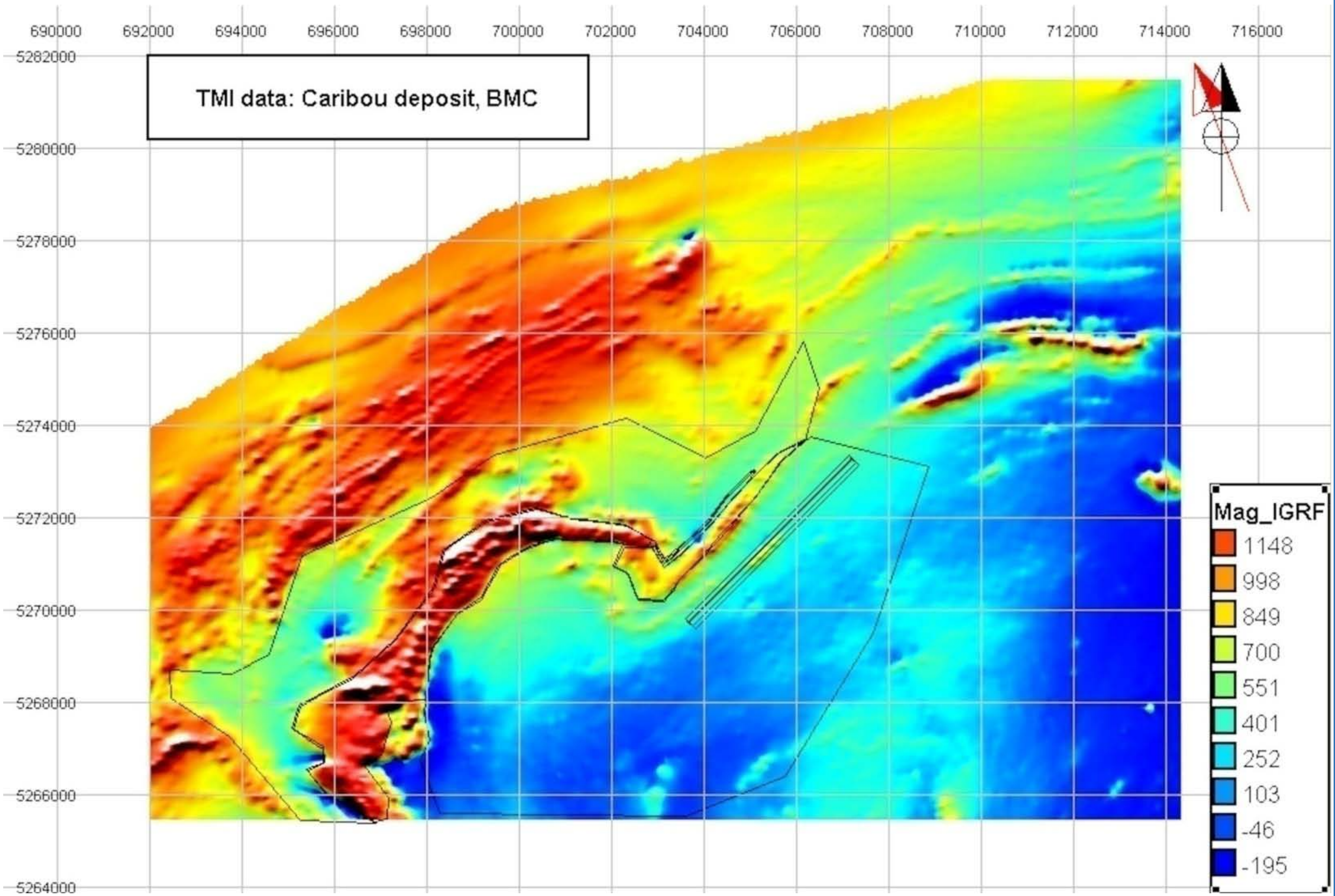
Mag model



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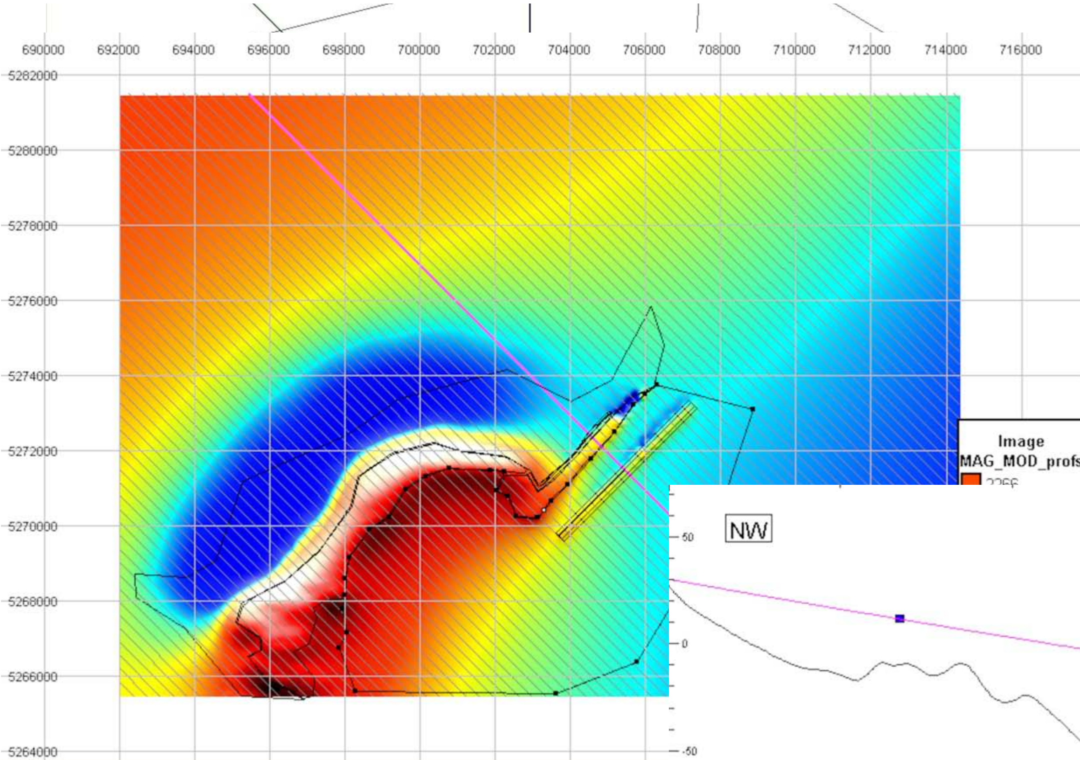
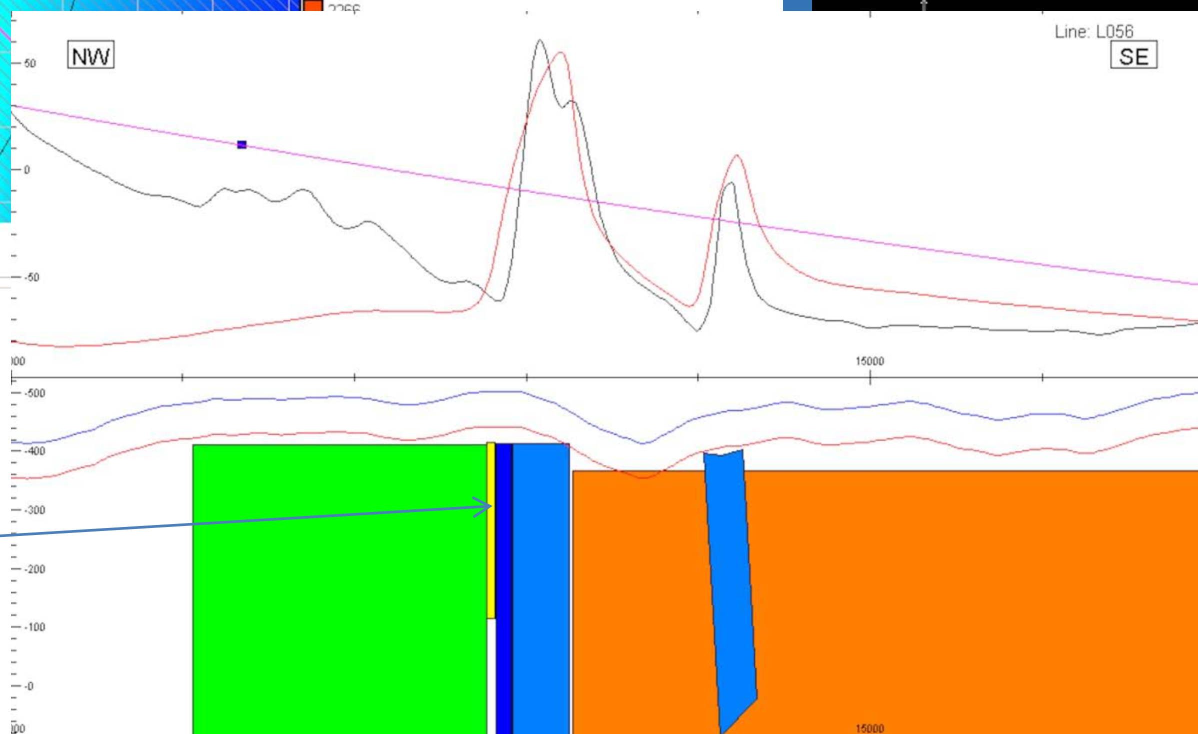
Mag model





MS Body

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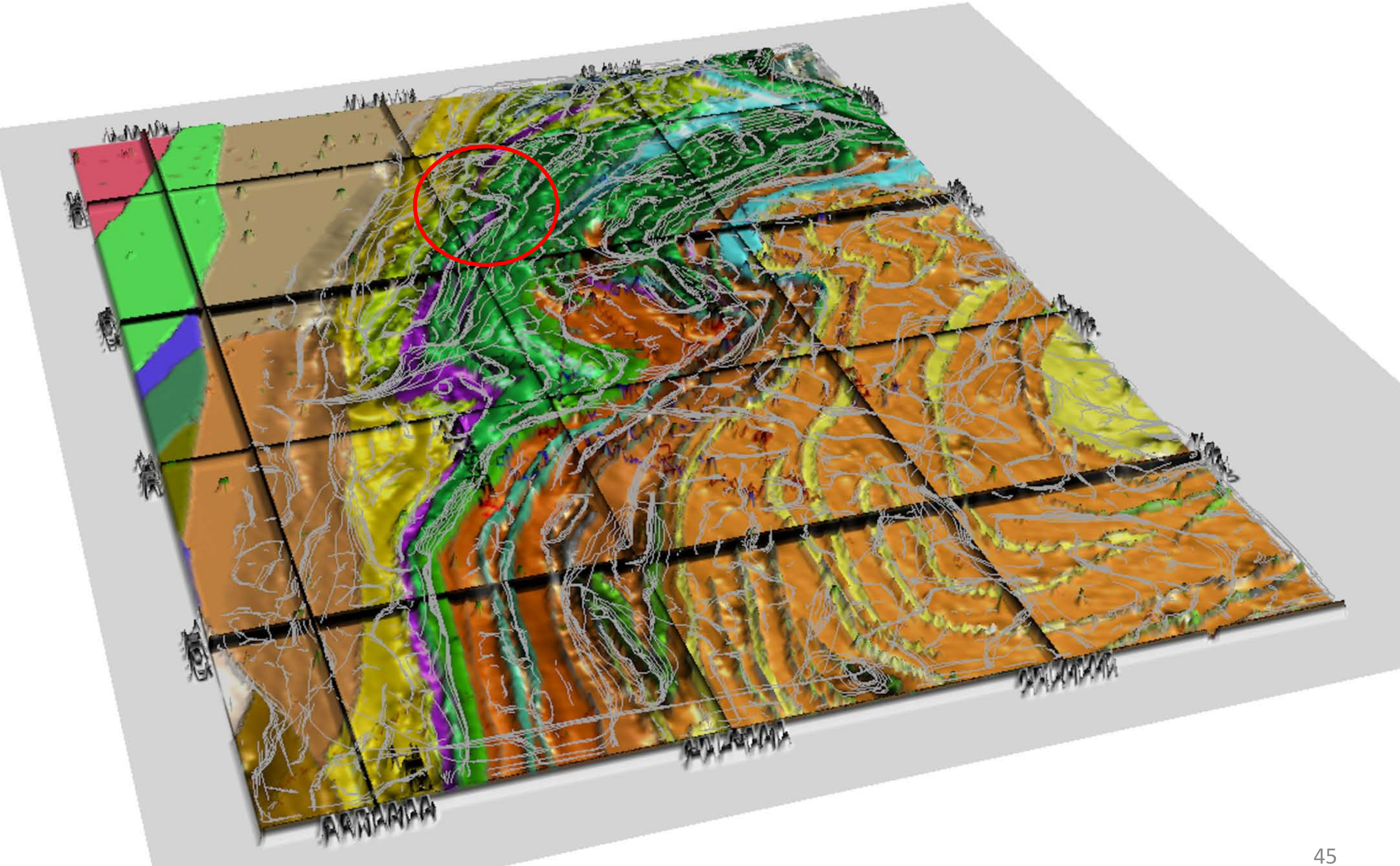
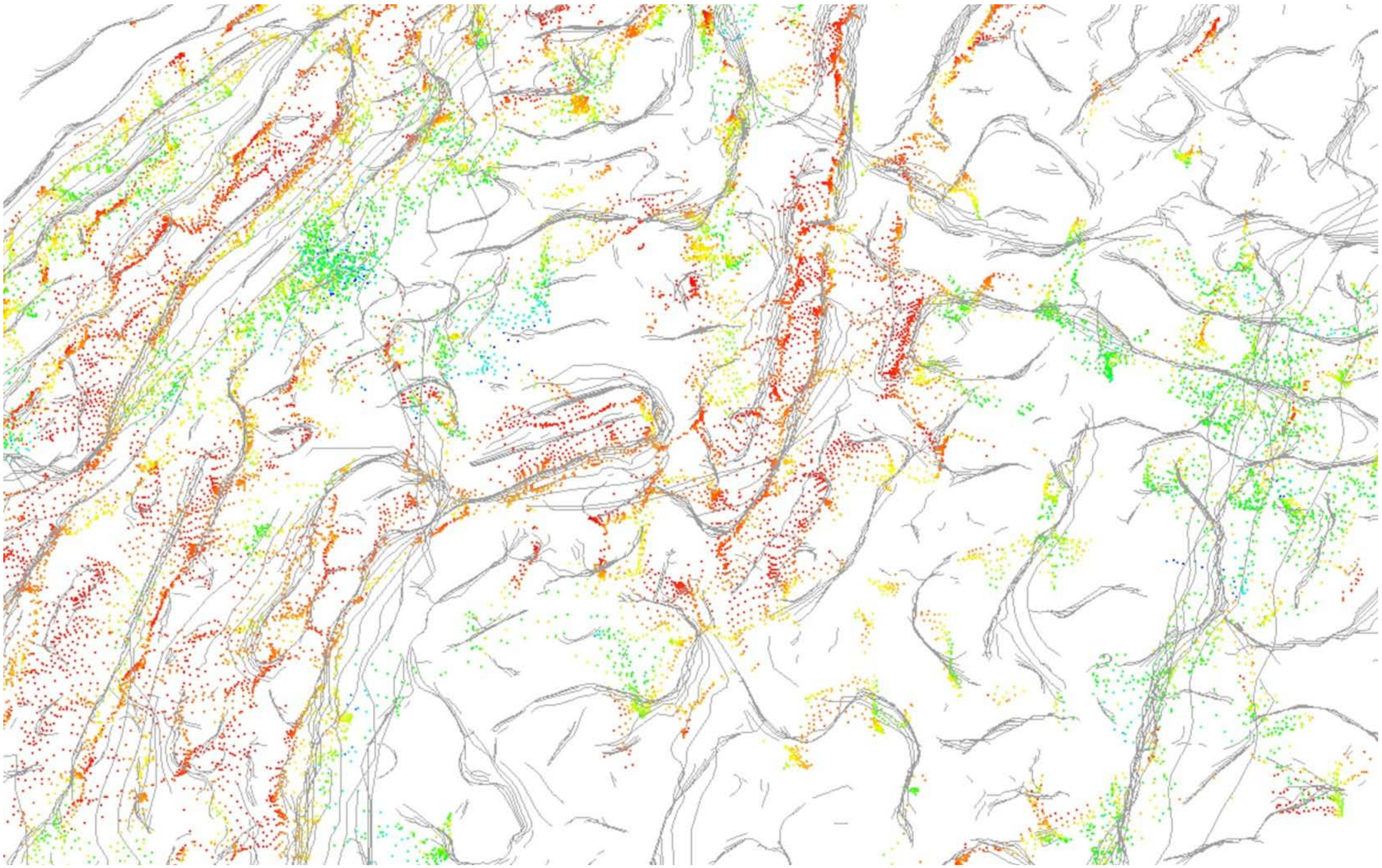
Mag refinements (worms)



Mag refinements (worms & Euler deconvolution)



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Caribou deposit: summary

- Gravity survey could not access the main mine operation
  - Not enough resolution over deposit area
  - Can not see the main sulphides area
- Magnetics is able to see the main volcanic units, but the signal is not coming from the sulphides (again, resolution and sampling issues, and property contrast)
- Geophysics should be aimed at mapping structure important for VMS emplacement/control/geometry

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Case 2:
Iron Ore exploration project, NWT

- Target: iron formation within the Rapitan Group
- Late Precambrian age
- Rapitan Group contains abundant evidence of glaciogenic deposition. It includes massive mixtites which contain numerous faceted and striated clasts. Finely bedded and laminated sedimentary rocks of the Lower Rapitan contain many large isolated intra- and extra-basinal clasts
- The iron formation (IF) is interbedded with thin mixtite beds and contains large exotic clasts

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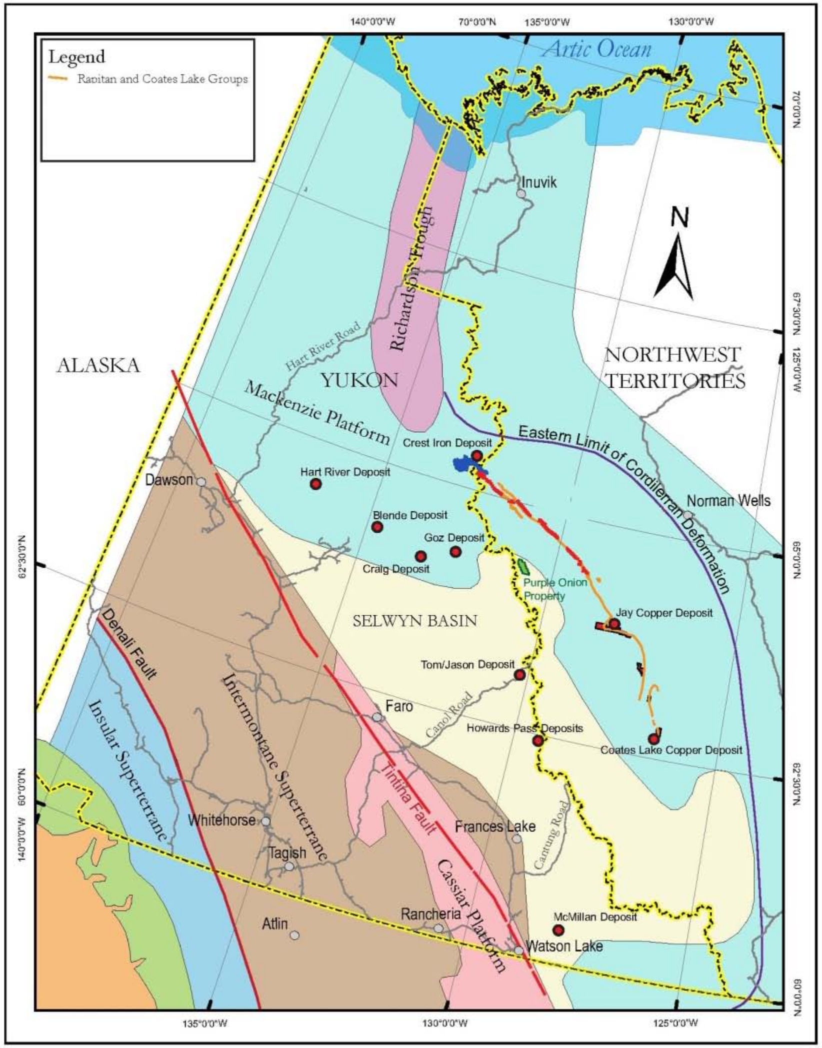
Case 2:
Iron Ore exploration project, NWT



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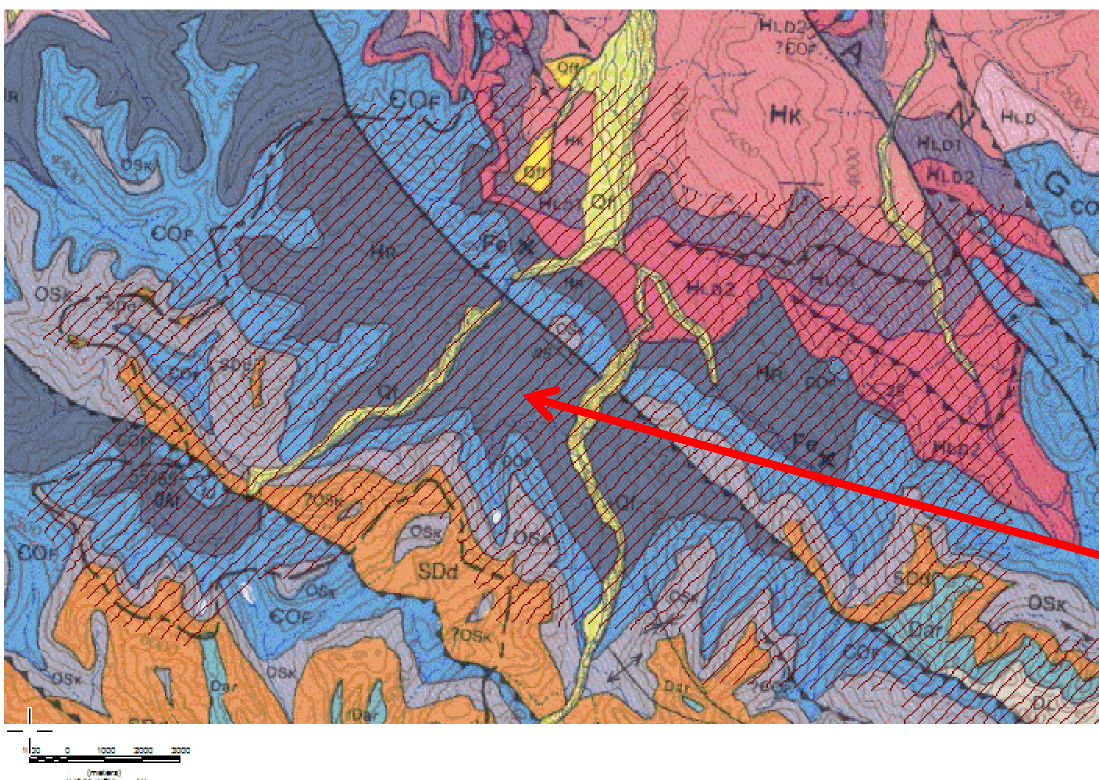

Case 2:
Iron Ore exploration project, NWT

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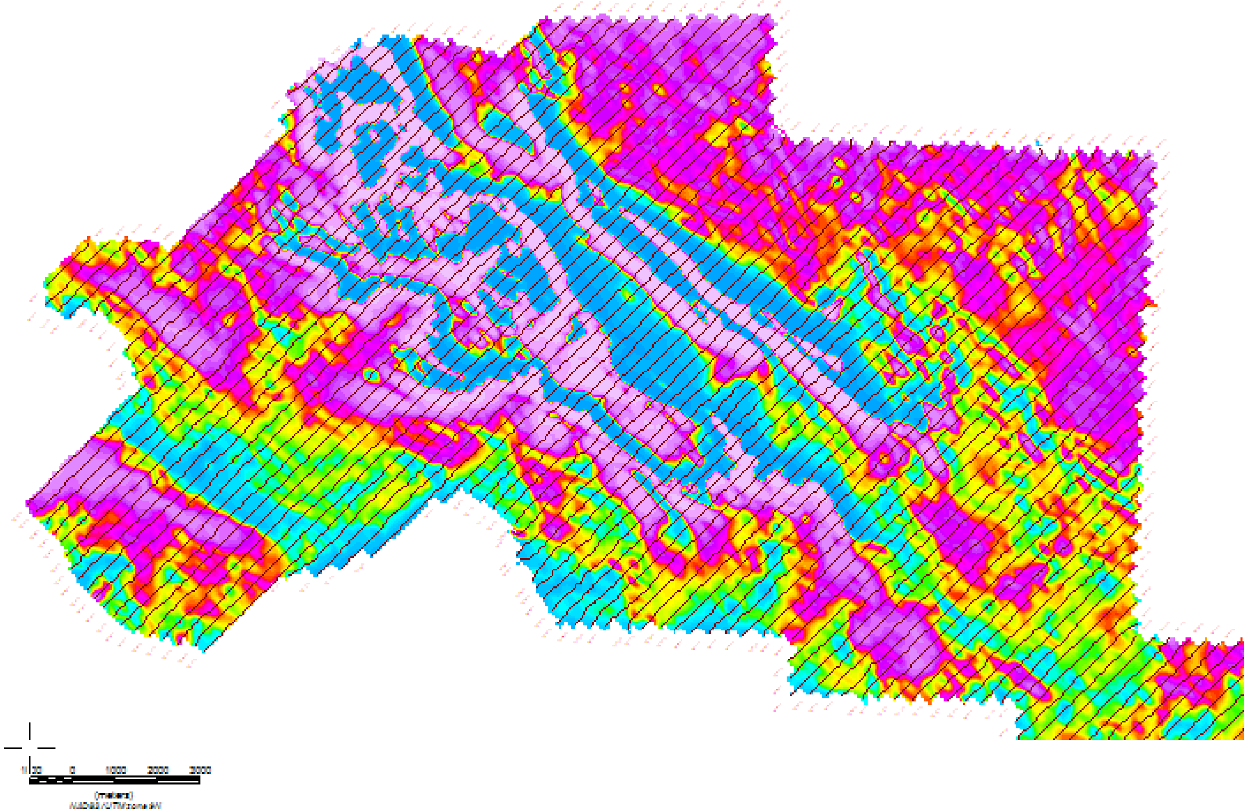

RTP_1VD Magnetics

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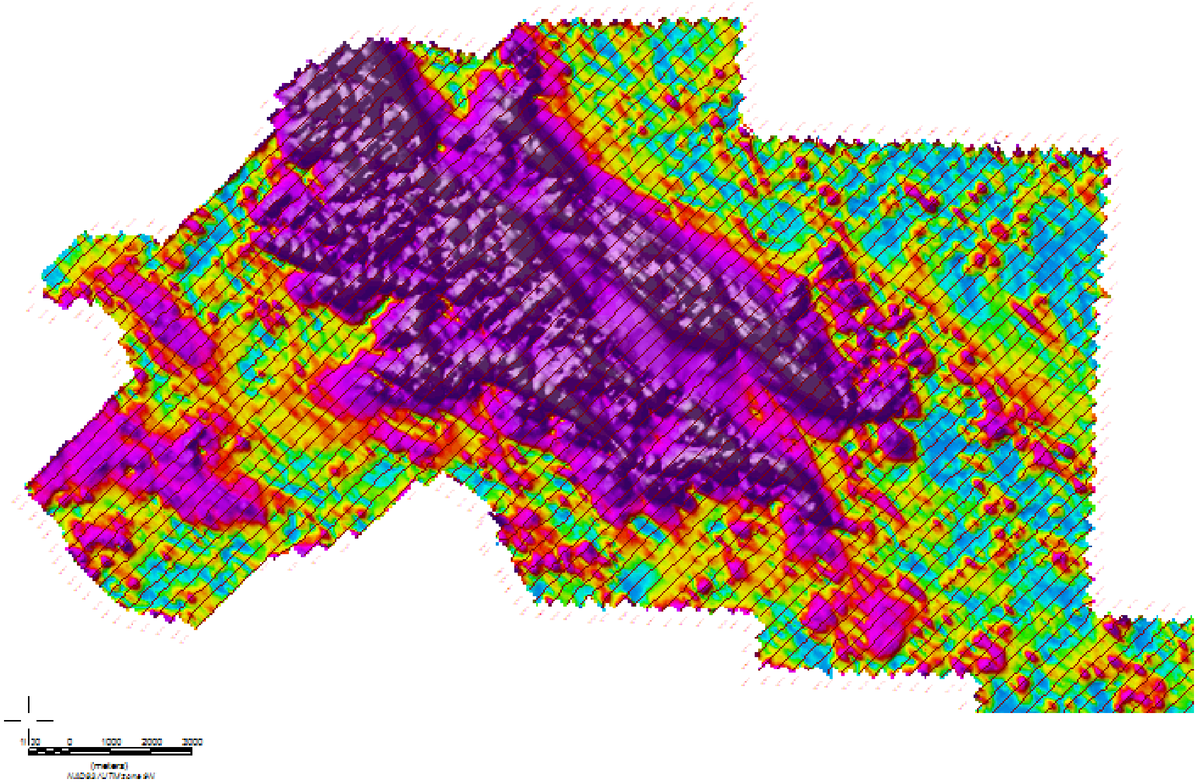

Amplitude of Analytic Signal (of TMI)

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Case 2:
Iron Ore exploration project, NWT

- ASIG exhibits high intensity and extended magnetic anomalies
- Fe target? All good!
- Interpretation 1:
  - Outline main magnetic horizons and recommend ground check

(Translated: try to get the VP Exploration a bit less excited about the mag anomalies and convince him to check before drilling…)

Case 2:
Iron Ore exploration project, NWT

- Ground follow-up (field mapping, susceptibility measurements & ground magnetic survey) results
  - IF non magnetic (hematite)
  - There is a large magnetic conglomerate unit ABOVE the IF
  - Secondary magnetic unit below the IF

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Case 2:
Iron Ore exploration project, NWT

- Option 1:
  - Say that geophysics does not work and look at something else.
- Option 2:
  - We already got the data. Let's try to get the most out of it…➔Model 2D sections for improved geologic control (*non direct targetting*)

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Case 2:
Iron Ore exploration project, NWT

Legend for all models:

- Carbonates from Mount Kindle formation. Non-magnetic (k=0.0)
- Carbonates from Mount Kindle and Franklin Mountain formations (undifferentiated). Non-magnetic (k=0.0)
- Non-magnetic Keele (HK) Formation (k=0.0)
- Non-magnetic Little Dal (HLD2) Formation (k=0.0)
- Non-magnetic Little Dal (HLD1) Formation (k=0.0)
- High-magnetic Sayunei (directly above IF; k=0.002)
- Iron Formation (non-magnetic; k=0.0)
- Moderately-magnetic Sayunei (directly below IF; k=0.0011)
- Undifferentiated non-magnetic Rapitan units (k=0.0)

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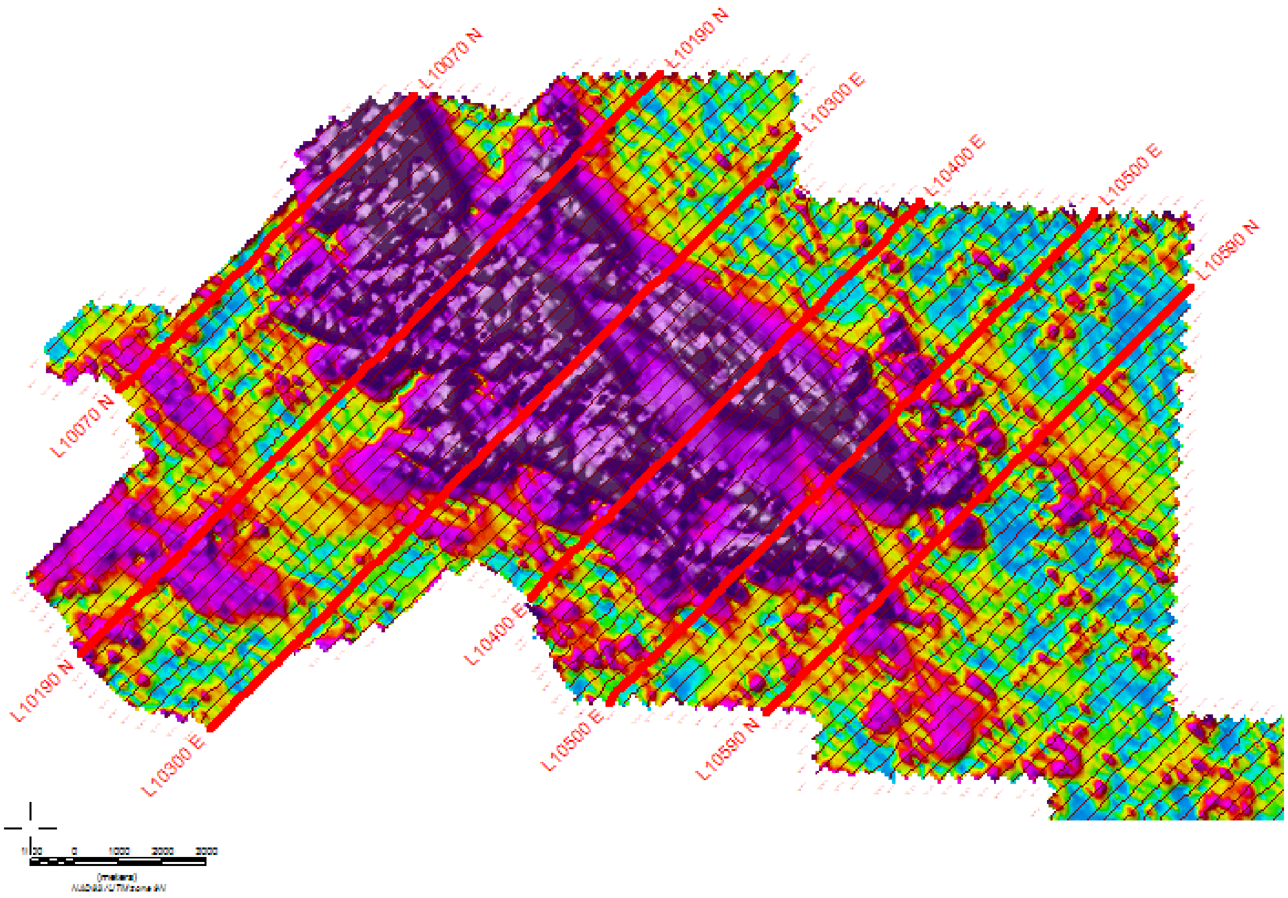

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Case 2:
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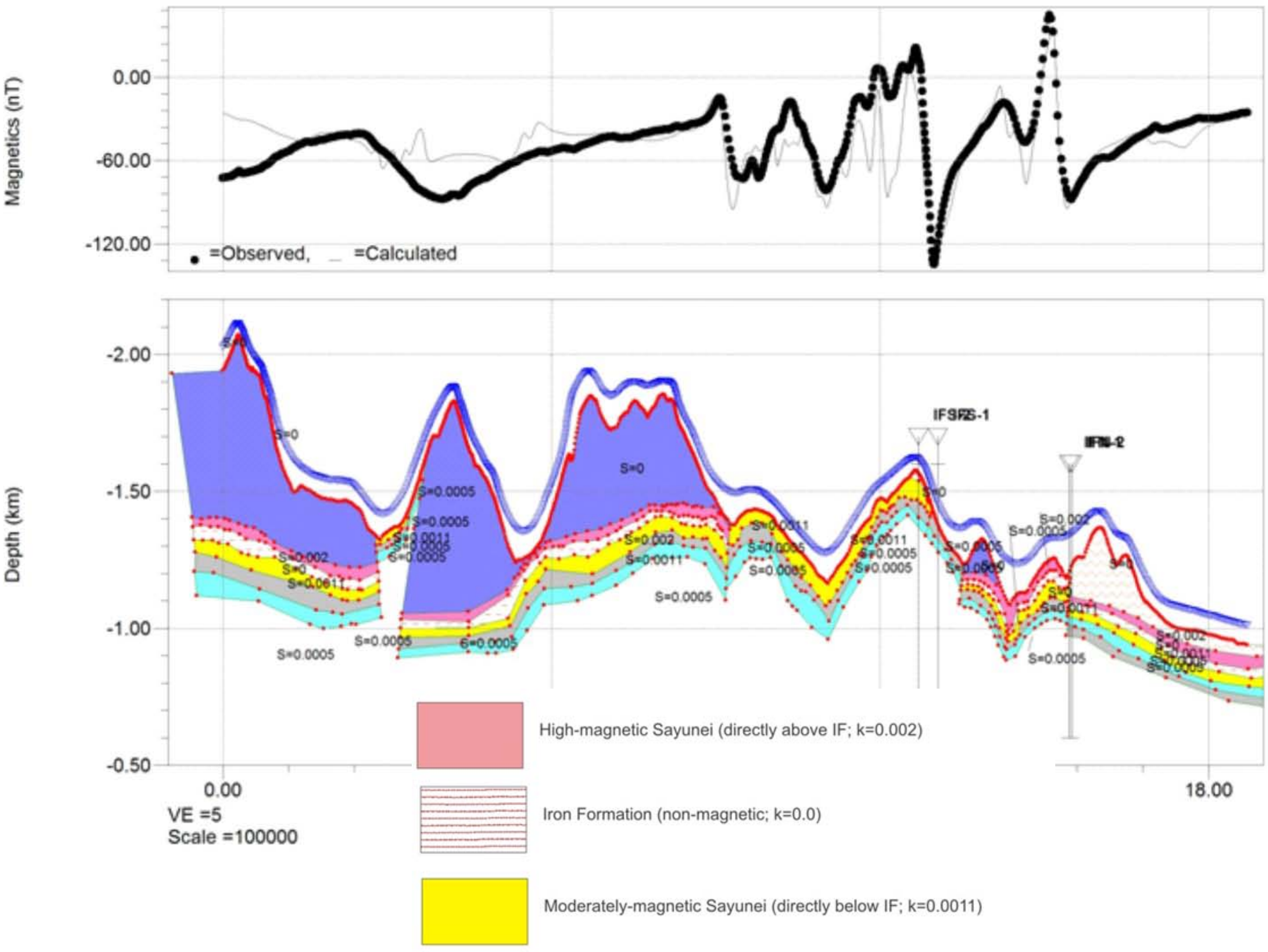

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Case 2:
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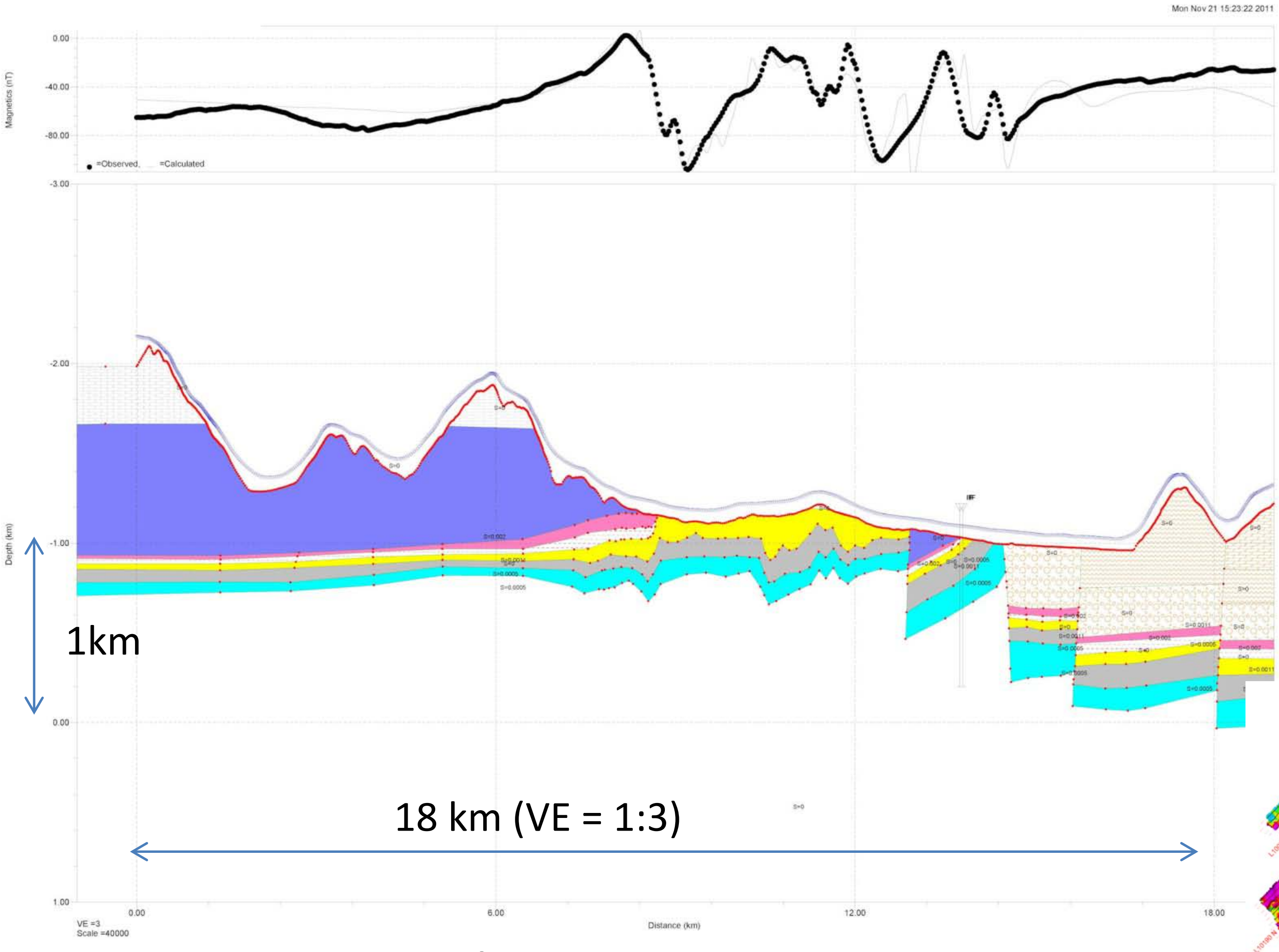
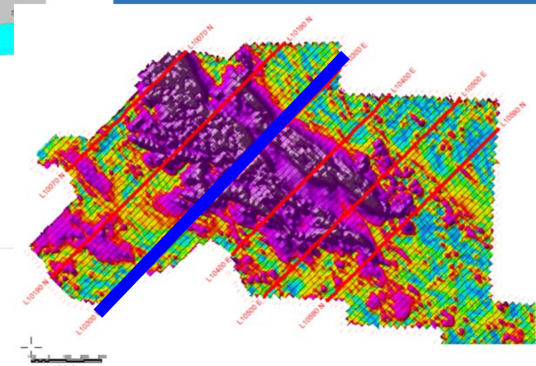


Line 10300



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Case 2:
Iron Ore exploration project, NWT

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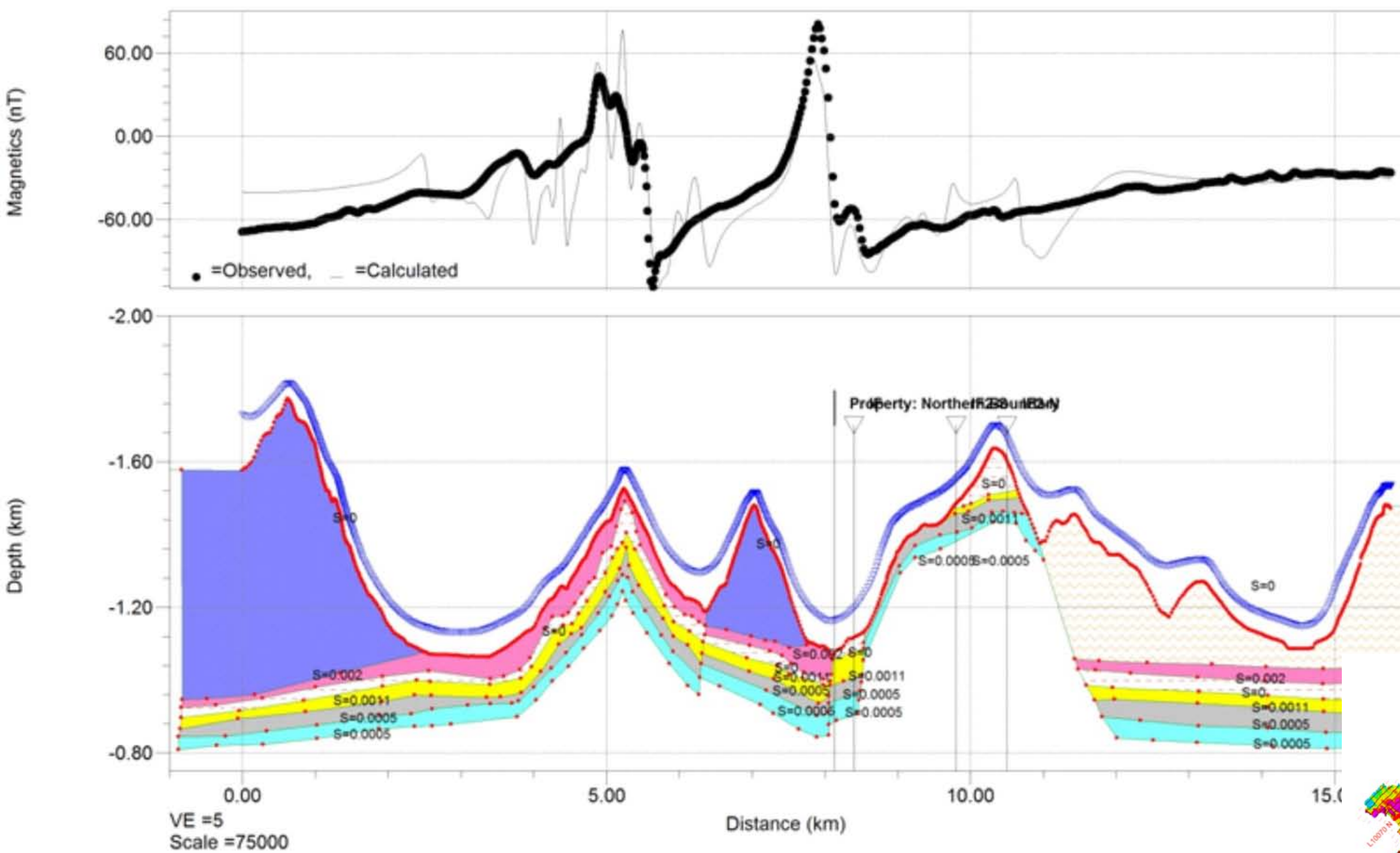

Line 10500

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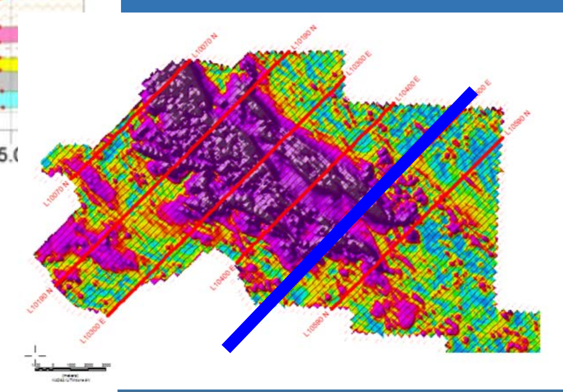
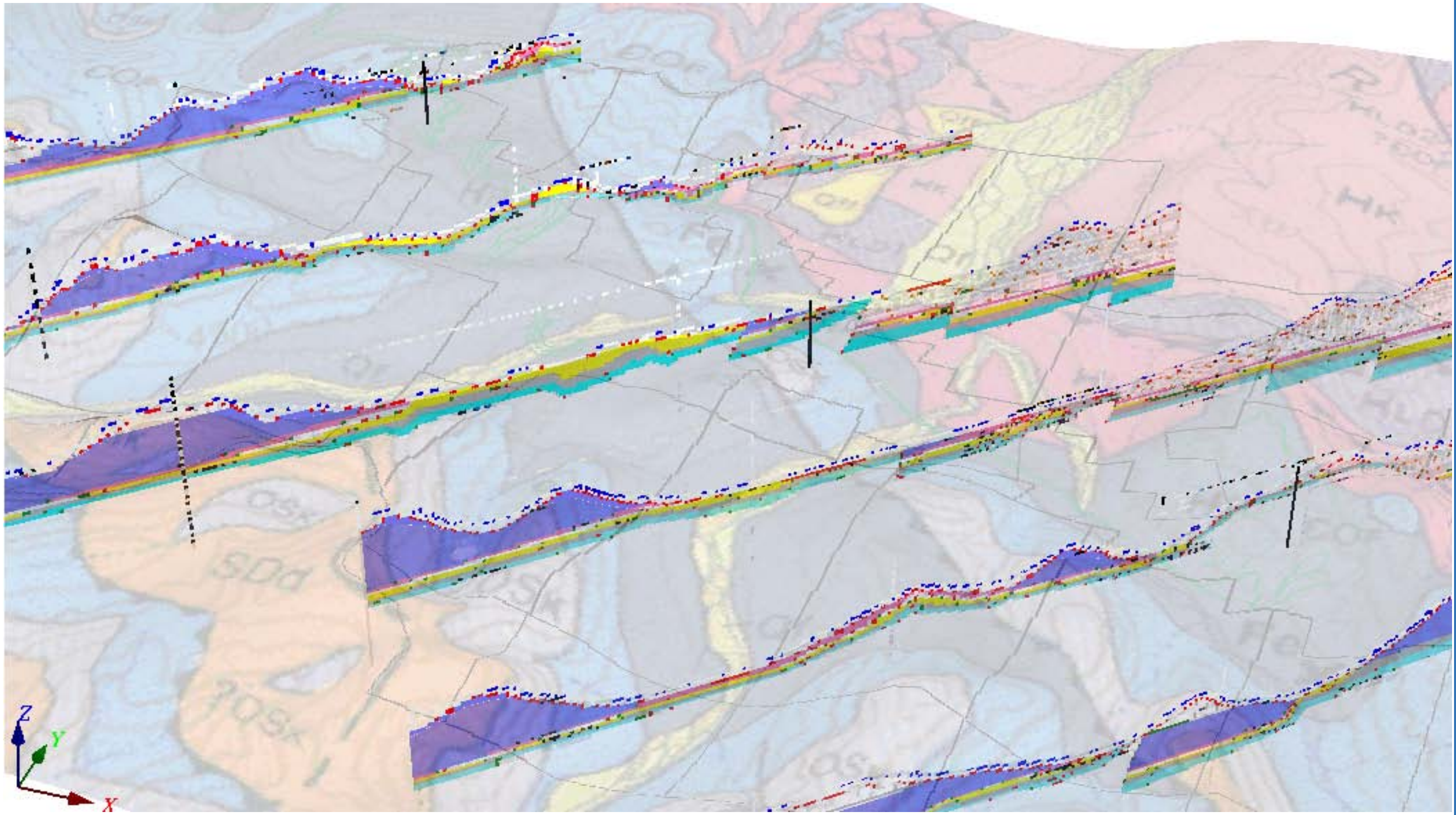


Case 2:
Iron Ore exploration project, NWT



3D model integration

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Case 2:
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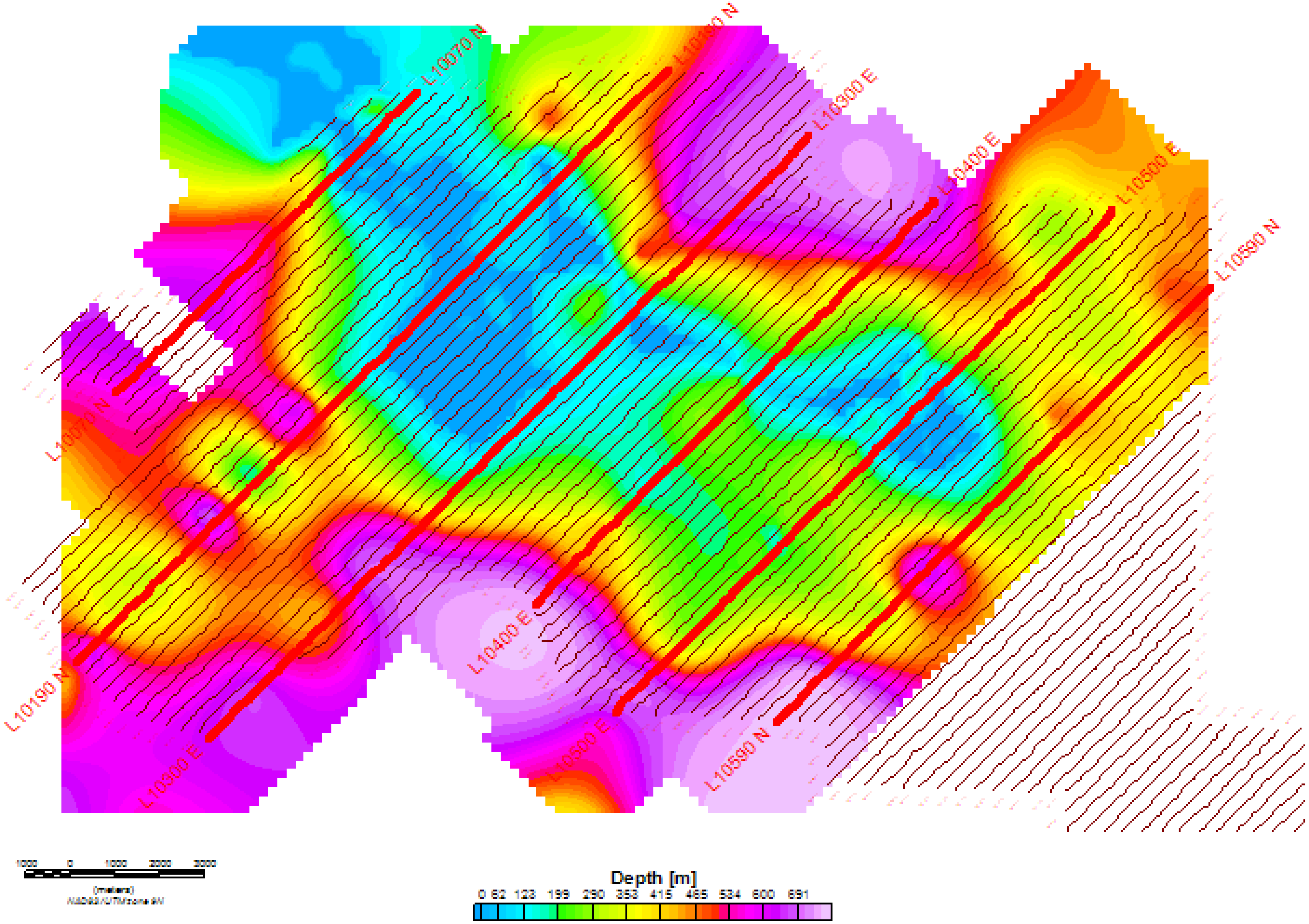

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Final: target definition, depth to IF

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Conclusions for this study

- 2D modelling, although "less sexy" than a 3D voxel gives the user full control on the geological constraints
  - Ability to obtain geometry (strike, dips), depth extension (depending on physical property contrast) and important structural information (folds & faults)
- Non-direct targetting & thinking out of the box allowed the generation of a wealth of geological information, even on less than favourable conditions (not magnetic target)

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So…do we invert in 3D?

- We know that modelling of geophysical data is not-unique
- Unless we have proper ground control (boreholes, mapping, physical properties), 3D inversions are very risky
- Building a “proper” 3D model (including all the above) is very time consuming, and it requires data that we can use as a control
- Rock properties!!

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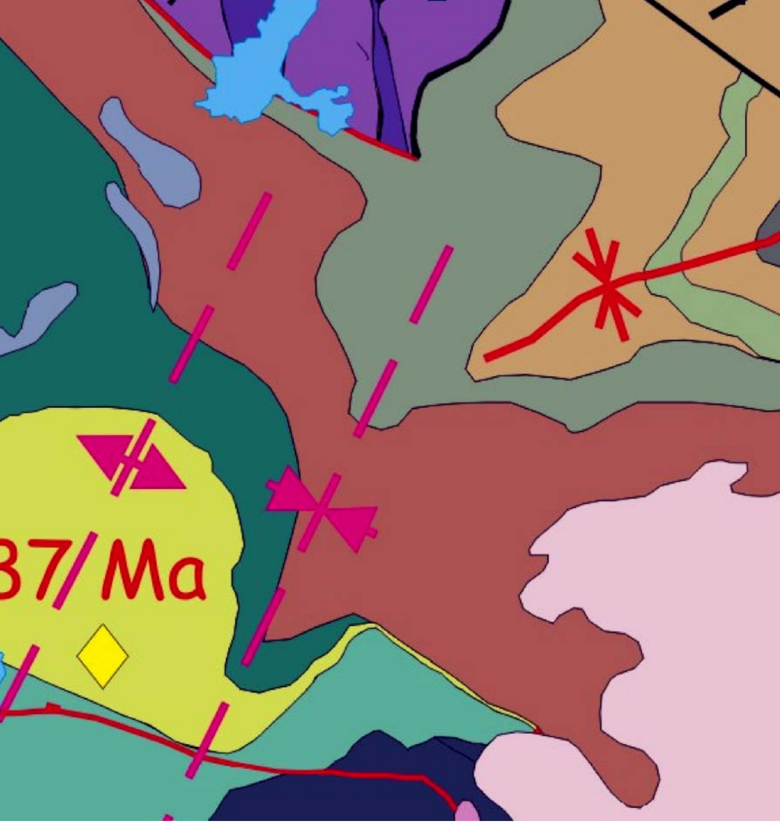

Geologically Constrained Inversion Surface geology and boreholes

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Convert Maps to geologic models
Then assign physical properties to units…

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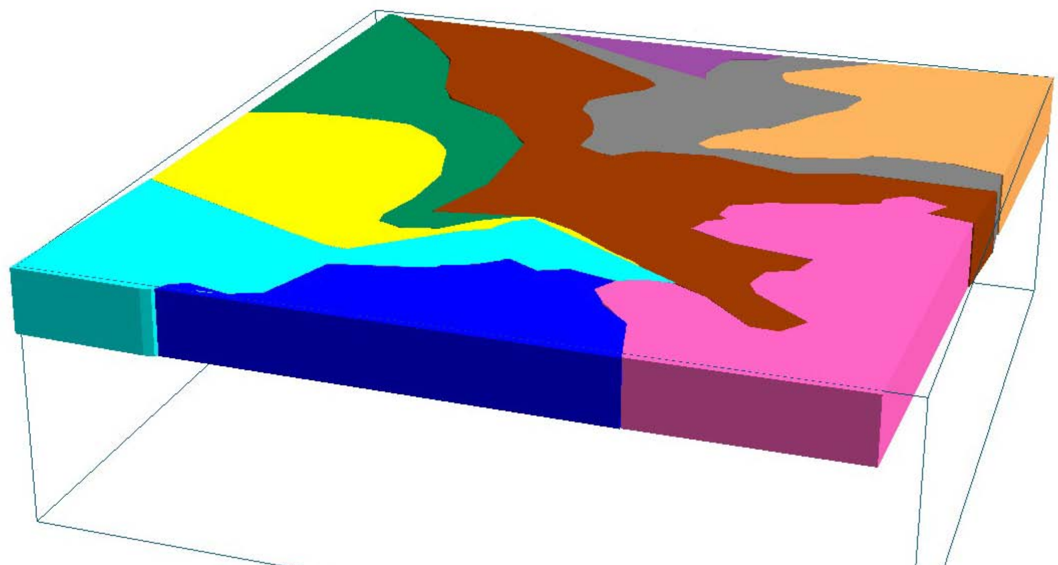
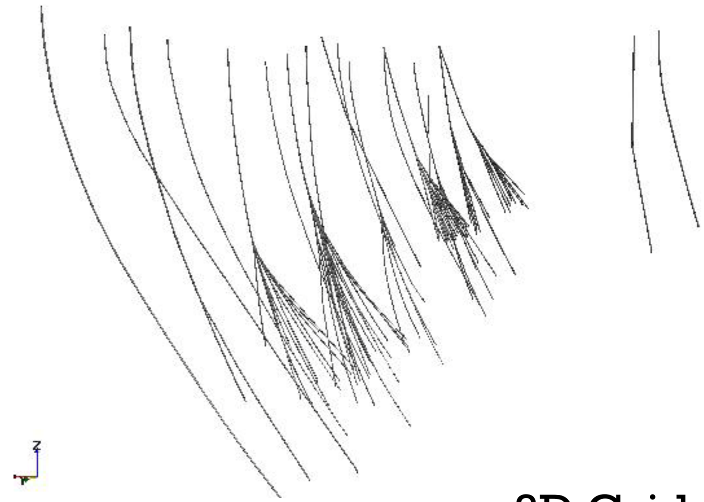
Rambler Structure Baie Verte, Newfoundland

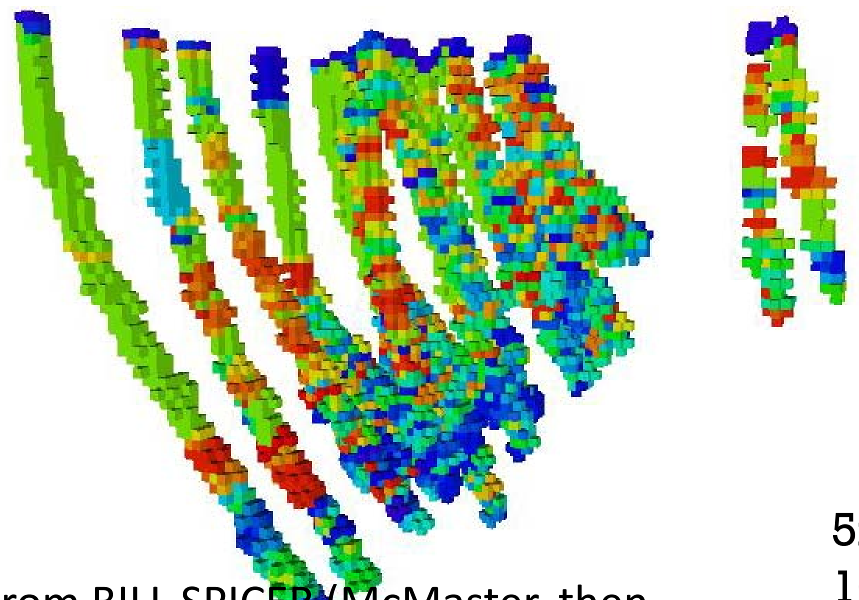
From BILL SPICER (McMaster, then Quadra FNX)

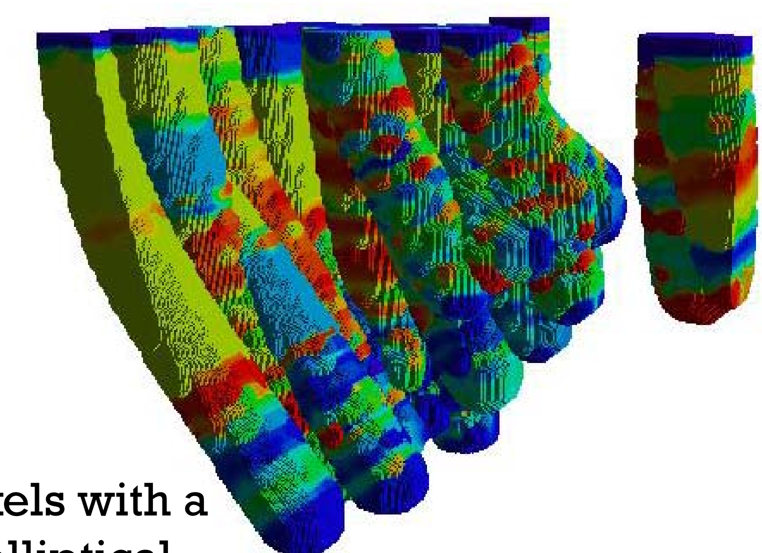




Convert Drill-hole information into voxels

3D Grids (voxel models) of physical properties

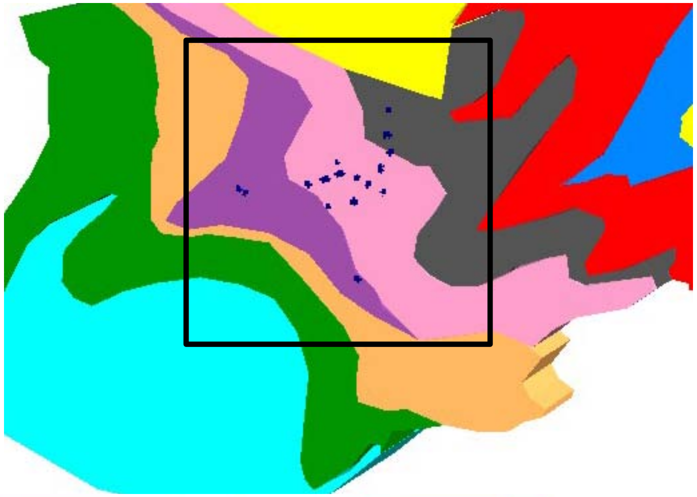


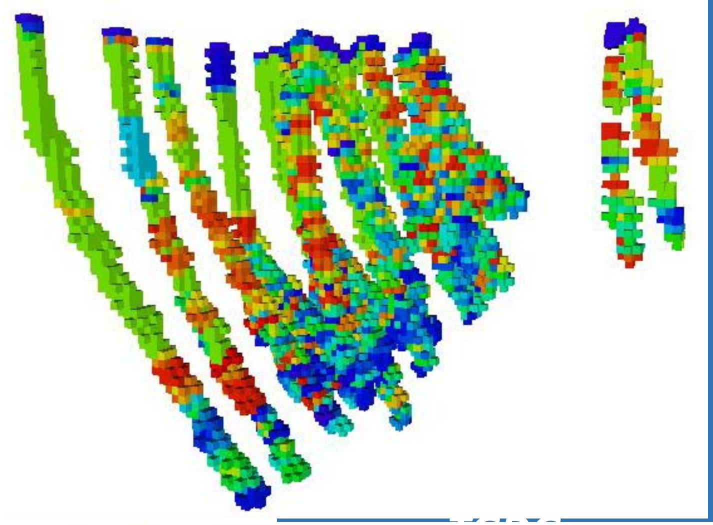


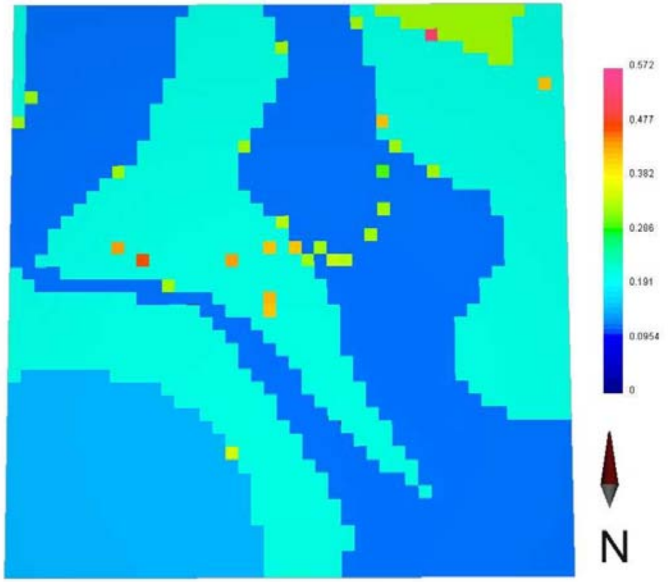
5m voxels with a 100m elliptical buffer

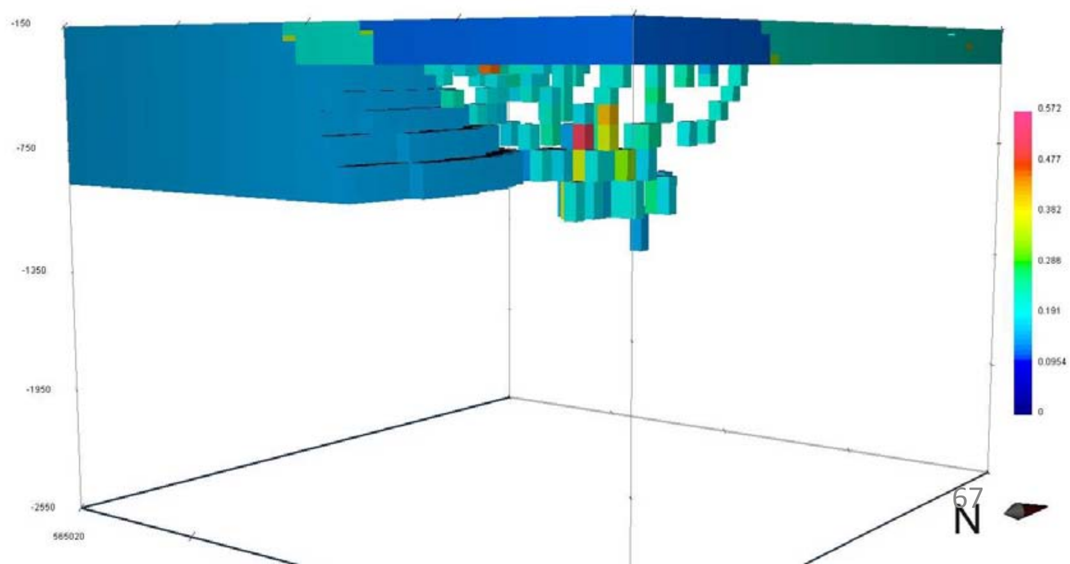
From BILL SPICER (McMaster, then Quadra FNX)

Final Reference Model









Check model by comparison with published geological models

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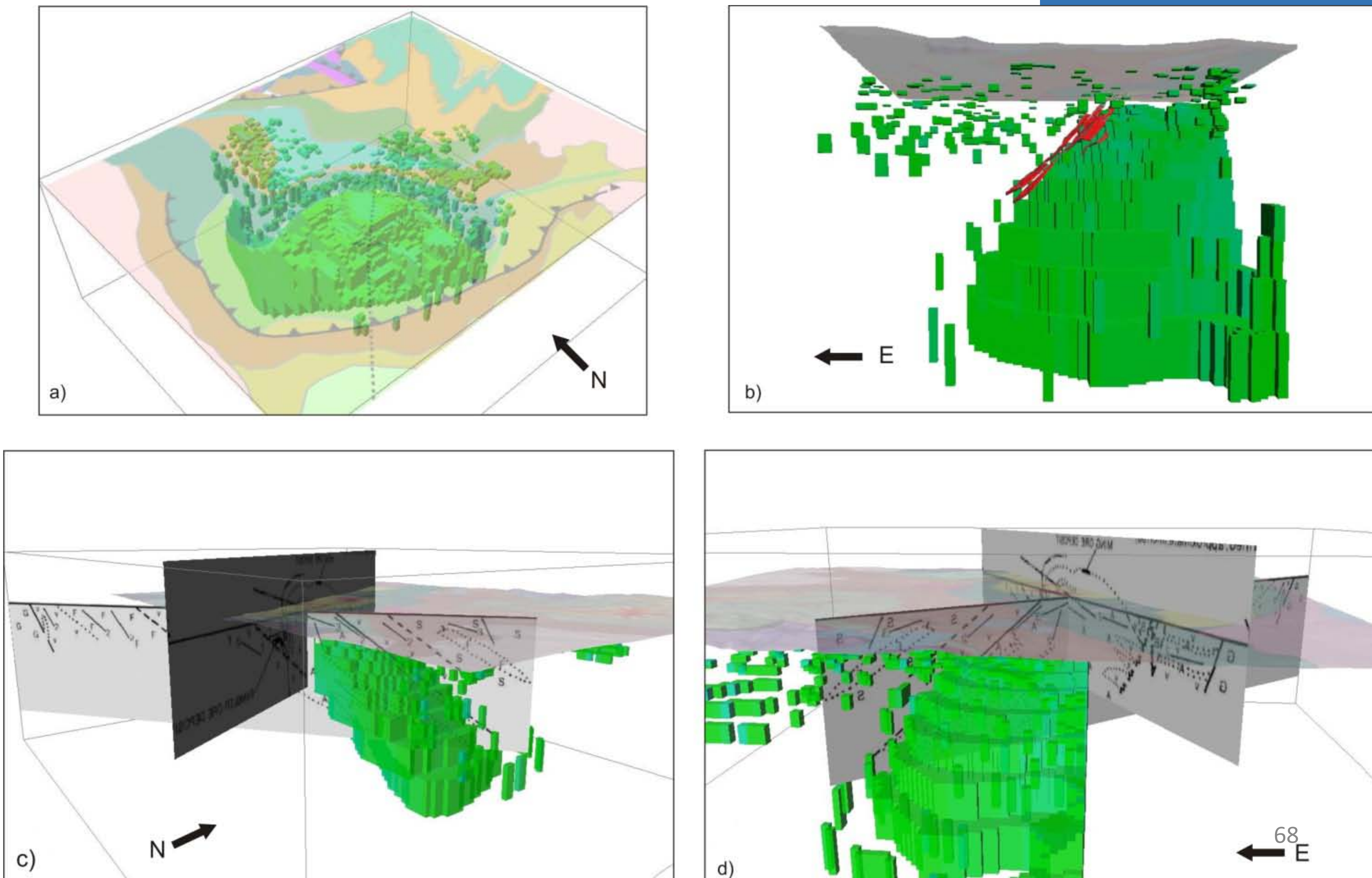

Another application of 3D modelling

- First part of the talk: how to obtain geology out of geophysics
- Second part: how to filter topography out of geophysical data
- Topography might or might not be related to the geology that we want to highlight

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Topographic effects on magnetic data

- Regular assumption on magnetic based exploration is that the observed field is <u>purely</u> a representation of magnetic mineral variations in the subsurface

- However, topography can have strong effects on the observed magnetic data, which are usually neglected

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Topographic effects on magnetic data

- Early results of topographic effects on magnetic data shown as early as 1971 (Gupta & Fitzpatrick, Geophysics, 1971), but hardly ever applied.
- Topographic corrections are a big deal in gravity…what about magnetics?

Topographic effect: magnetic anomalies induced by topography, no matter the magnetic mineralogy of the associated rocks

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Main sources of topographic effects

The topographic effect on magnetic data is a function of:

1) Large magnetic susceptibility contrast on surface (air – rock)
2) Source-sensor separation
3) Amount of topographic relief
4) Total magnetic inclination
5) TMF angle vs Topographic slope

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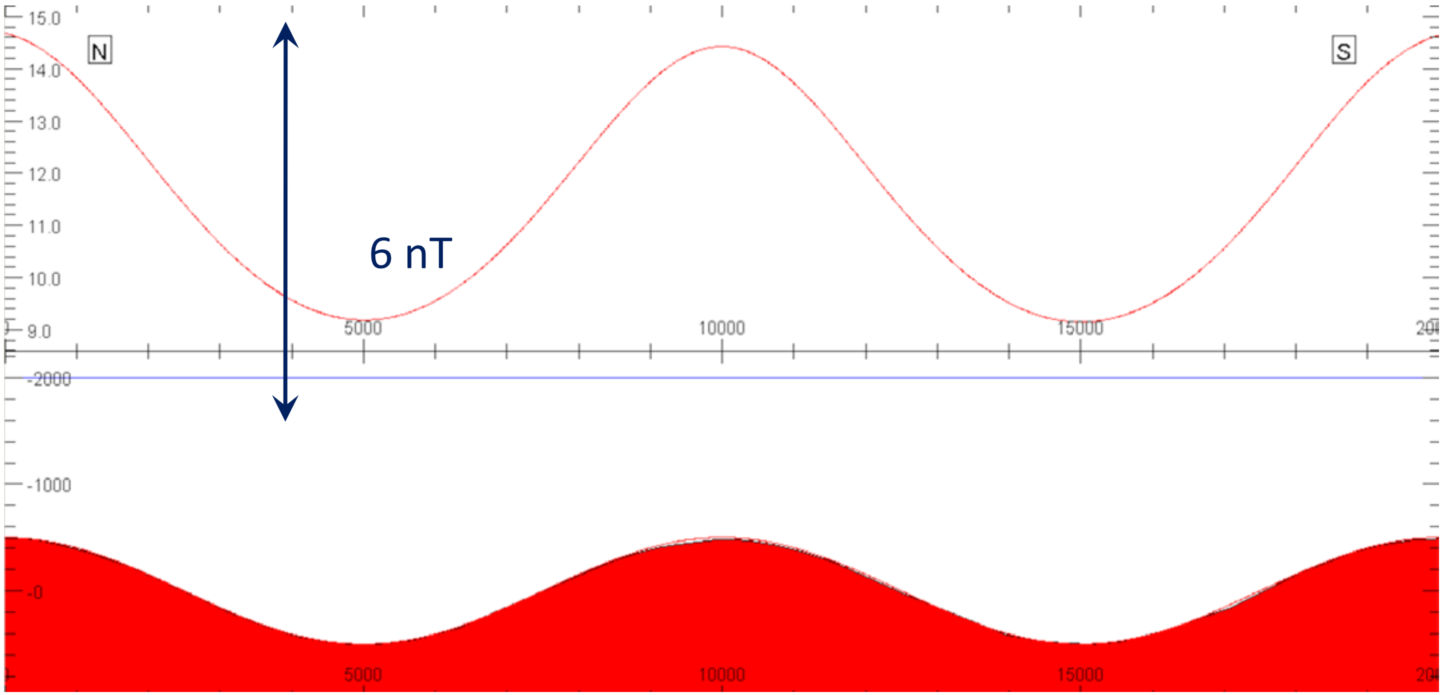
In practical terms…



Uniform susceptibility k=0.001 SI
Sinusoidal shape
Observation surface flat at Z=2 km
Bottom flat at 5600 m

EMF: Intensity, 60000 nT
Inc = 90; Dec = 0

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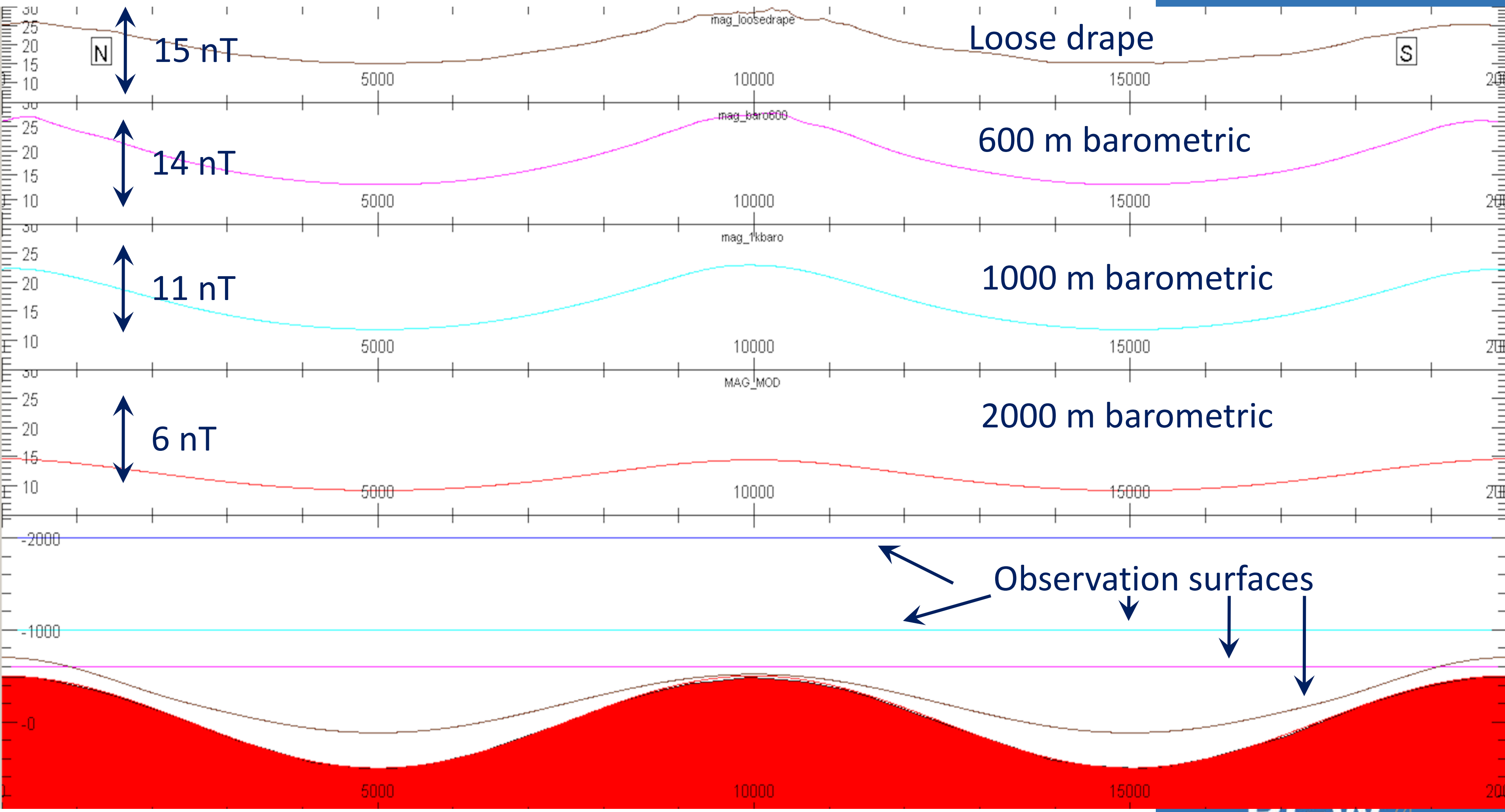
Source – sensor separation



Drape vs not-drape

1. Flying as low as possible certainly improves resolution of sampled anomalies
2. Flying surface parallel to the ground: normalizes amplitudes, so that all anomalies are comparable

The above does NOT get rid of topographic effects on the data.

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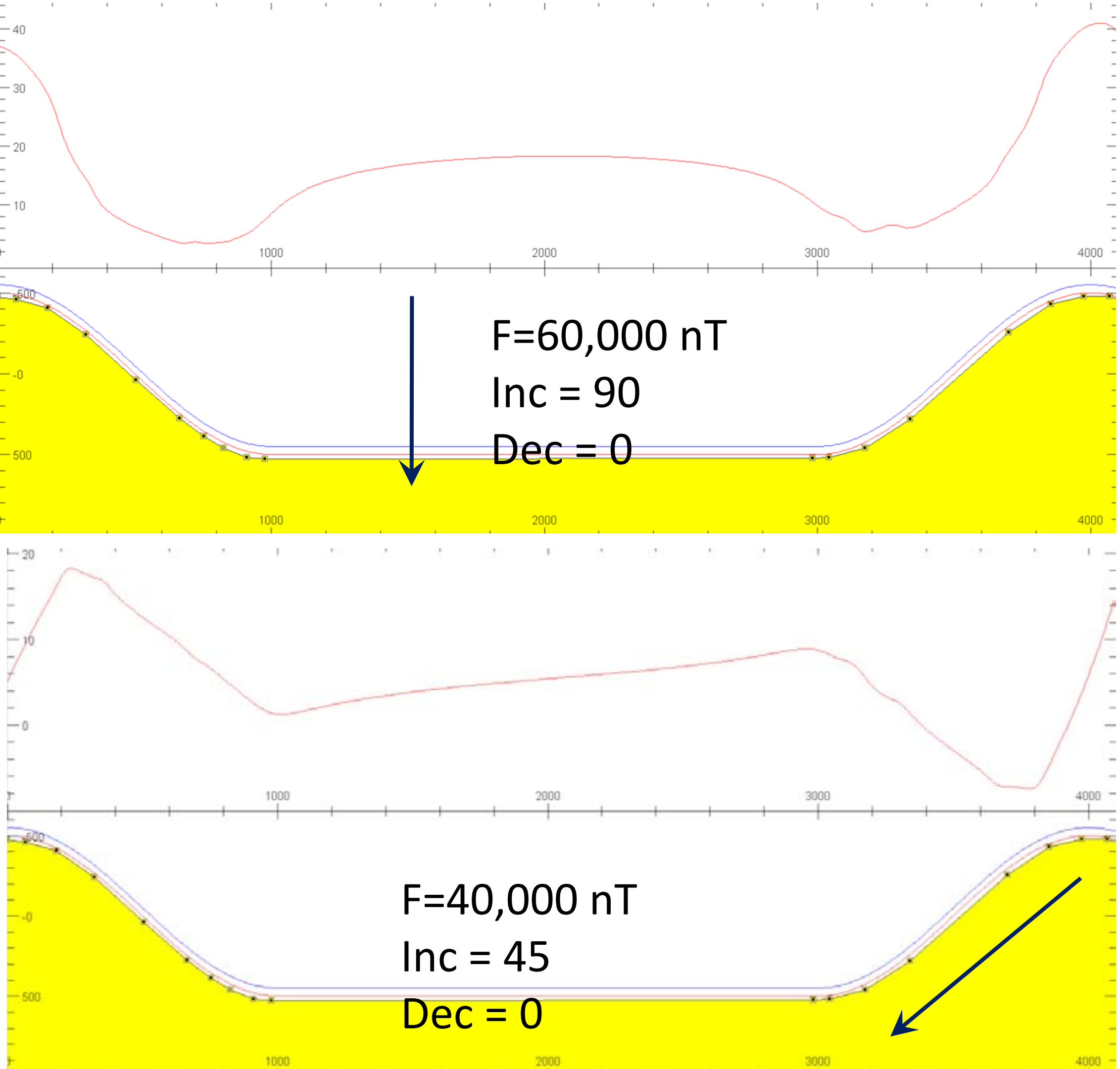
Inclination of the EMF



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Inclination of the EMF

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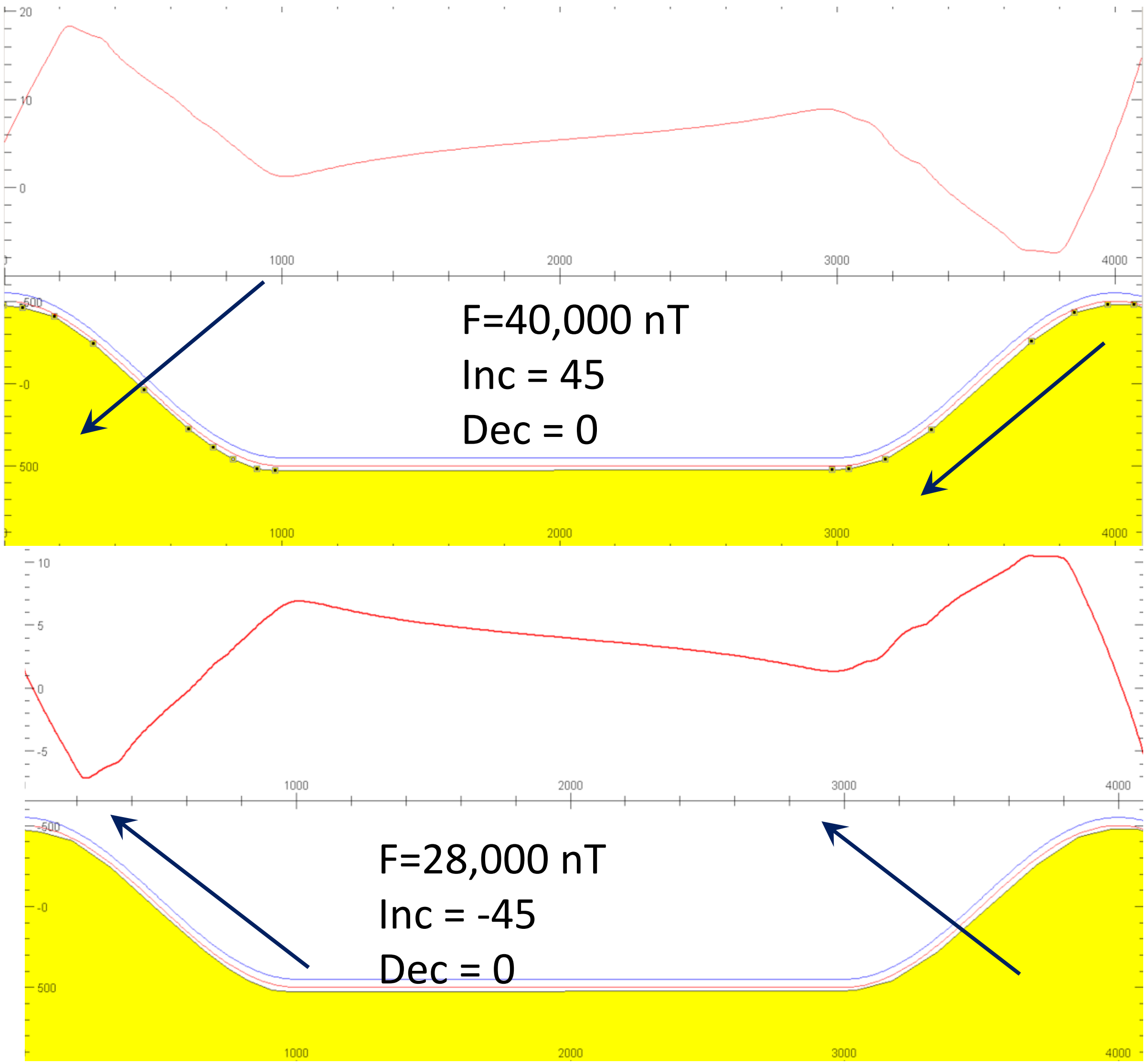

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Consequences for interpretation routines

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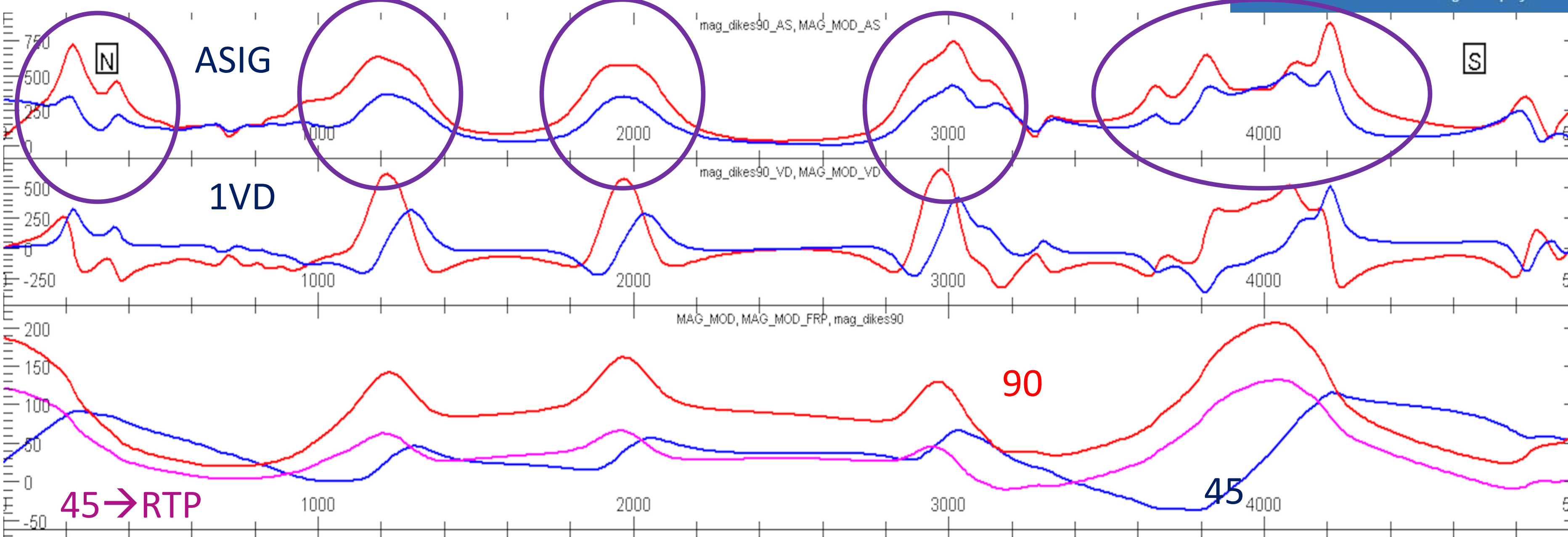

Same model as before, host with k=0.005 and with the addition of dikes (k=0.01 SI)
Where are the dikes?

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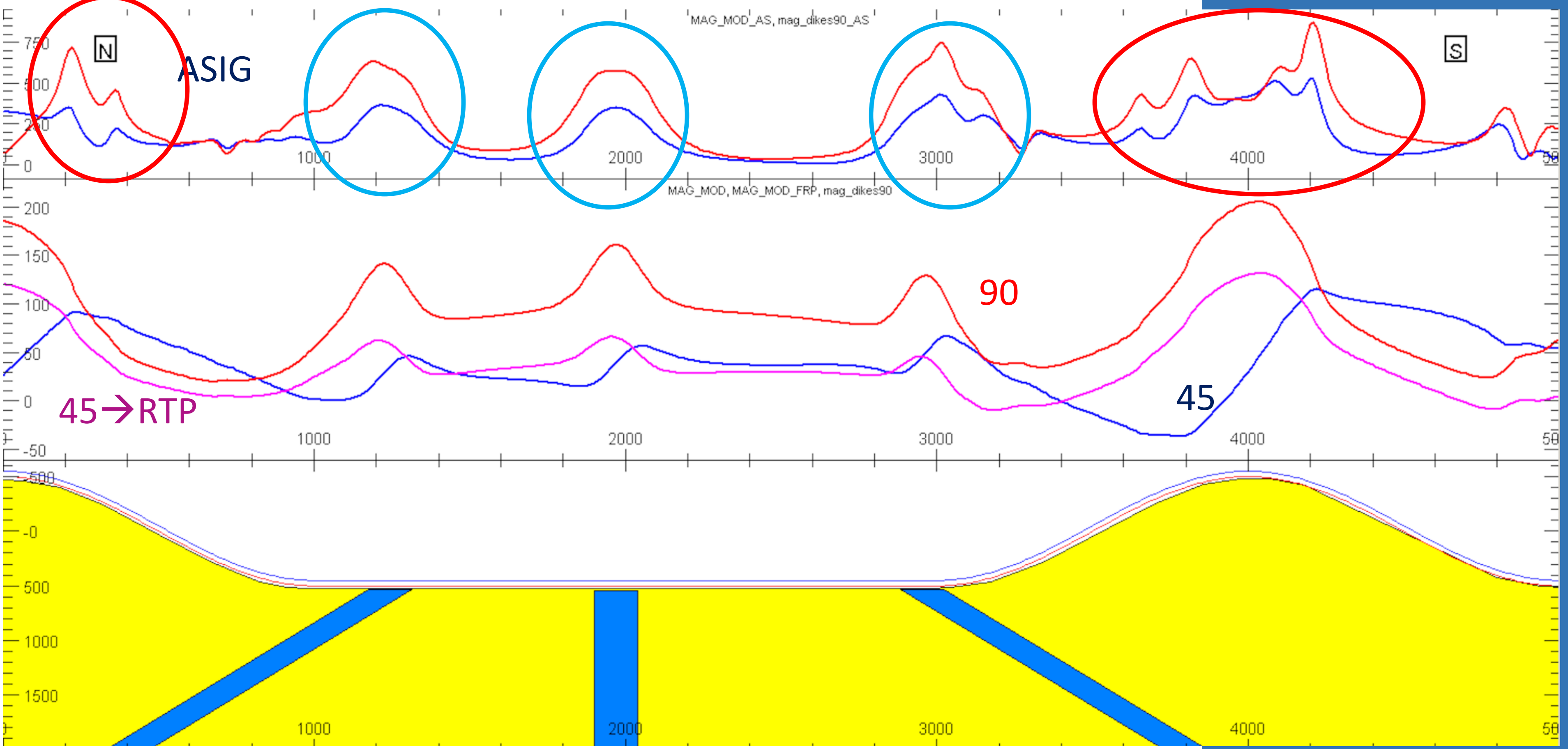
Consequences for interpretation routines



Consequences for interpretation routines:

Any interpretation routine based on derivatives (Euler, ASIG, Tilt, etc.) or a plain inspection of TMI without accounting for topography will be biased.

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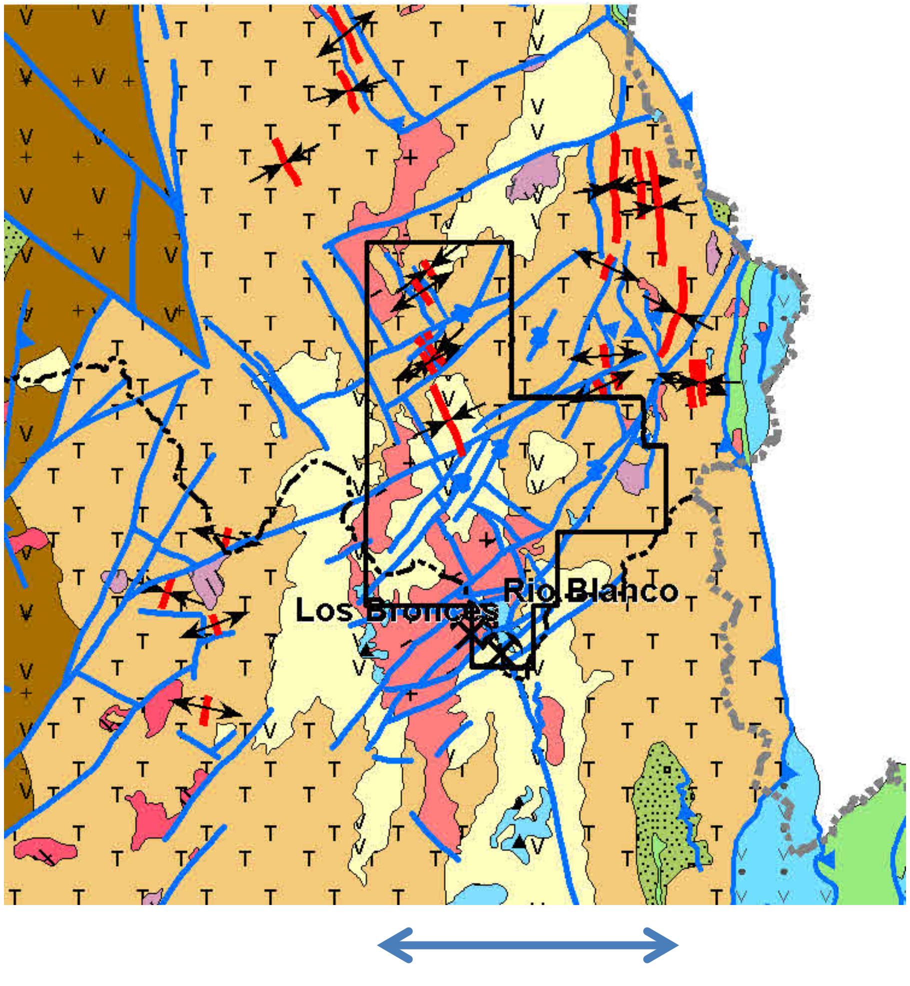
Application: Southern Andes (Central Chile)



Andina:

- Eocene-Miocene volcanics (Abanico Fm 1st, then Farellones Fm)
- Diorites and granodiorites controlled by structures striking N30W

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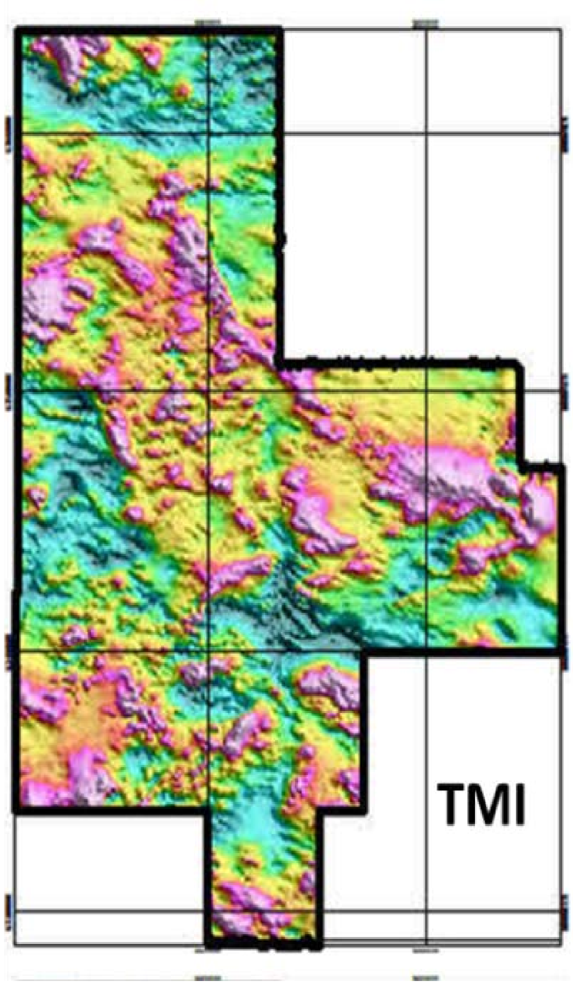
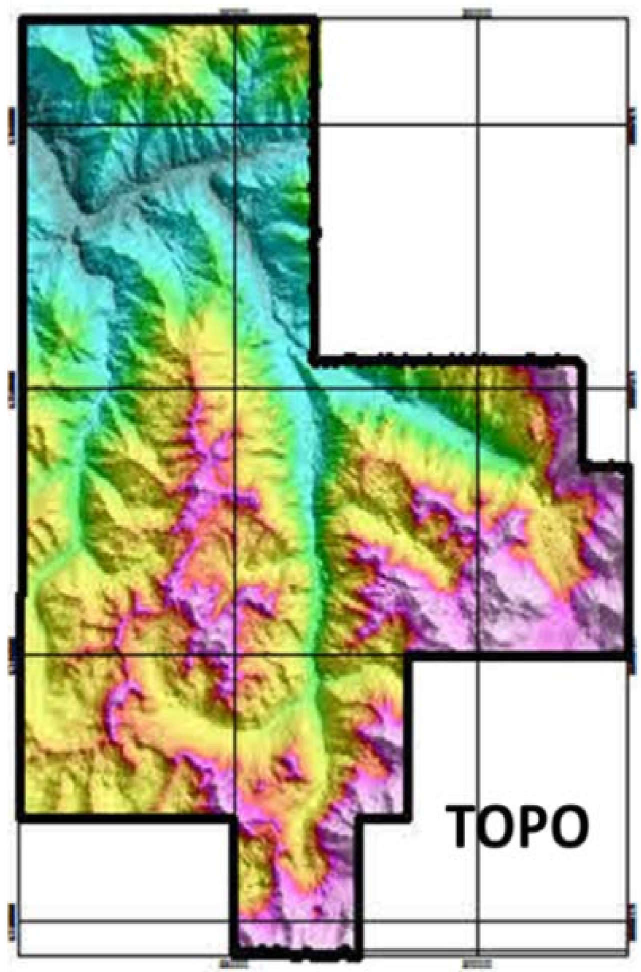
Application: Southern Andes (Central Chile)





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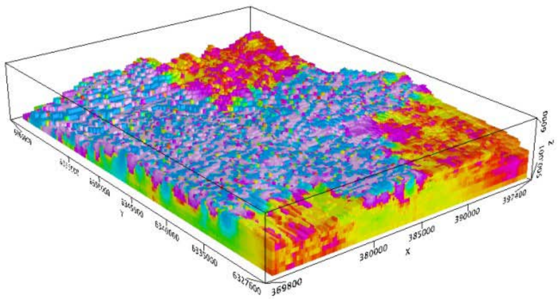
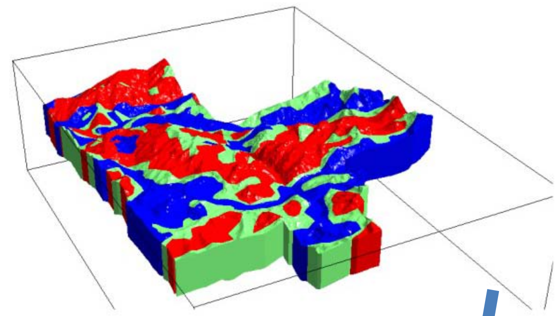
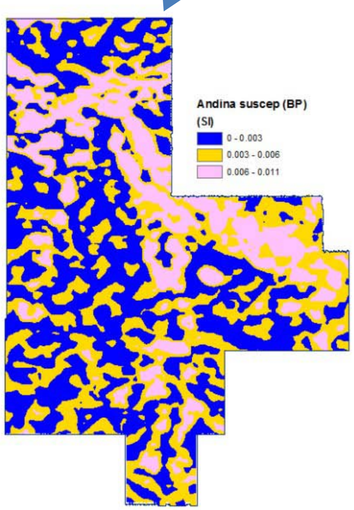
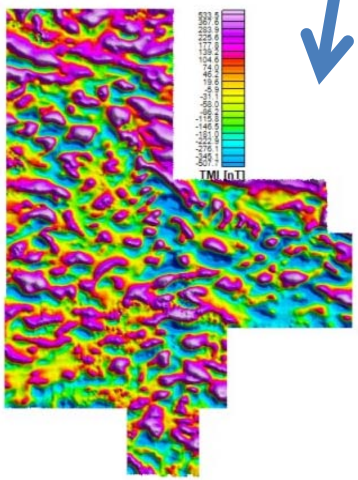
Application: Southern Andes (Central Chile)









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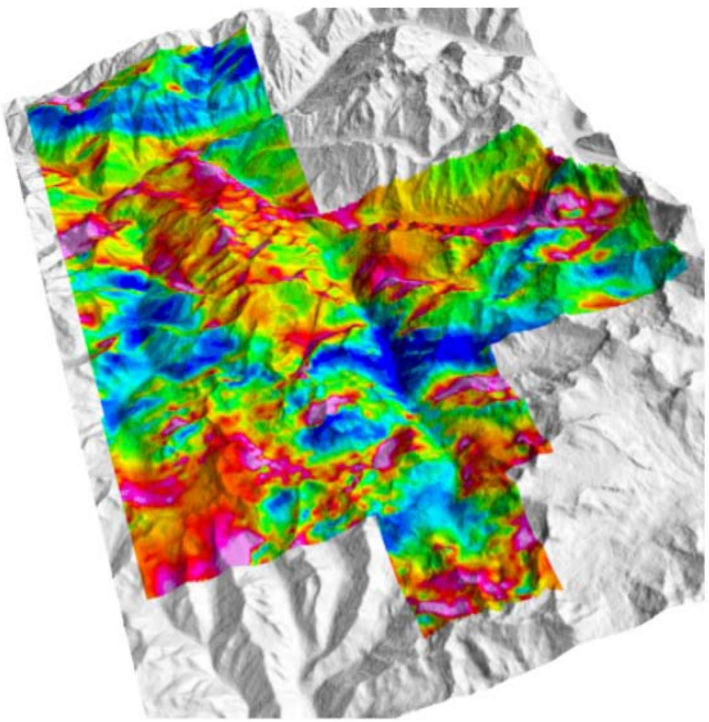
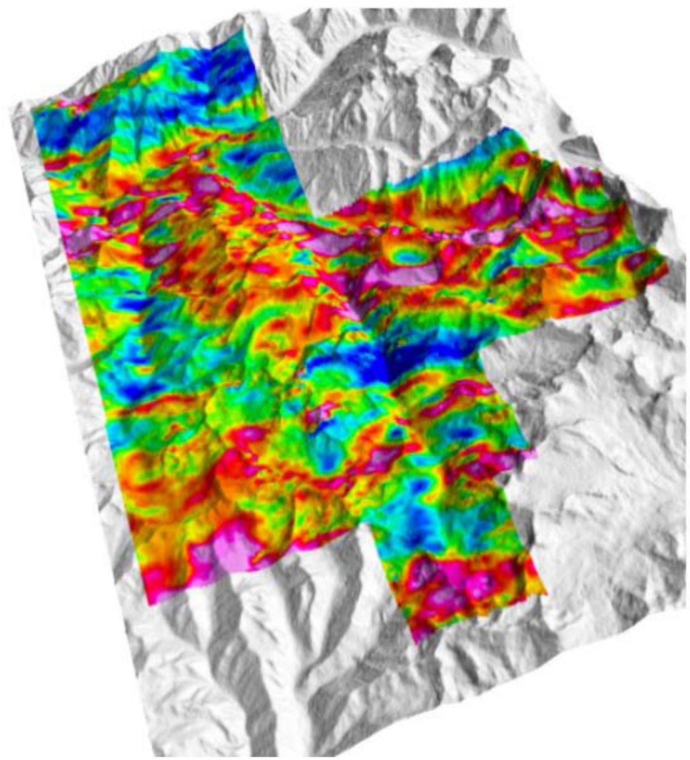


TMI: Before



TMI: After

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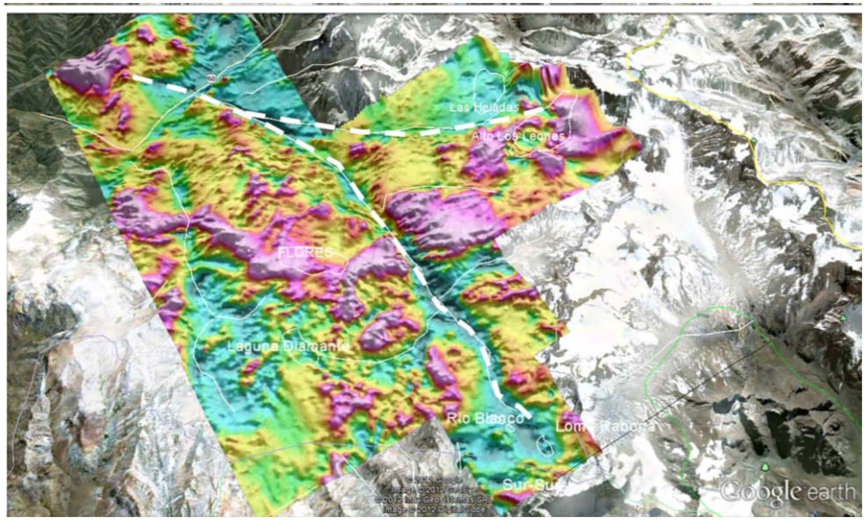
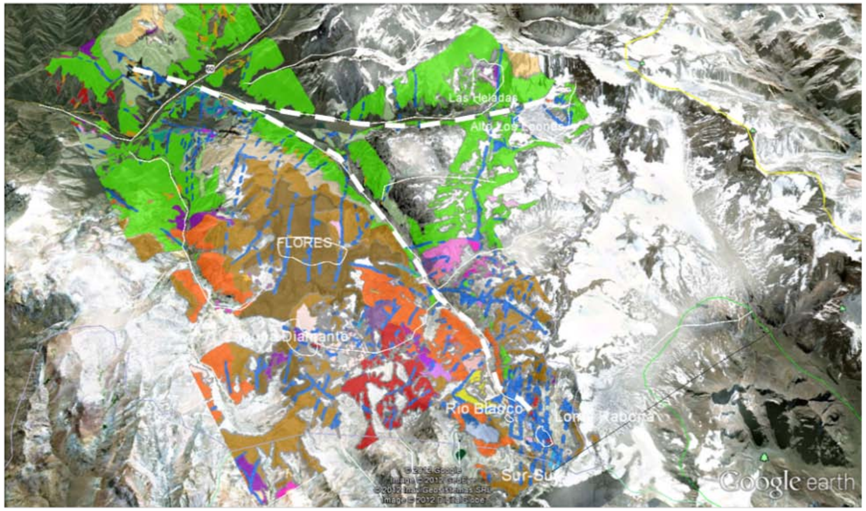
Application: Southern Andes (Central Chile)



RTP Mag (Before correction)



Geology

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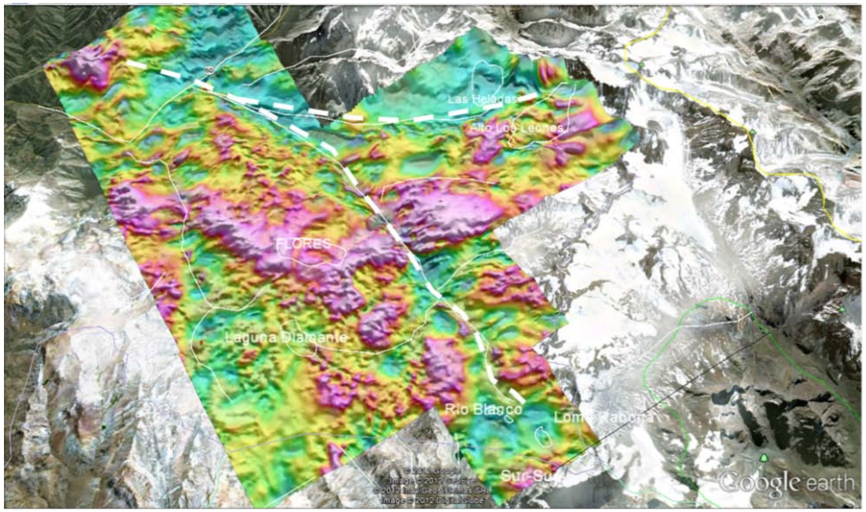
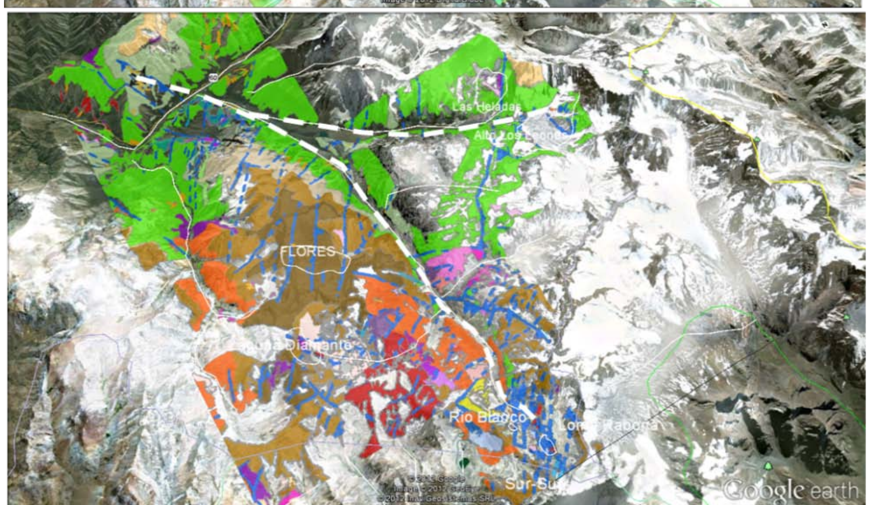
Application: Southern Andes (Central Chile)



RTP Mag (After correction)



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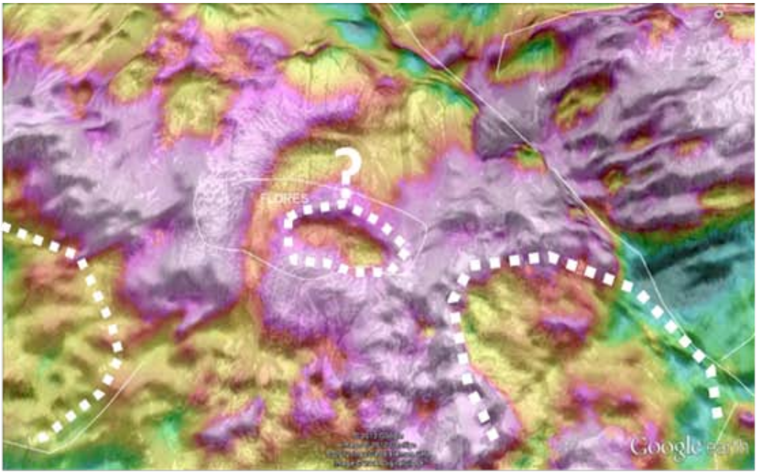
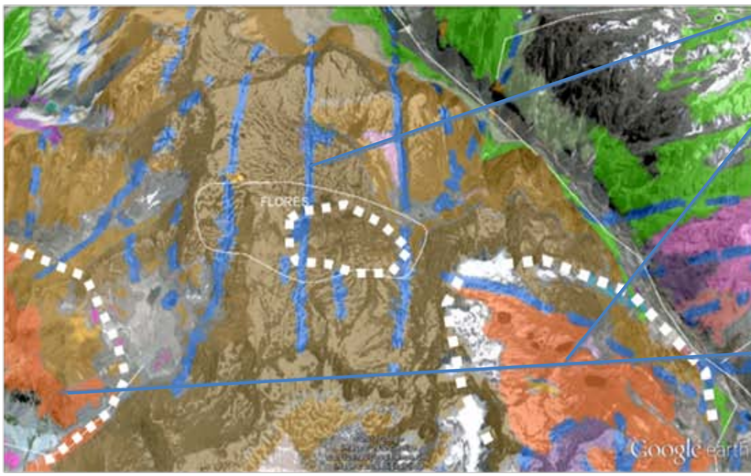
Detail



RTP Mag (After correction)

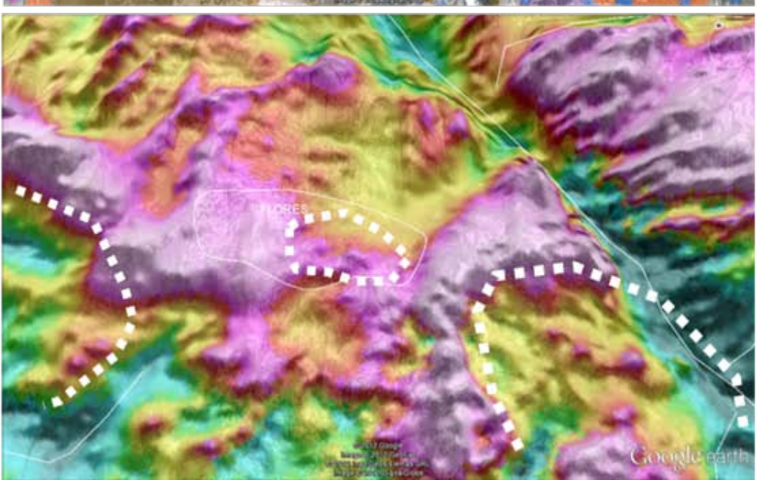


Andesite

Diorite

Geology

Intrusive



RTP Mag (Before correction)

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Summary of Topographic correction

- Topographic effects on magnetic data can be quite misleading before doing a “map” interpretation
- This will affect any semi-automatic routine that is based on TMI/RTP or its derivatives (e.g. Euler, Tilt, SPI, etc.)
- Combination of 3D inversion & 3D forward model techniques allow to compute the topographic effect on magnetic data, and produce a much cleaner data set
- If we are modelling the data, model **must** incorporate topography. Then the software takes care of the topo effects
- Computation requires 5 pieces of software and detailed, case by case analysis

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Summary & Conclusions

- Detailed exploration projects:
  - Resolution of the data versus size of the target and physical contrast is key.
  - NWT project shows that thinking out of the box and focusing on geological mapping rather than on direct targetting ("drill the purple"), can provide with meaningful information

Summary & Conclusions

- The advancement of computing power and inversion algorithms have made 3D inversions of potential field data quite popular
- However, care must be taken on when and how can we apply them. Main questions to answer before inverting:
  – Can I resolve the target? (do we have enough physical property contrast?)
  – Is the size of the project (small enough) and the resolution of the data sufficient for the 3D inversion?
  – Do we have enough geological constraints?
  – Do we know anything regarding rock properties?

Summary & Conclusions

- Each geological problem is unique, therefore we can’t treat them all as a uniform case
- Therefore, we can’t push data through a black box and pretend to have decent results without inspection
- Geological mapping (structural data, contact locations) and rock properties are the main control for the success of any geophysical interpretation/modelling program

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Acknowledgements

- Geological Survey of Canada, TGI3, for funding (Bathurst) and extensive geological discussions
  - Neil Rogers, Cees van Staal
- Dave DuPre, for the many discussions over the iron ore project
- Bill Morris, Gonzalo Yañez for “simmering” and developing of topographic effect ideas

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