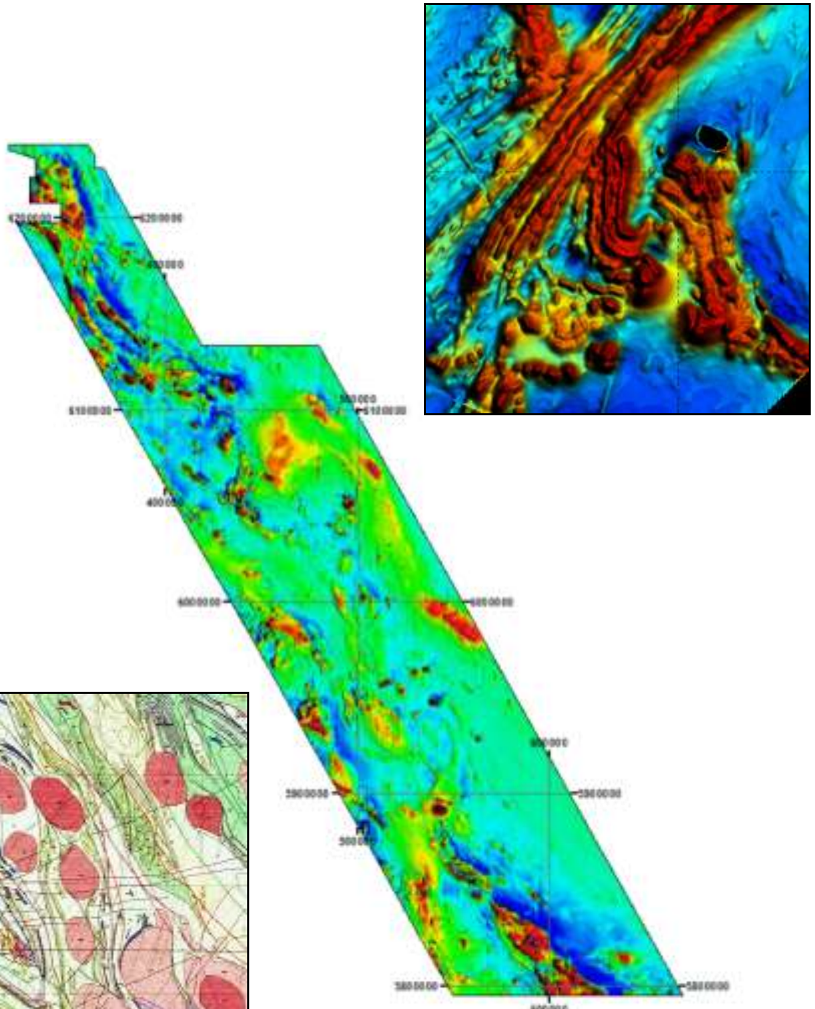

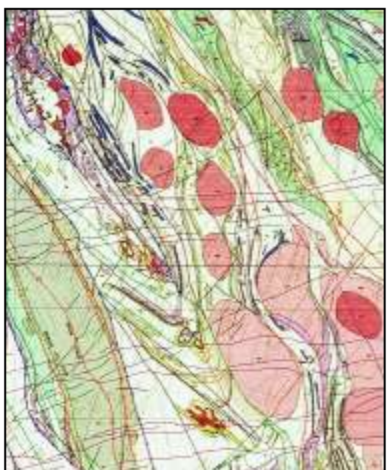

Advanced Geological Interpretation of Aeromagnetic Data: Applied Indirect Exploration Targeting

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SRK Consulting (Canada) Inc.
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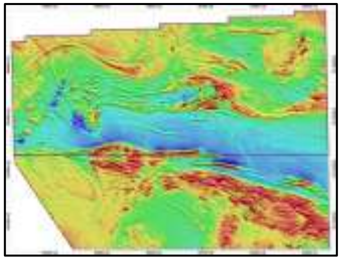
Aims of Talk

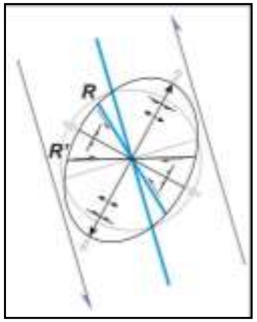
- Define possible uses of aeromagnetic data;

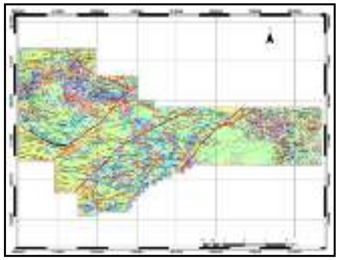
- Demonstrate why geological interpretation of aeromagnetic data is important to mineral exploration;

- Examine the tools you require to do a geological interpretation of aeromagnetic data; and

- Give you the confidence to apply these tools, and therefore to make a real difference!

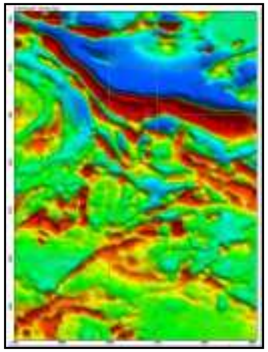


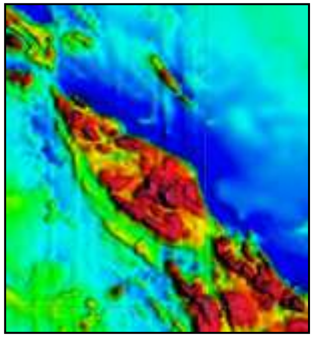


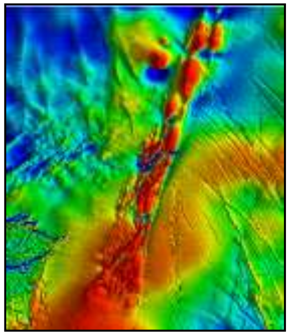


Uses of Aeromagnetics

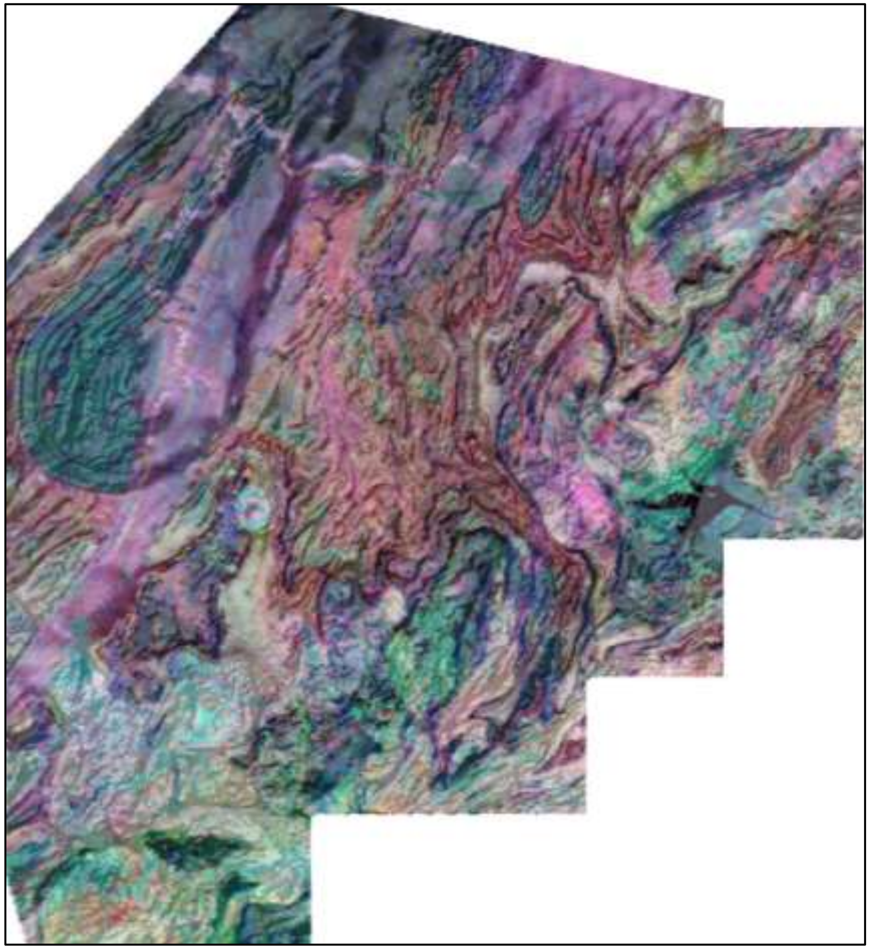
- **Mapping geology…..what attributes?**
  - Lithology;
  - Structure;
  - Alteration;
  - Metamorphism; and
  - Mineralization.
- **Mapping geology…..why/how is it possible?**
  - Magnetic minerals are present in (almost) all 'rock types';
  - Magnetometers can measure tiny magnetic signals; and
  - Airborne surveys allow rapid and inexpensive coverage.
- **When do we need aeromagnetics?**
  - Poorly exposed areas…..help interpolate between outcrops;
  - Covered areas……provide some geological control; and
  - Well exposed areas……there are always surprises.

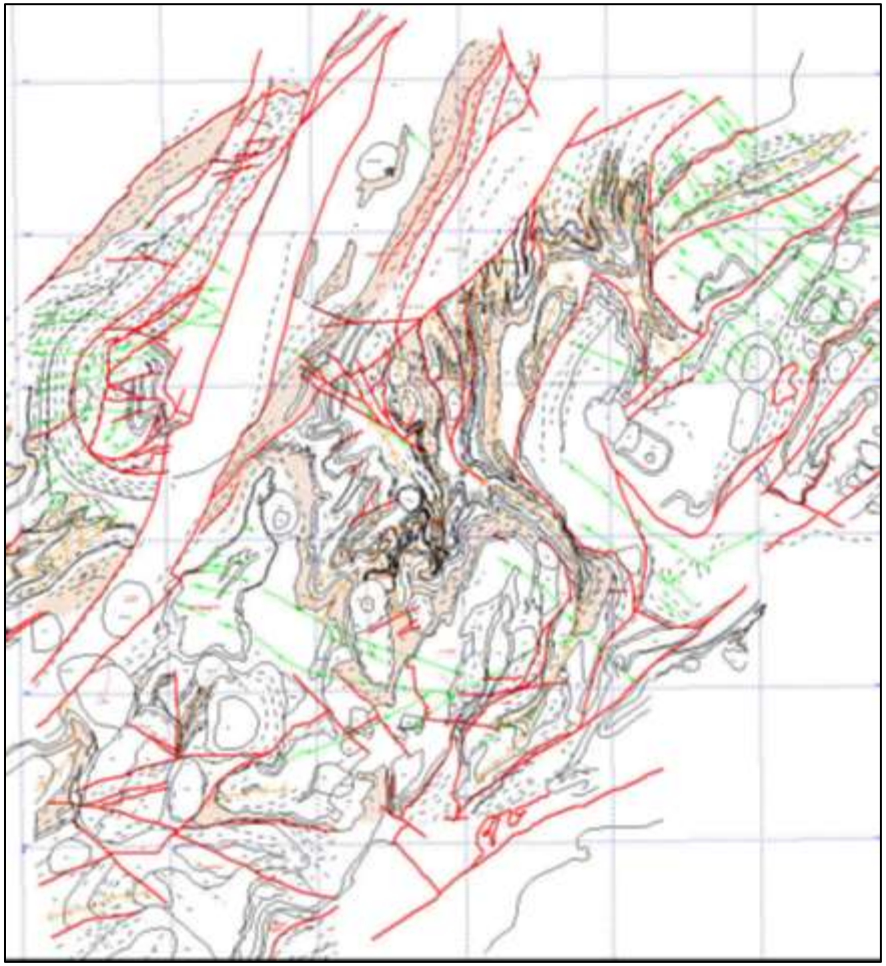




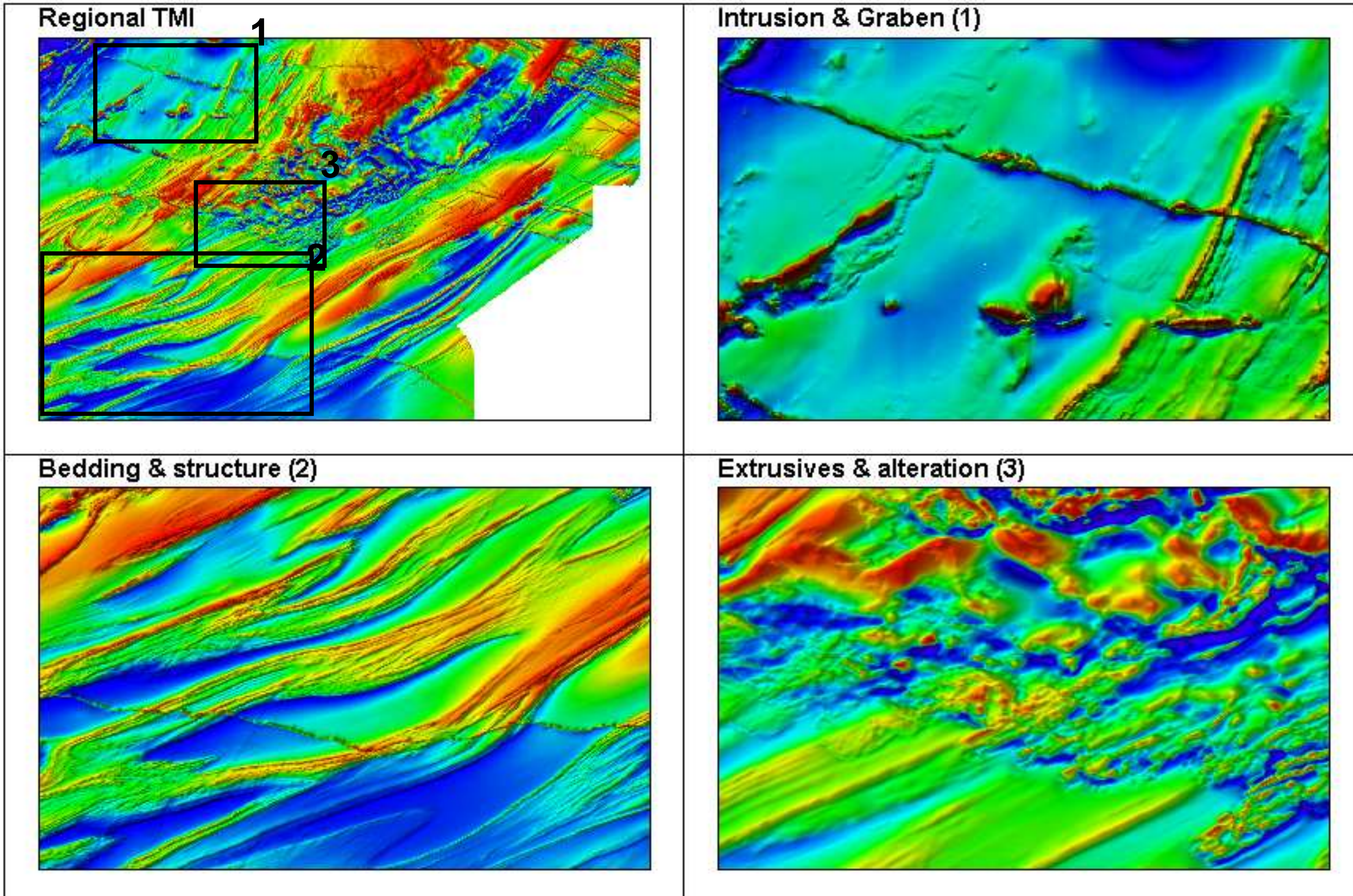


Magnetics as an Effective Mapping Tool

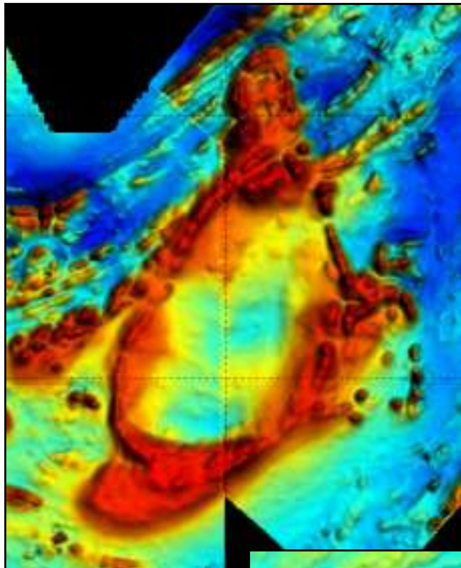


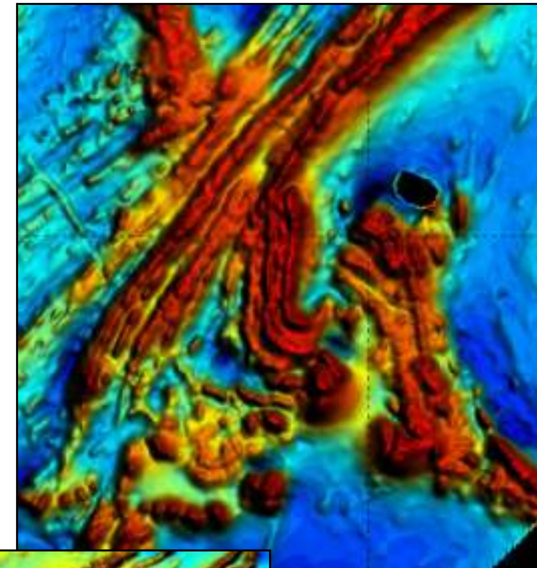


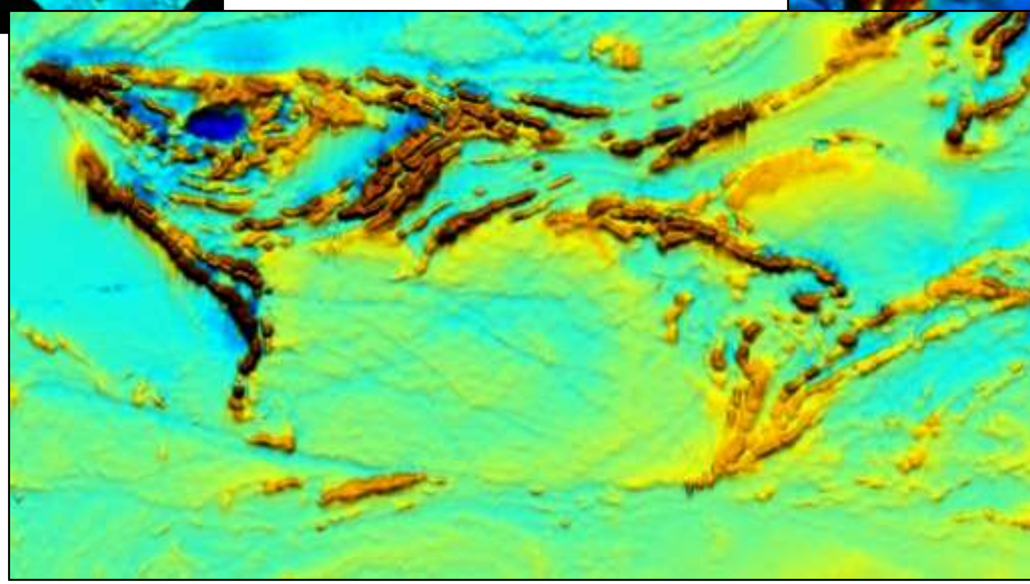
Aeromagnetic Expressions - 1



Aeromagnetic Expressions - 2







Digital Data Filters

LOW PASS FILTERS

Retain long wavelength, low frequencies = **deep sources**.

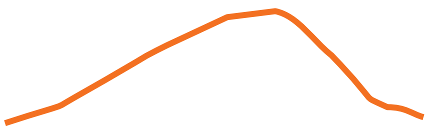
E.g. Upward continuation.

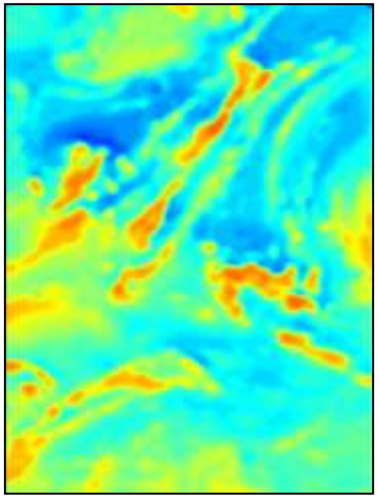
MEASURED DATA

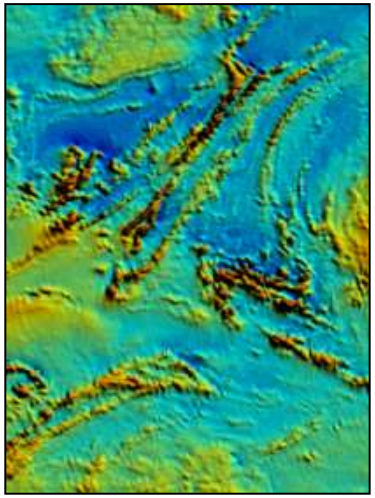
HIGH PASS FILTERS

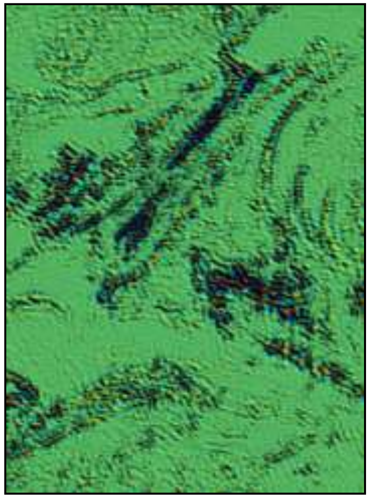
Retain short wavelength, high frequencies = **shallow sources.**

E.g. 1VD, 2VD, downward continuation.

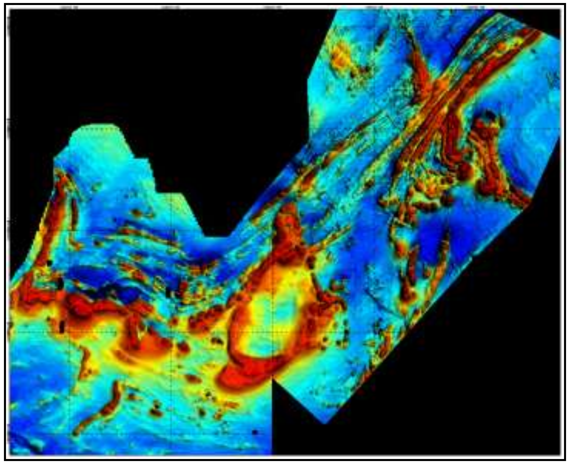




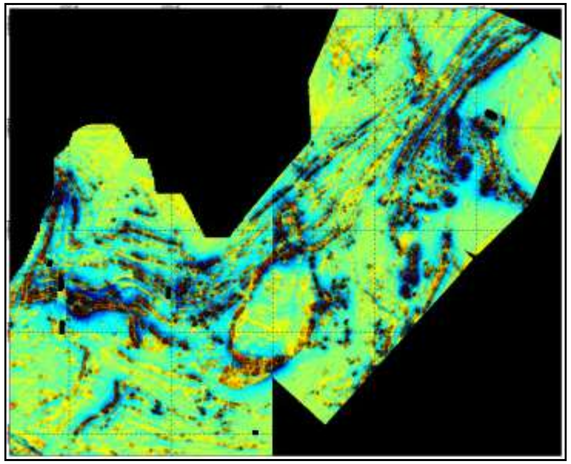




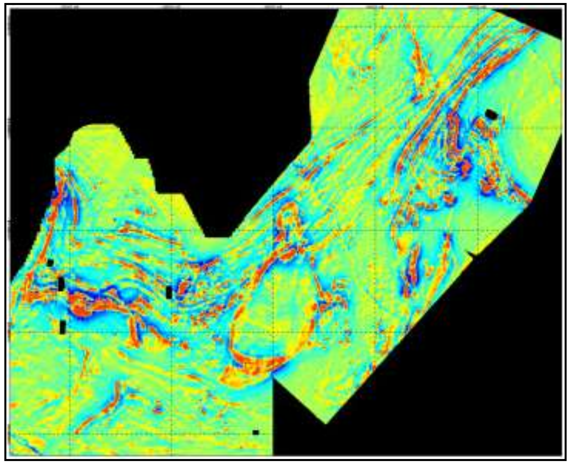
Typical Datasets Used



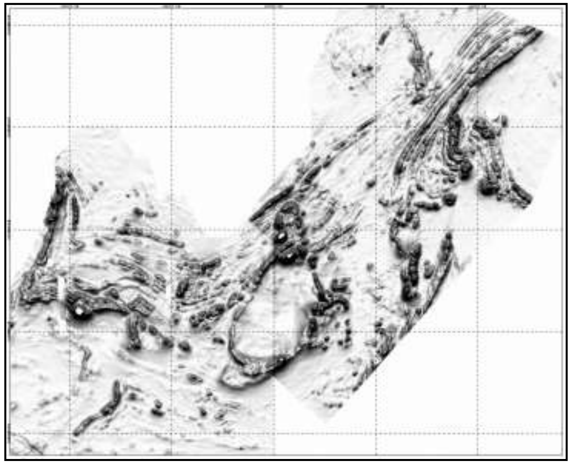
TMI – colordrape



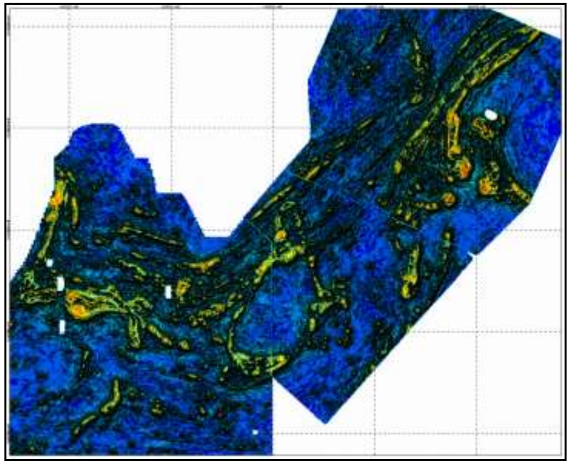
RTP1VD – colordrape



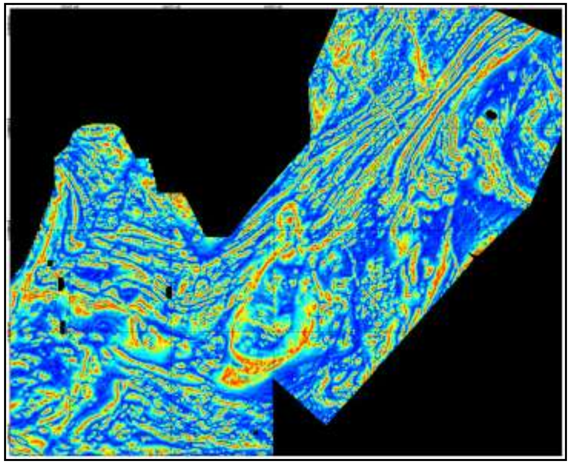
RTP1VD – density sliced



TMI – intensity



AS – colordrape



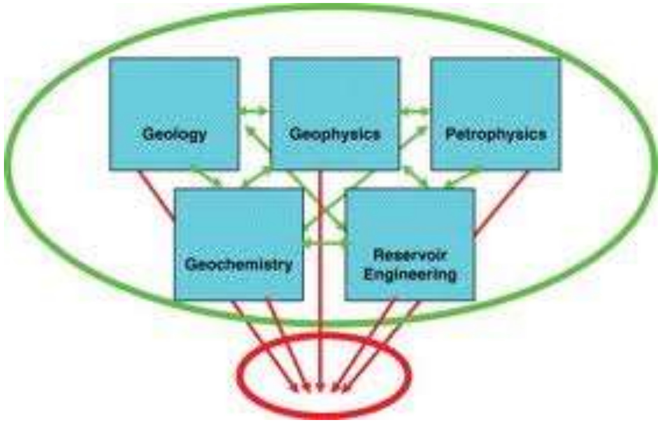
TILT – density sliced

Images Courtesy of Rainy River Resources Ltd.

The Need for Integrated Teams

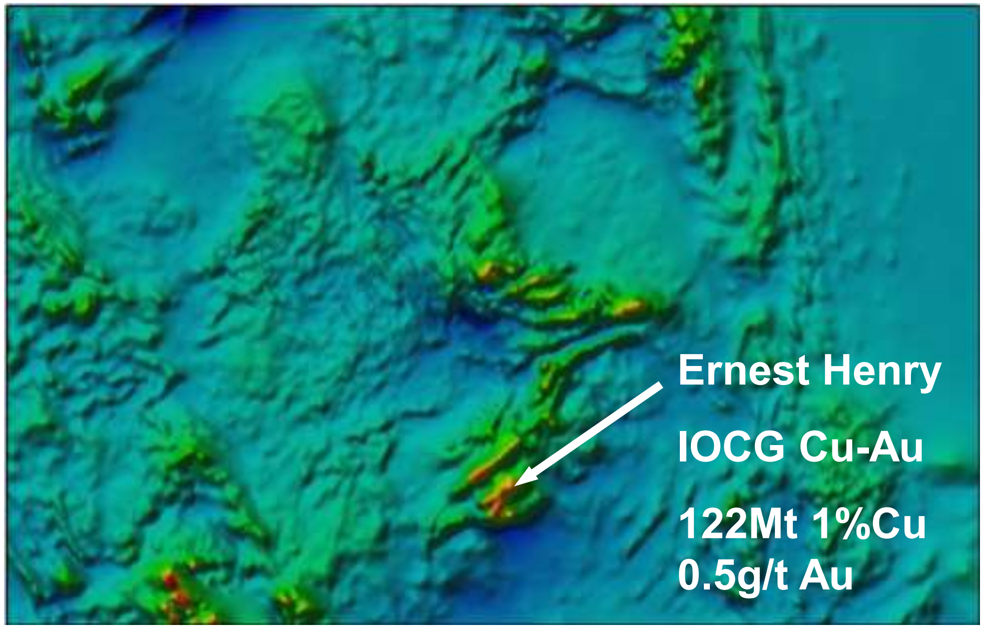
- **Geological interpretation of geophysical data in mineral exploration requires input from several disciplines, working together:**
  - Geophysics;
  - Stratigraphy;
  - Structural Geology; and
  - Ore Deposits Geology

- **Not dissimilar to long-standing exploration teams in the petroleum industry:**
  - Geophysics;
  - Stratigraphy;
  - Structural Geology; and
  - Reservoir Engineer.



Indirect versus Direct Targeting

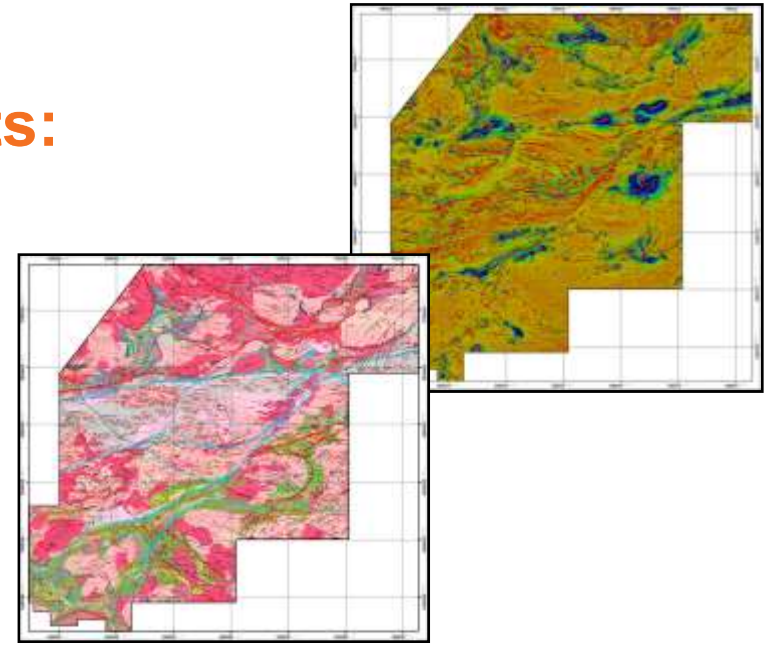
- **Indirect targeting (most common):**
  - Interpretation & structural analysis of magnetic data assists by:
    - Highlighting suitable fluid conduits and traps; and
    - Recognition / interpretation of favorable host (& source) lithologies.
- **Direct targeting (magnetic signature associated with deposit):**
  - Kimberlites;
  - BIF's;
  - Some porphyries & skarns;
  - Some IOCG's.



Indirect Targeting Concept

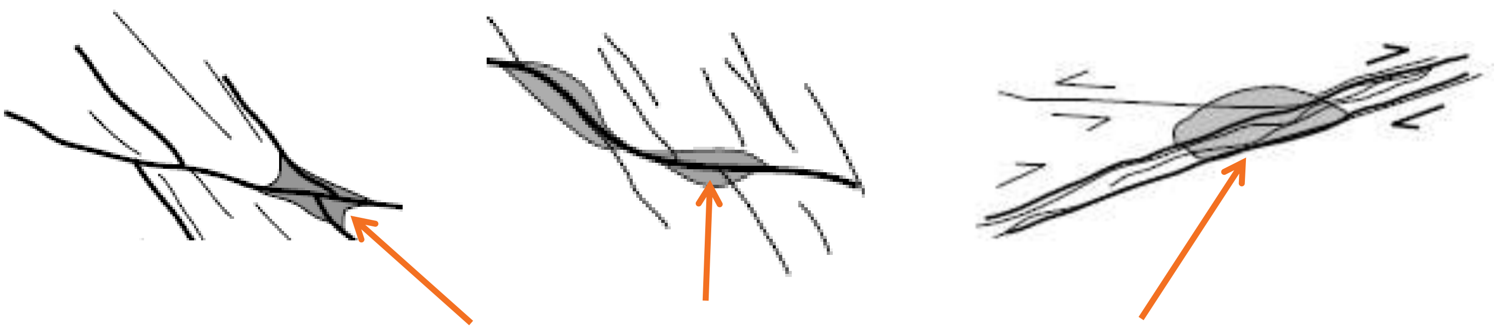
- **To define geological relationships that will:**
  - Increase understanding of the processes that control ore deposition within a target area;
  - Reduce exploration risk by defining the constraints on ore distribution.

- **Can include the following inputs:**
  - Structural distribution;
  - Structural evolution;
  - Lithological distribution;
  - Stratigraphic relationships.
  - **Timing.**



The Principles of Structural Control

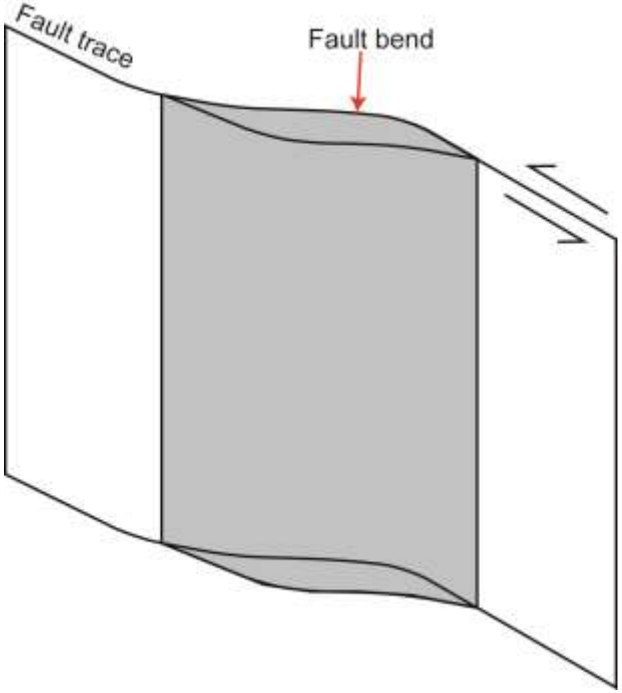
- Permeability is **unlikely** to be the same everywhere on an active fault zone.
- Permeability will generally be highest where damage within and around the fault zone is highest.
- This will depend to some extent on host rock type, but will principally be localised by irregularities (e.g. bends, branches, steps, jogs) along the fault.



Damage zones around irregularities along fault zone are zones of enhanced permeability

Applied Structural Control Principles

- Determine the **direction and sense of movement** on the faults, in order to predict the location, shape and plunge of zones of maximum damage / dilation.



Zone of dilation associated with bend on sinistral fault

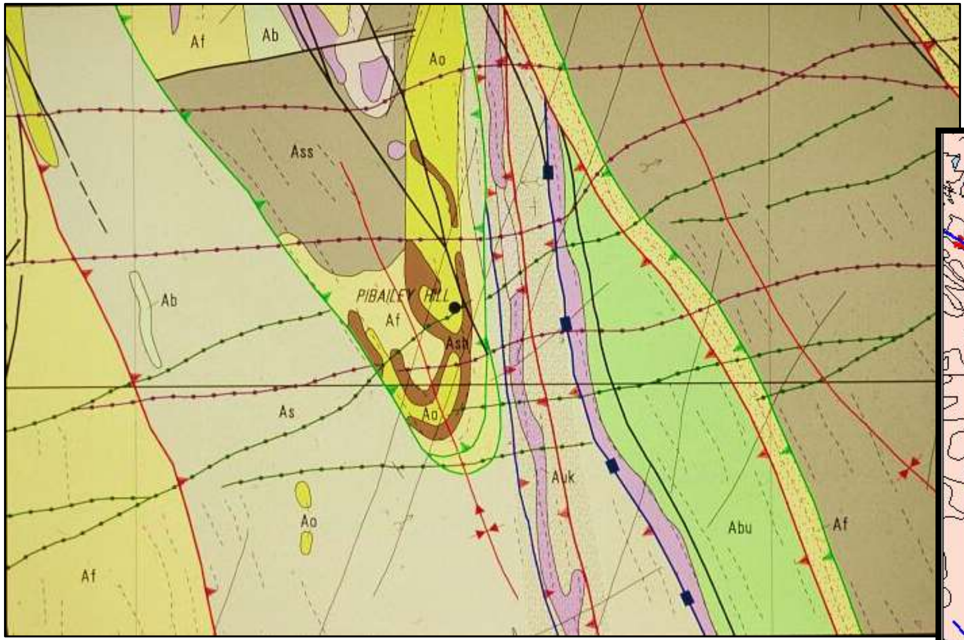
The Importance of Getting Timing Right

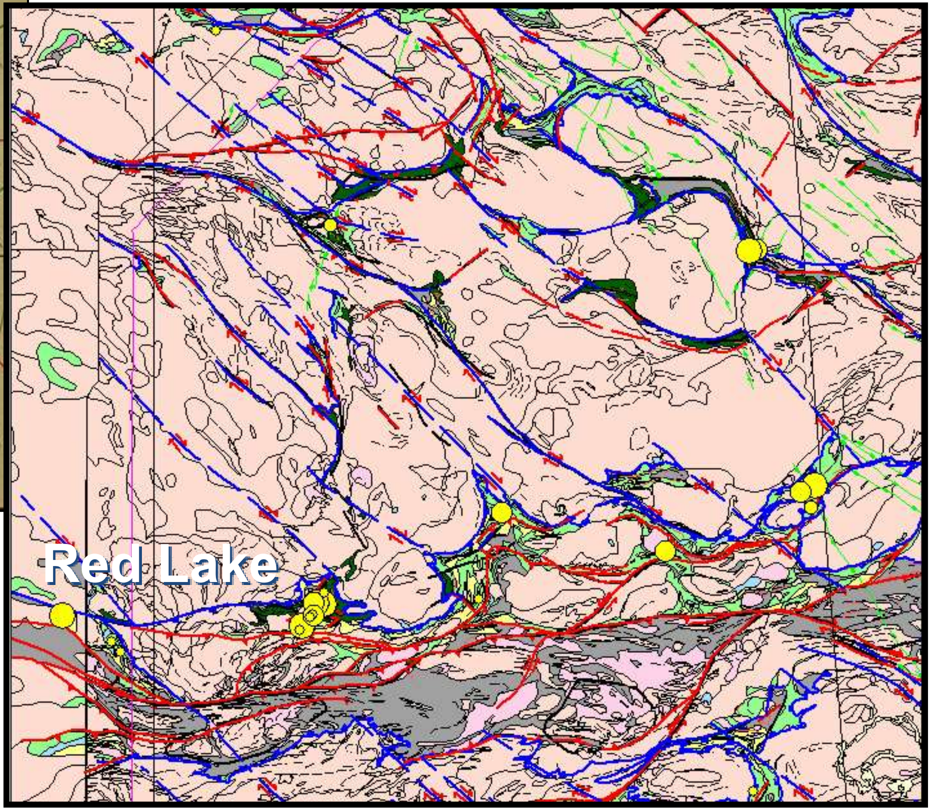
- Application of structural control principles requires that the **timing of mineralisation** must be carefully matched with the history of activity on a fault system.

Regional cleavage cuts high-grade mineralization

The Importance of Getting Timing Right

- Our interpretations must capture timing in terms of deformation and mineralization.

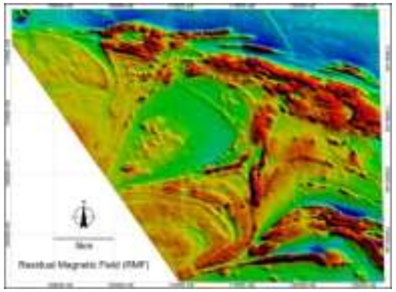




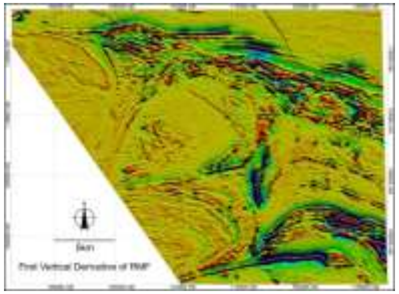
Interpretation Process

Interpretation - 1

- **Aeromagnetic interpretation should be broken down into three stages:**
  - OBSERVATION;
  - COMPILATION; and
  - INTERPRETATION.

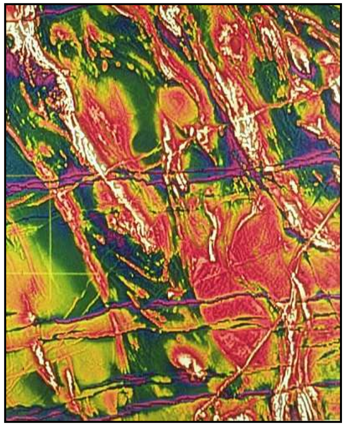


- **All of the principles of geological mapping and interpretation apply equally to aeromagnetic data; and**
- **Decide on the:**
  - Scale;
  - Filters;
  - Resolution achievable and the resolution required; and
  - Time needed and time available.

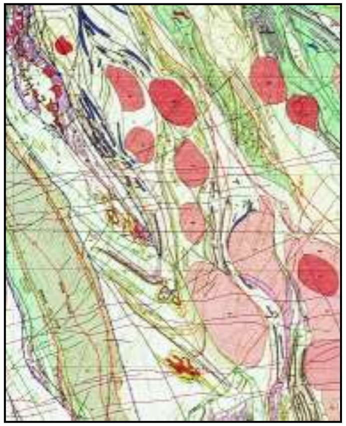


Interpretation - 2

- **When relating lithology or stratigraphy to magnetics, think:**
  - Which rocks contain the magnetic minerals (field evidence, susceptibility measurements, petrology)?
  - Do these rocks always contain magnetic minerals in this area?
  - How and when did the magnetic minerals form?

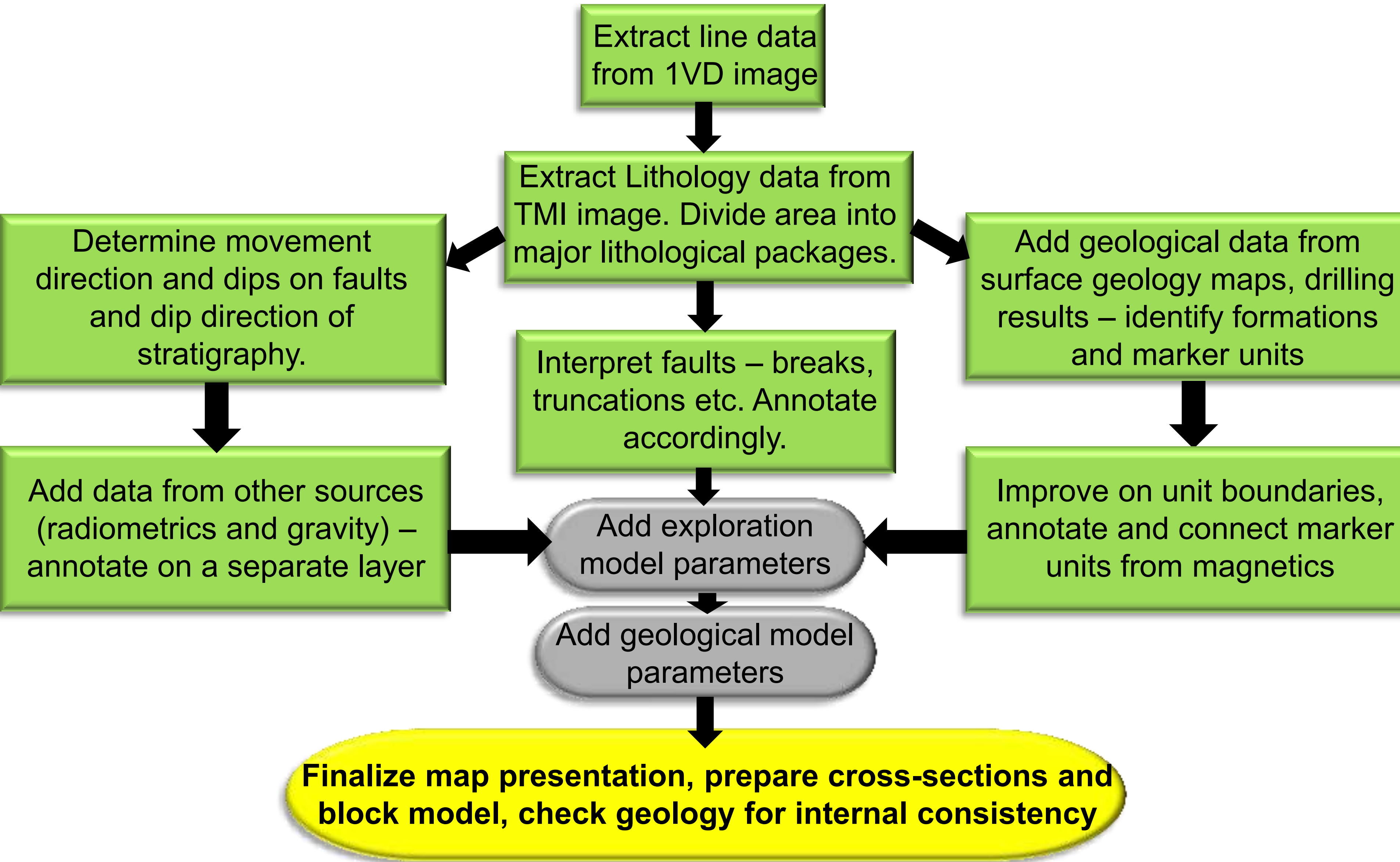


- **Be wary of making the following generalizations:**
  - "The XYZ Formation is highly magnetic" - *Is it?? Always?? Everywhere?? Uniformly??*
  - "The igneous and metamorphic rocks will be more magnetic than the sedimentary rocks" - They are frequently not!!
  - "The mafic rocks will be more magnetic than the felsic rocks" - They are frequently not!!

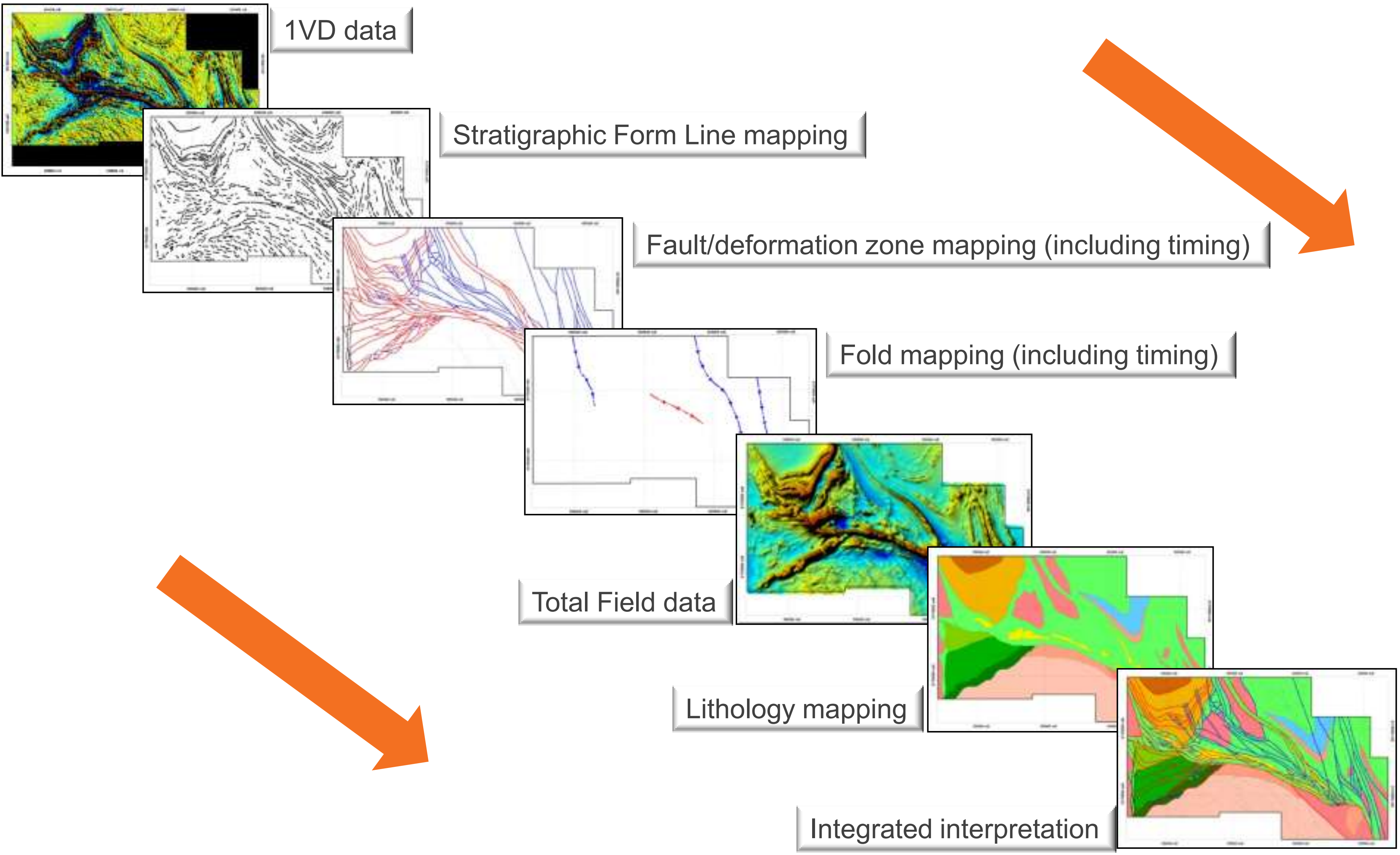


- **Think in terms of the magnetic rock body in the ground….not the magnetic field it causes.**
- **Formulation of structural history consistent with observations.**

Interpretation Flowchart

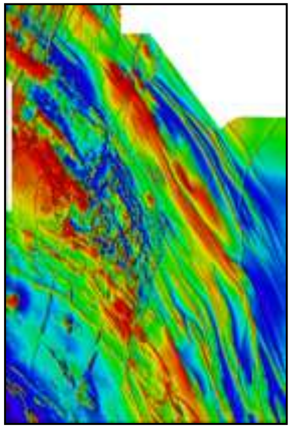


Method

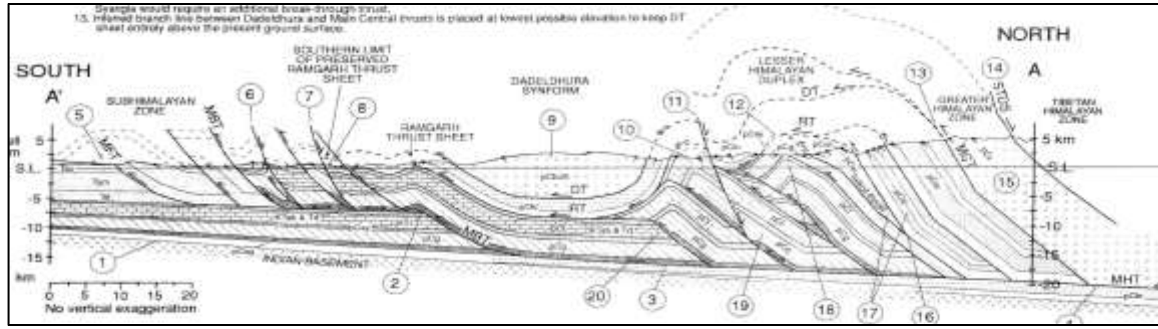

1VD data
Stratigraphic Form Line mapping
Fault/deformation zone mapping (including timing)
Fold mapping (including timing)
Total Field data
Lithology mapping
Integrated interpretation

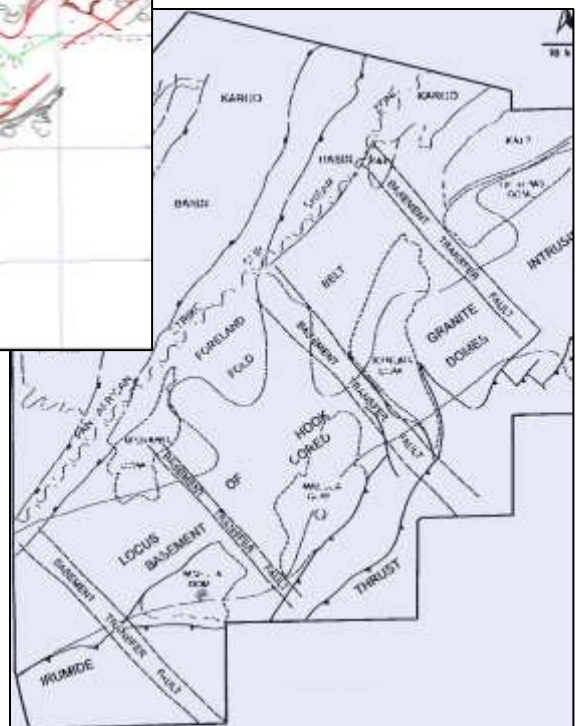
Geological Models for Mapping

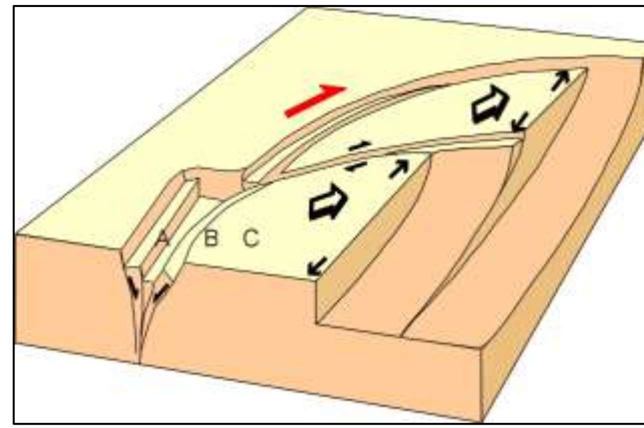
- Geological models are a **primary** component of the interpretation process for producing maps;
- In order to present an **interpretation** of the geology of the region, there needs to be a coherent framework of stratigraphic and structural principles that form the basis of the interpretation;
- A coherent regional geological pattern can be followed through the series of maps;
- Individual structures can be interpreted in both a time and space context. We can interpret when and how faults moved;
- **The spatial distribution of mineral deposits in relation to structures becomes evident, and can be related to the geological evolution of the region, not just the geometry;**
- Areas and structures with potential for reactivation at later times become apparent; and
- Cross-sections can be developed which provide a realistic 3D form consistent with the geological models.



Apply Structural Models

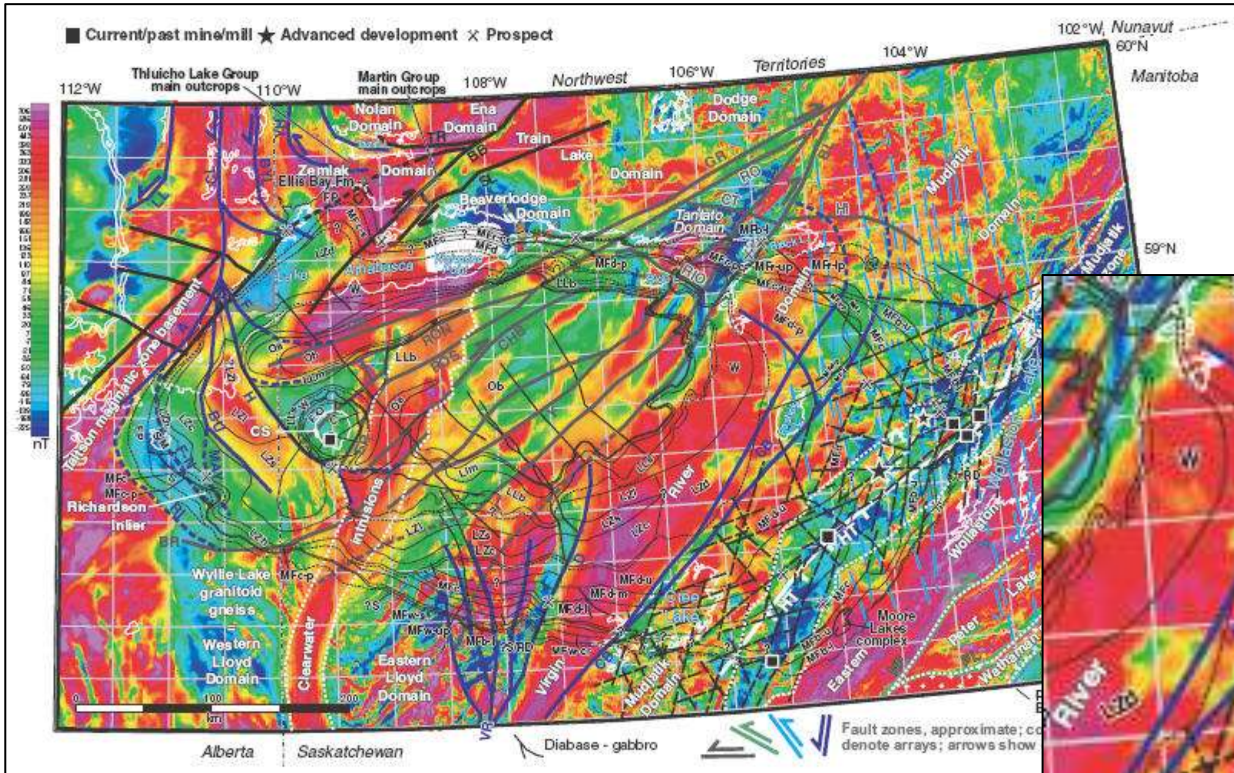


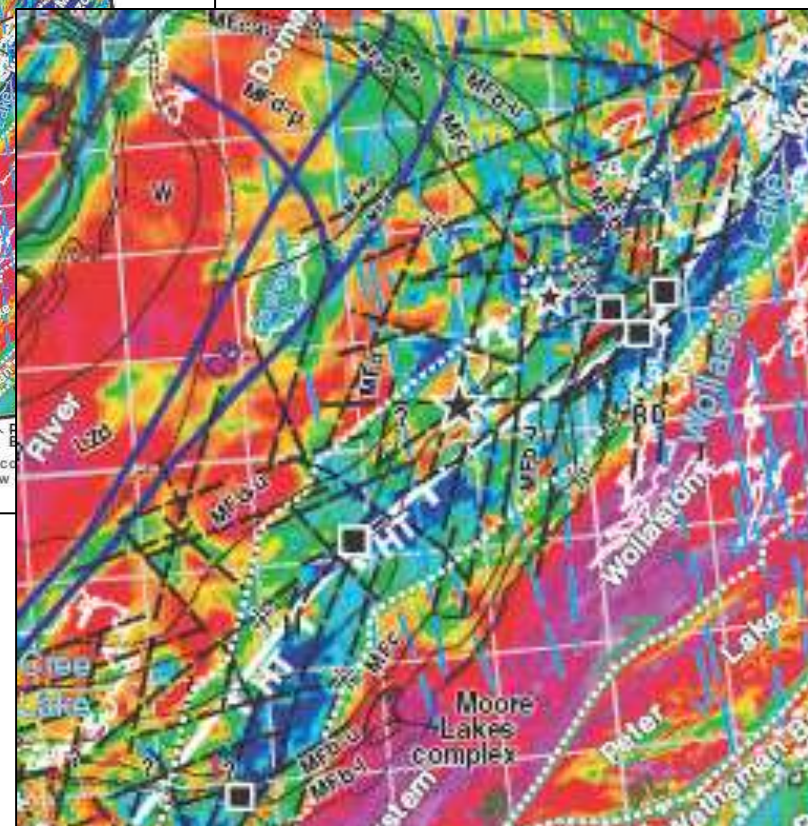




- Incorporate structural reality;
- Based on modern analogues.

Fault Patterns in Athabasca Basin



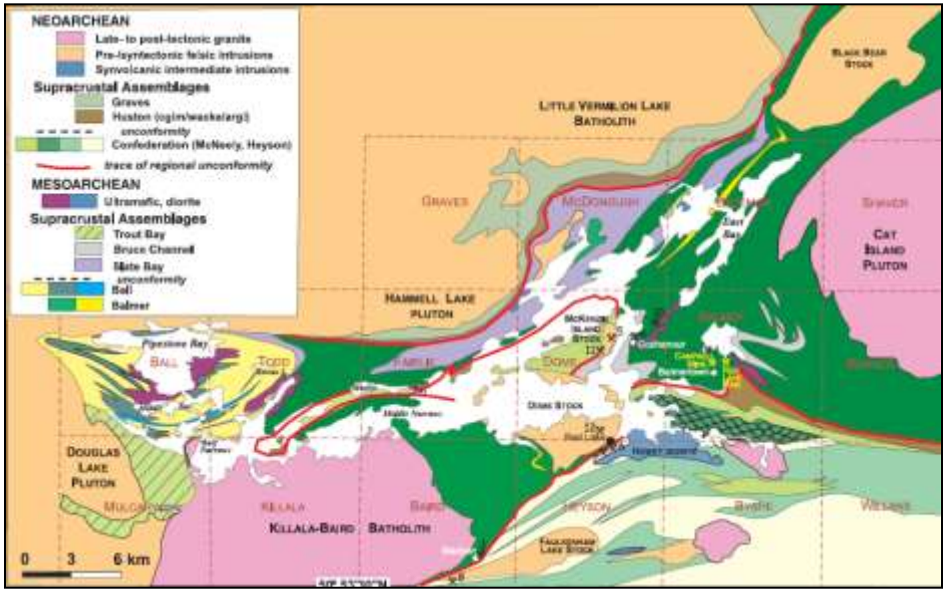


What is wrong with this interpretation?

From Jefferson et al. 2007

Reviewing Geological History

- **Stratigraphy:**
  - **Balmer Mafic volcanism:** **3.0-2.98 Ga[1]**
  - **Confederation Mafic-Intermediate volcanism:** **2.75-2.73 Ga[1]**
  - **Granodiorite plutonism:** **2.720-2.704 Ga[1]**
  - **Granodiorite dykes (Madsen, post-gold):** **2.699 Ga[2]**
- **Deformation:**
  - **D_1** **Northwest trending, south plunging F_1 folds** **2.744 Ma-2.733 Ga[1]**
  - **D_2** **East to northeast trending F_2 folds** **~2.720 Ga (Coeval with Dome Stock)[1]**
  - **D_3** **Coplanar with D_2** **~2.690 Ga[1]**
- **Metamorphism: Peak ~2.720-2.715 Ga[1]**
- **Gold mineralization @ Madsen :**
  - **2.744-2.699 Ga[2]**
  - **Or 2.723-2.712 Ga[3]**
- **Gold mineralization @ Red Lake, Campbell, Cochenour:**
  - **2.712 and 2.702 Ga[3]**



Red Lake Age Data Map, Figure 3, Sanborn-Barrie et al. 2004.

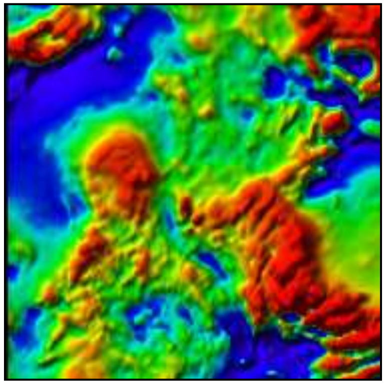
[1] Sanborn-Barrie et al. 2004. Geology, Red Lake greenstone belt, western Superior Province, Ontario. GSC Open File 4594.

[2] Dube et al. 2000. A preliminary report on amphibolite facies, disseminated-replacement style mineralization at the Madsen gold mine, Red Lake, Ontario. GSC Current Research 2000-C17.

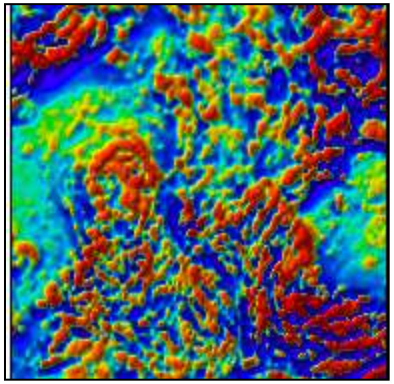
[3] Dube et al. 2004.Timing of gold mineralization at Red Lake, NW Ontario, Canada. New constraints from U-Pb geochronology at the Goldcorp High-Grade Zone, Red Lake Mine, and the Madsen mine. Economic Geology, V.99.

Structural Analysis - 1

• What can you use it for?

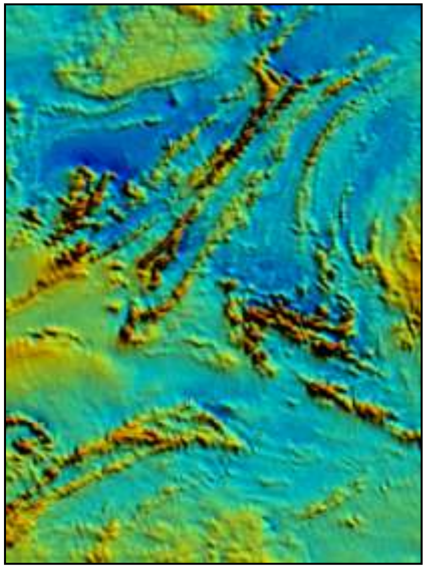


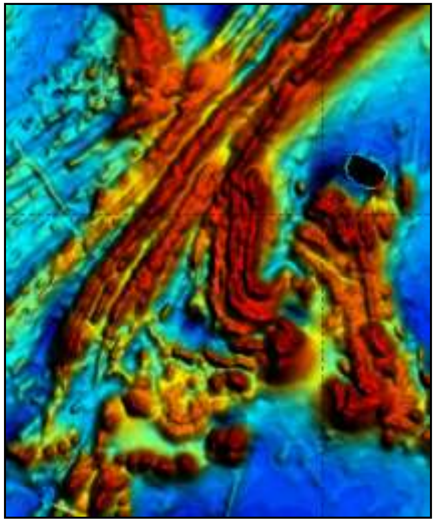
- Provide regional framework for understanding of known mineralization & regions of unknown geology;
- Develop tectonic / metallogenic models;
- Predictive targeting (regional and prospect scale);
- Problem solving (“where’d it go??”);
- Attempt reconstruction of early tectonic settings;
- Comprehensive metallogenic targeting; and
- Engineering geology problems.



Structural Analysis – 2

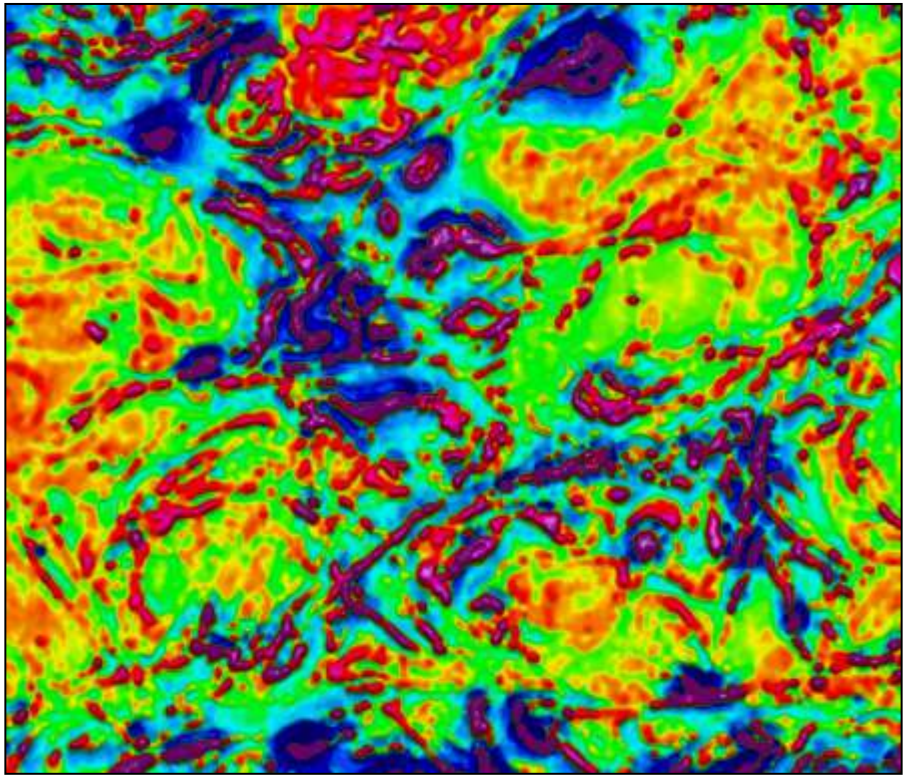
- **What can we get out of the data?**
  - Distribution of structures (folds / faults etc), lithologies & alteration - form surface mapping - extend from 2D plan view to 3D Kinematics?
  - Relative timing?
  - Development of tectonic models (local & regional);
  - Predictive targeting:
    - Direct anomaly;
    - Direct structural analogy; and
    - Indirect structural targeting (new models?);
  - Extension of models outside immediate area to different areas or terranes.





Structural Analysis – 3

- **Key Questions:**
  - What structures occur?
  - What is their extent?
  - Relative geometry?
  - What strain was produced?
  - What P/T conditions did they form at?
  - What is the 3D geometry?
  - What was the tectonic driving force & history?
  - What is the relationship of all this to mineralization?

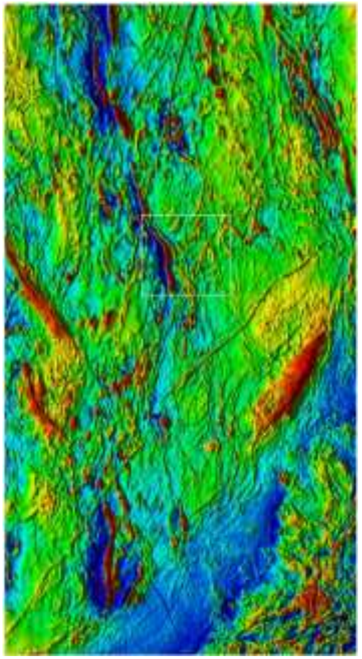


Ontario – Superior/Grenville Compilation, 400m line spacing, RTP1VD. Wabigoon subprovince.

Structural Analysis – 4

Important Observations To Make:

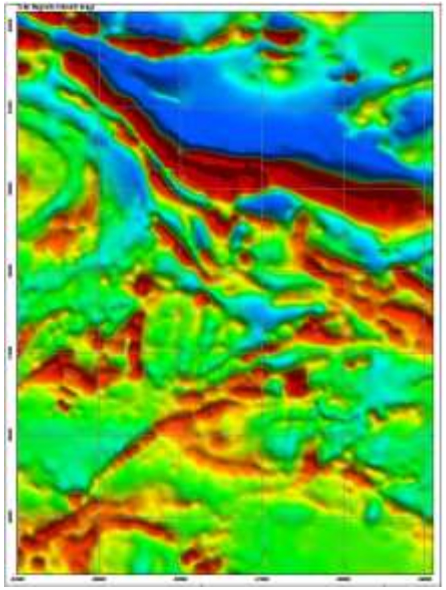
- Map structural traces (geophysics, field data, maps, remote sensing);
- 3D - fault dips (field data, magnetic profiles);
- Fault displacement vectors:
  - Relative displacements;
  - Kinematic indicators;
  - Associated structures (veins / R, R' faults & fractures);
- Timing relationships:
  - Fault - fault relationships;
  - Displacement of marker units;
  - Absolute dates.
- Fault characteristics:
  - Thin, straight (brittle, shallow, low T);
  - Broad zone with discrete breaks (brittle-ductile zone - mod P & T); or
  - Broad zone, no breaks (ductile - deep, high T).



Structural Analysis – 5

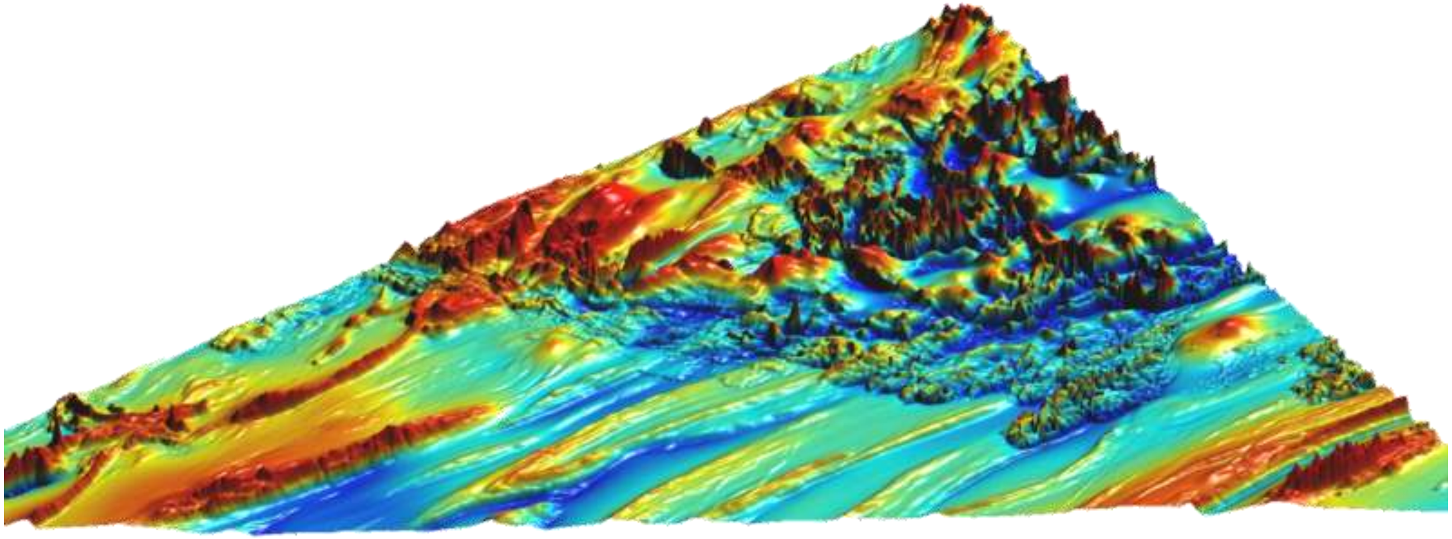
Important Observations To Make (cont….):

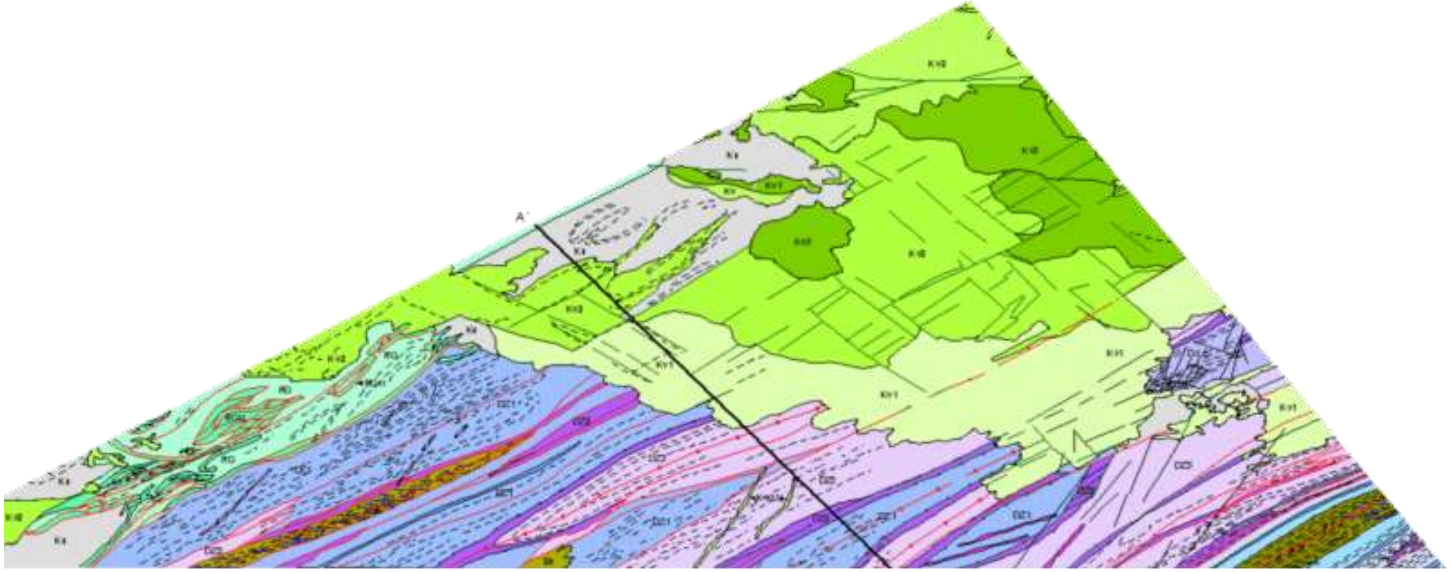
- Associated features:
  - Folds (parallel / oblique);
  - 2nd order sediments / basins;
  - Associate intrusives / extrusives;
  - Veining / alteration; and
  - Recognition of fault hierarchy (1st order, 2nd order etc).
- Strain variations inferred from block geometries:
  - Structures at block margins; and
  - Strain within blocks (possible modified stress fields).
- Regional context:
  - Relationship of area to regional structures;
  - Setting (e.g. basin, mobile belt, arc etc.);
  - Orogenic events elsewhere at inferred time of faulting?
  - Pre-existing structures possibly reactivated?



Examples

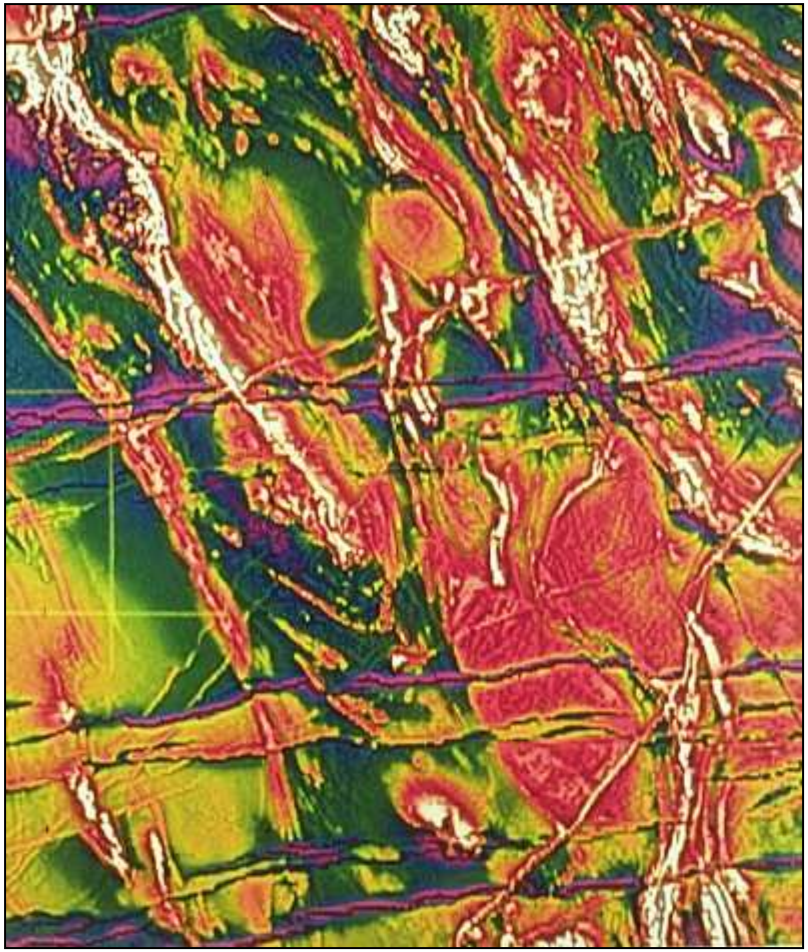
Example of Final Geological Maps

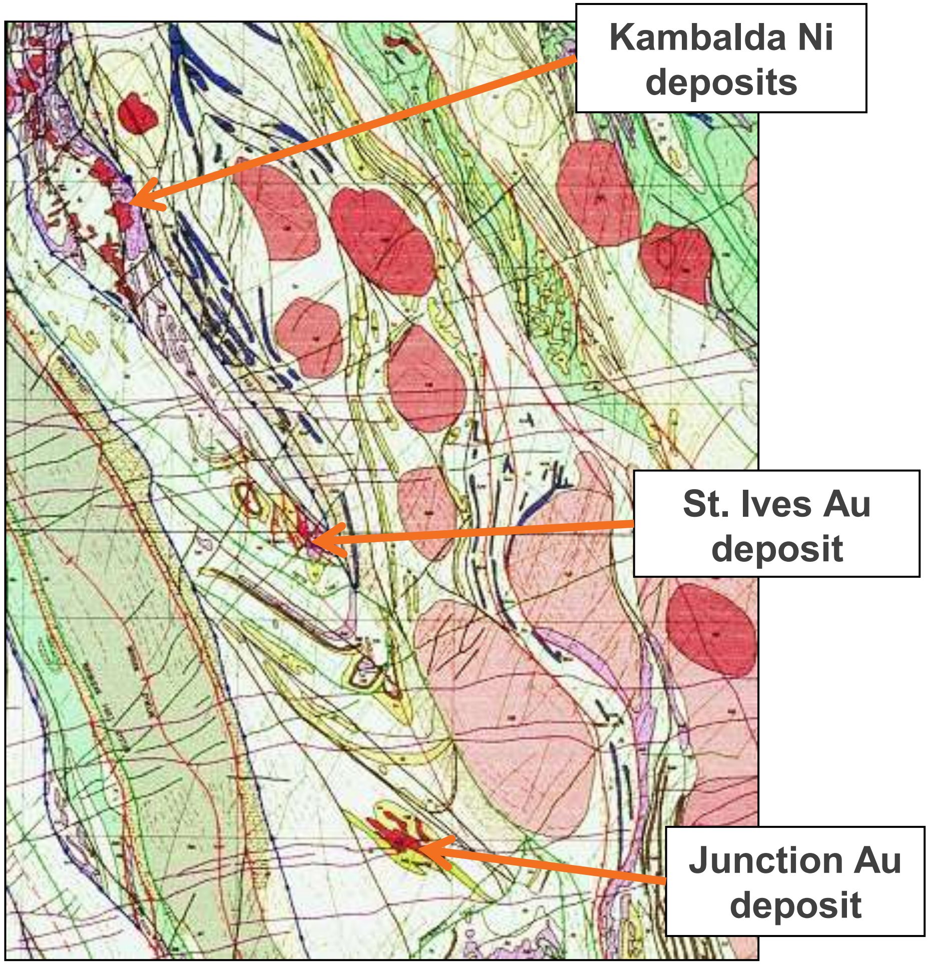




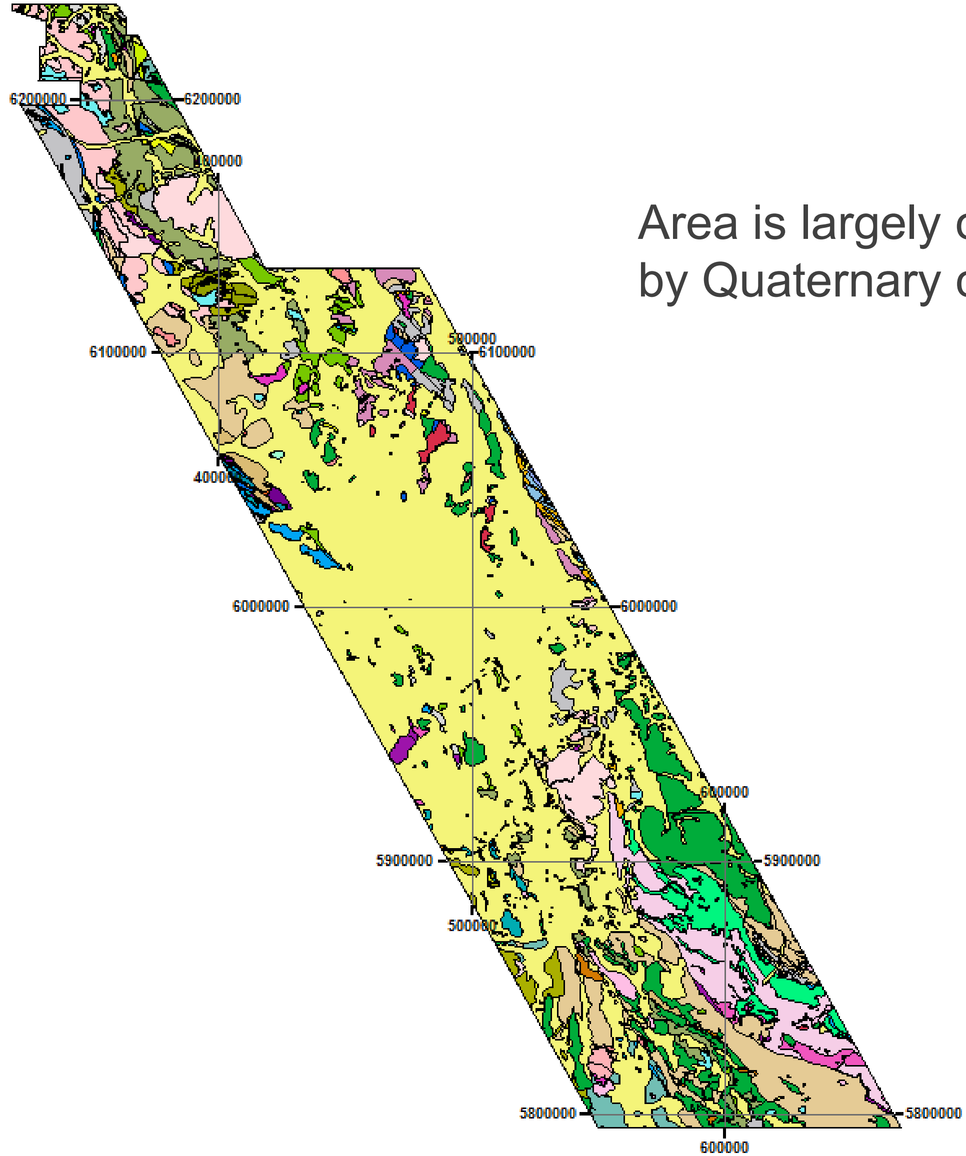
Final Geological Maps - Yilgarn

The Yilgarn Craton in Western Australia - a Late Archean Granite-Greenstone terrane.





Quest – The Problem?

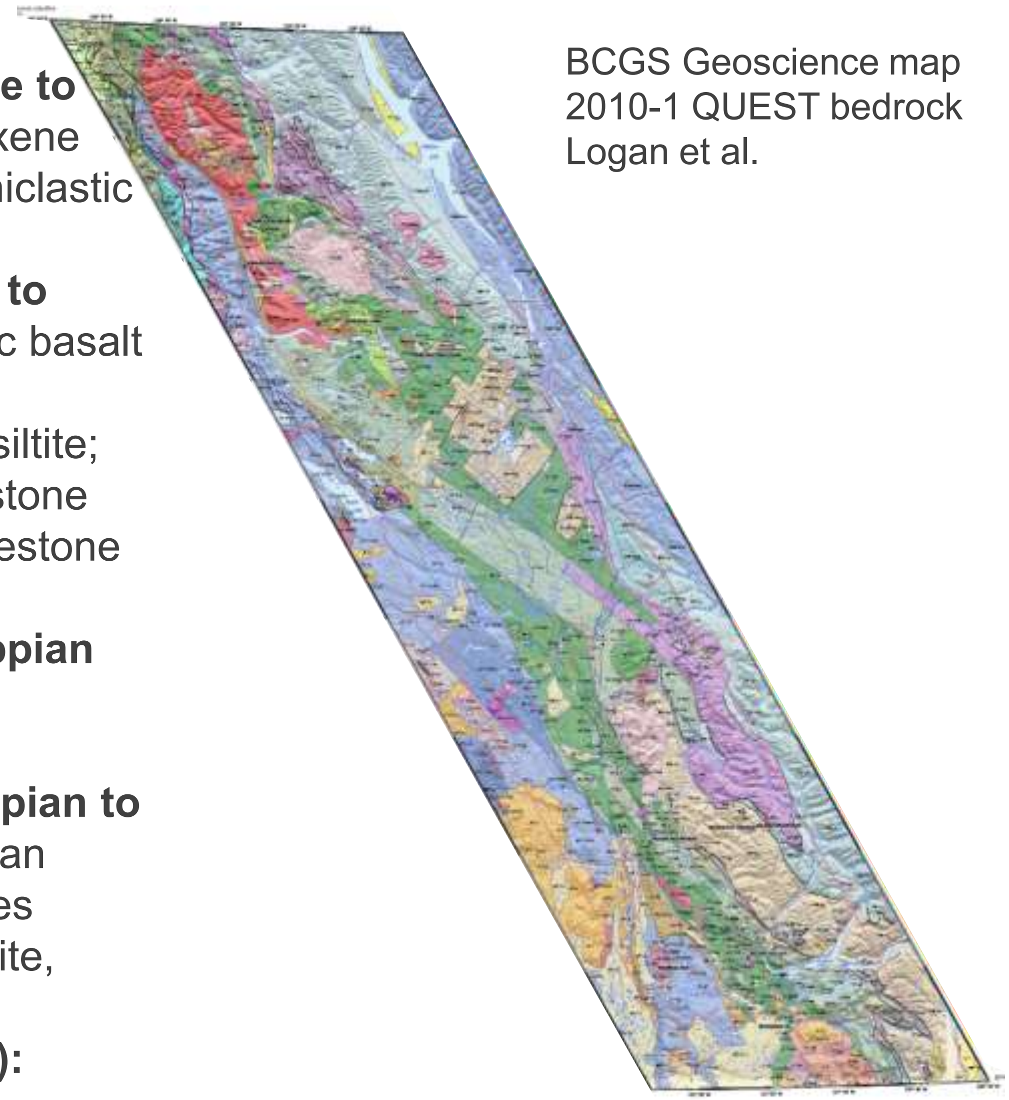


Area is largely overlain by Quaternary cover.

Reviewing the Geological History....e.g. Quest

• Stratigraphy:

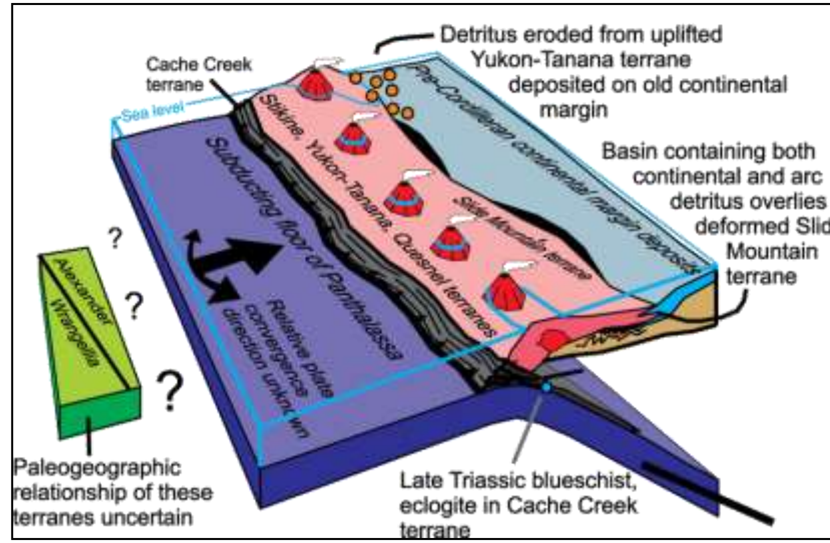
- **Nicola Group (Southern Quesnel; Middle to Upper Triassic):** Pyroxene, feldspar-pyroxene and feldspar phyric basalt breccias, volcaniclastic units and sandstone;
- **Takla Group (Northern Quesnel; Middle to Upper Triassic):** Augite-phyric and aphyric basalt breccia, agglomerate, tuff and flows; red fragmental basalt; tuffaceous argillite and siltite; conglomerate, sandstone, greywacke, siltstone and chert; local andesitic basalt; minor limestone and diorite;
- **Cache Creek Complex (Lower Mississippian to Lower Jurassic):** Mafic volcanic rocks, limestone, argillite, chert, serpentinite;
- **Slide Mountain Group (Lower Mississippian to Middle Permian):** Basalts and Mississippian chert-quartz sandstones and conglomerates
- **Snowshoe Group:** Quartzite, schist, phyllite, gneiss, marble, conglomerate; and
- **Chilcotin Group (Oligocene to Pliocene):** Columnar jointed olivine basalt.

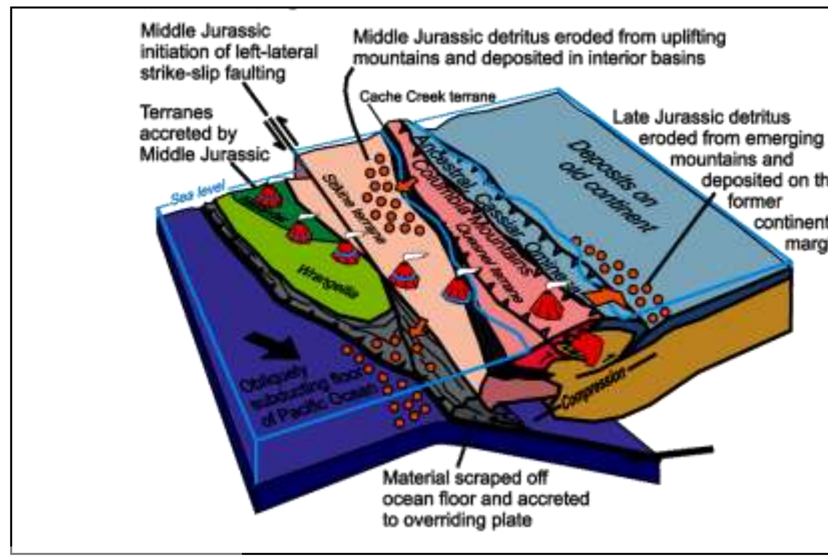


BCGS Geoscience map 2010-1 QUEST bedrock Logan et al.

Reviewing the Geological History....e.g. Quest

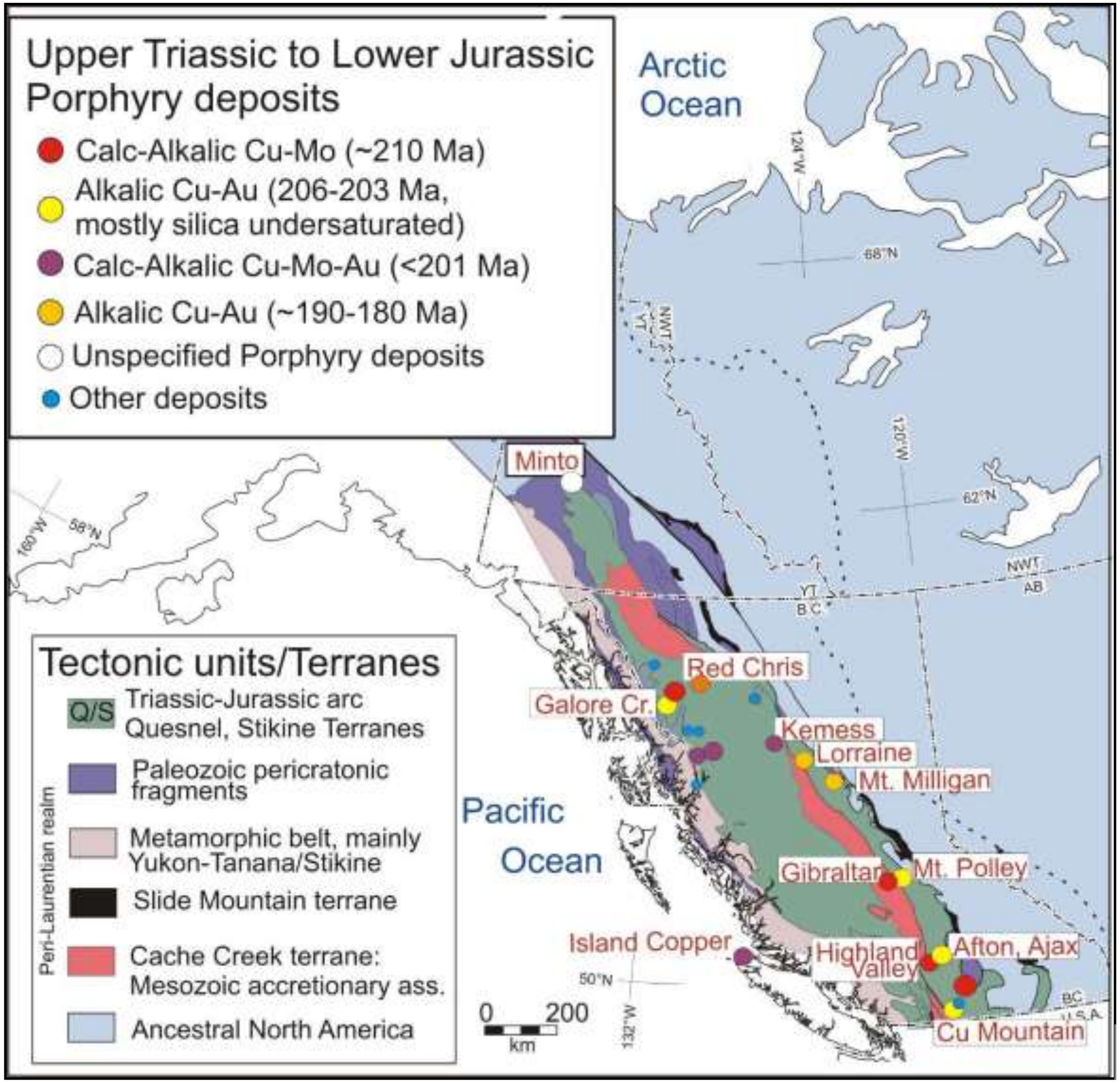
- **Deformation:**
  - Subduction and accretion of intermontane terranes to Laurentia, ca. 200 Ma;
  - Subduction and associated sinistral transpression with movement of Quesnel terrane northwards, ca. 185 Ma;
  - Subduction and associated dextral transpression, ca. 100 Ma; and
  - Dextral transtension and major dextral movement along the Denali-Tintina fault system, ca. 55 Ma.





Monger, 2008

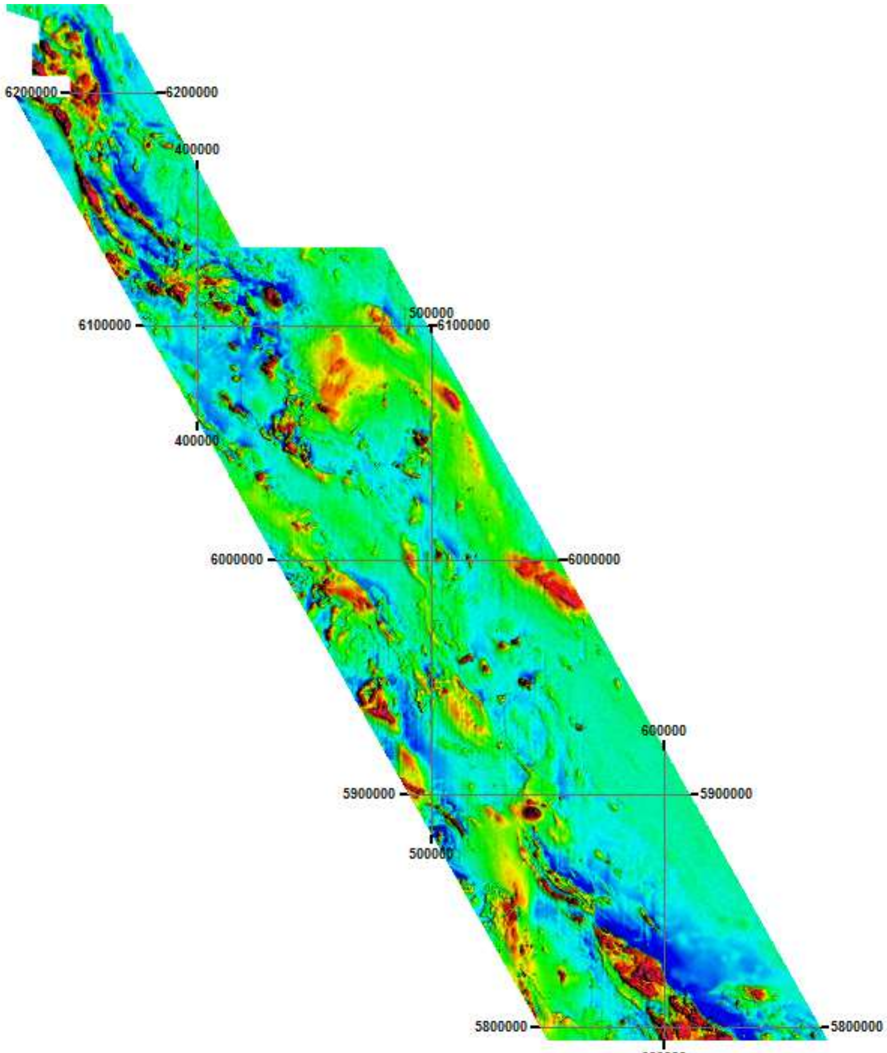
Upper Triassic-Upper Jurassic Porphyries



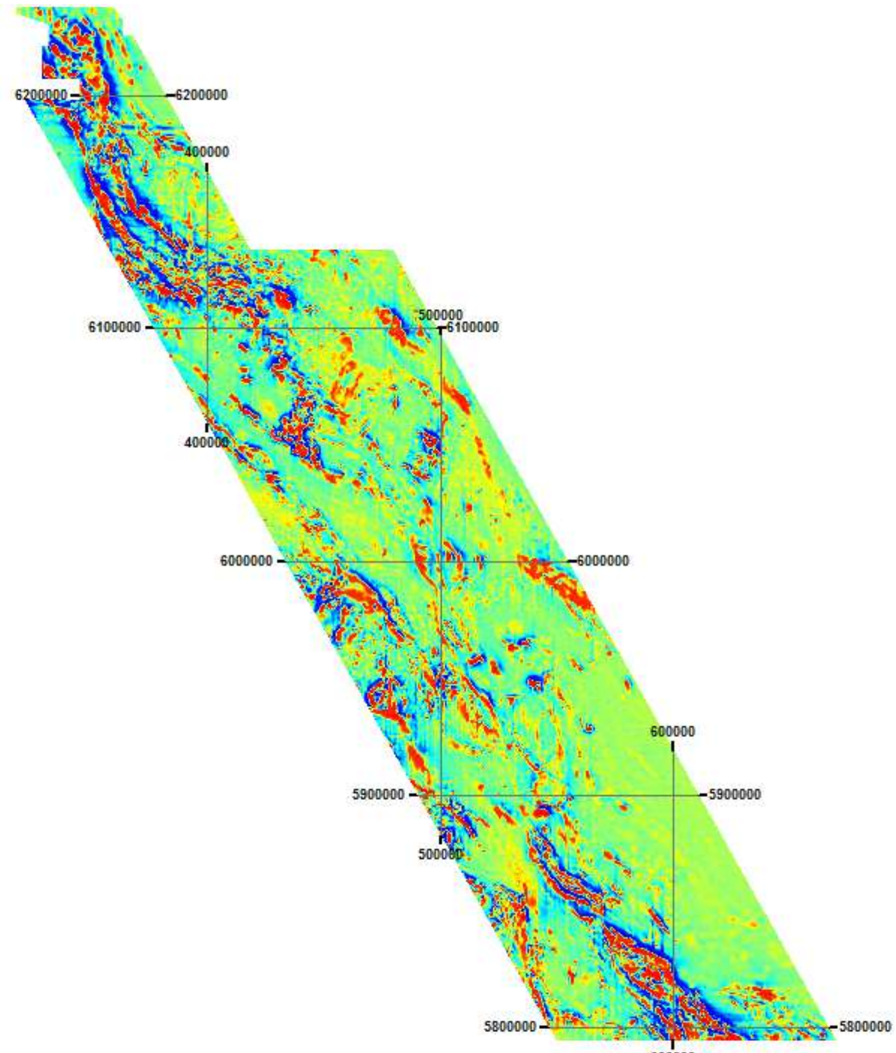
- Pre- to syn- accretion;
- Early Calc-alkalic Cu-Mo (Au) porphyries;
- ~206-203 Ma Alkalic Cu-Au porphyries;
- ~ 200 Ma Calc-alkalic Cu-Mo and Cu –Au porphyries;
- 190-180 Ma Alkalic Cu-Au porphyries; and
- < 170 Calc-alkalic Cu-Mo-Au porphyries (Island Cu).

Modified after Nelson and Colpron, 2007

Quest - Datasets

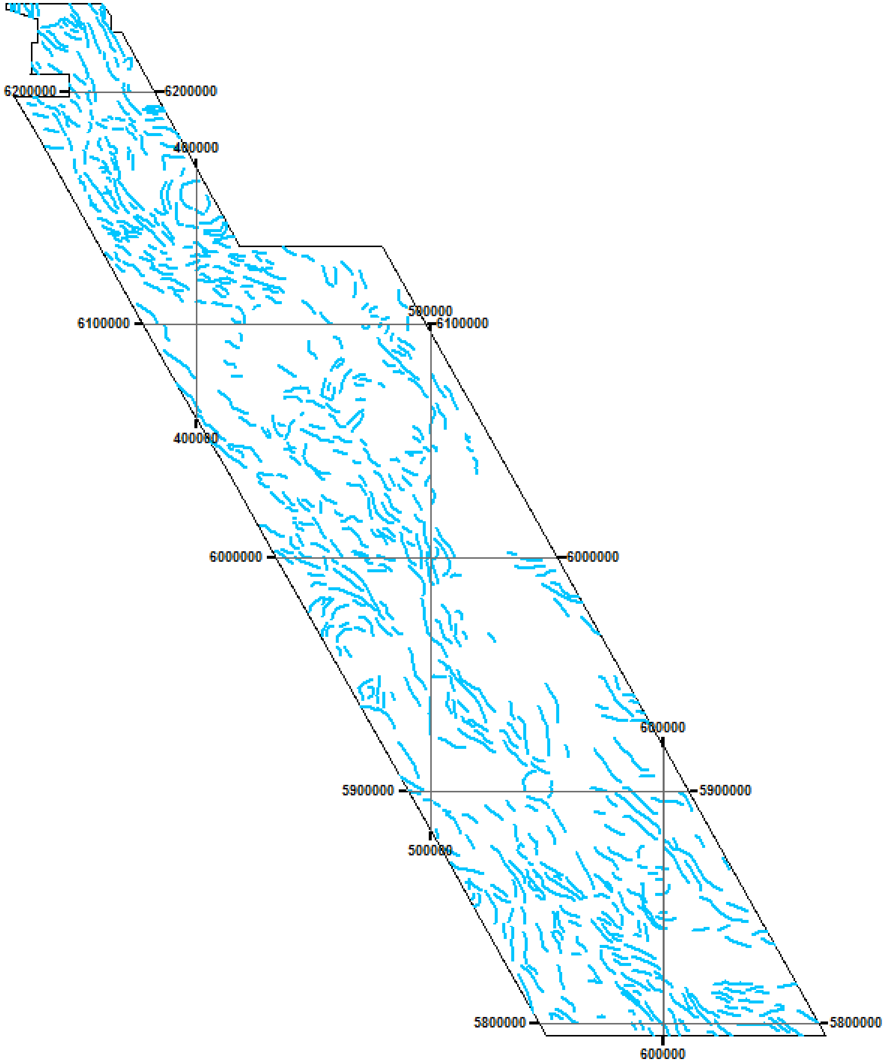


GSC Aeromagnetic Data, RTF, 800 m line spacing

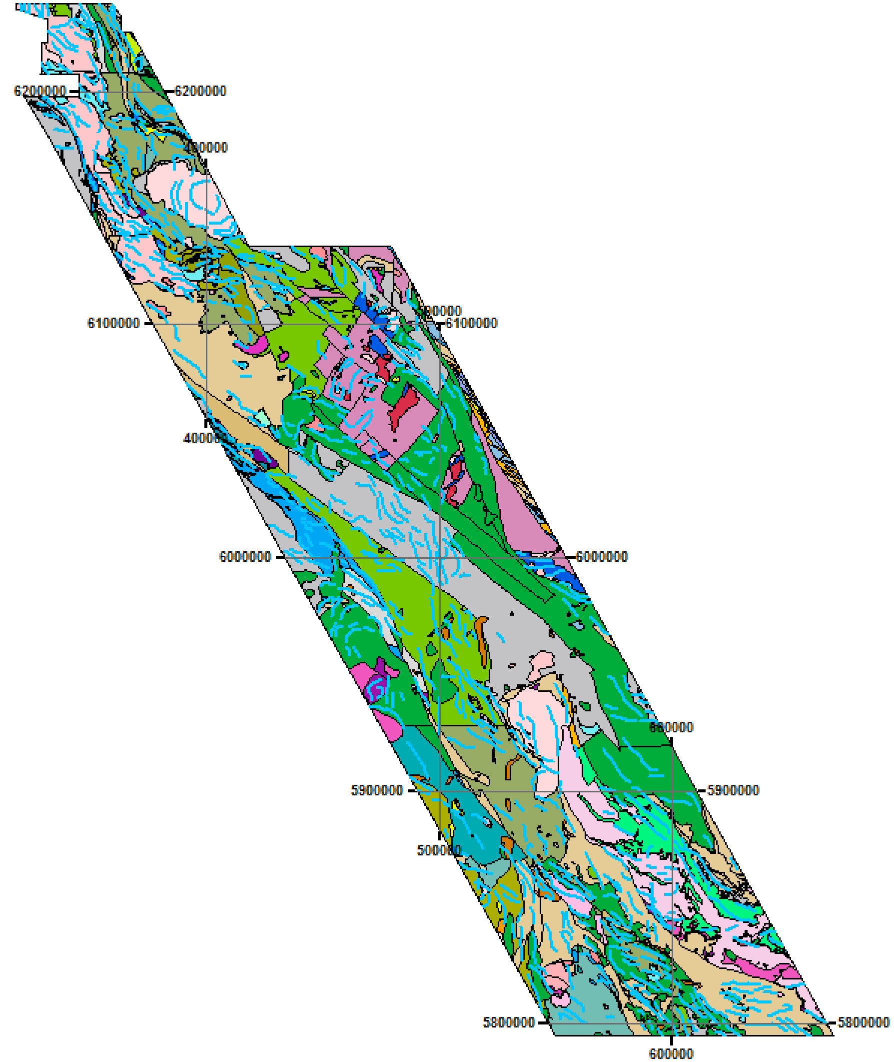


GSC Aeromagnetic Data, 1VD, 800 m line spacing

Quest – Form Line Mapping

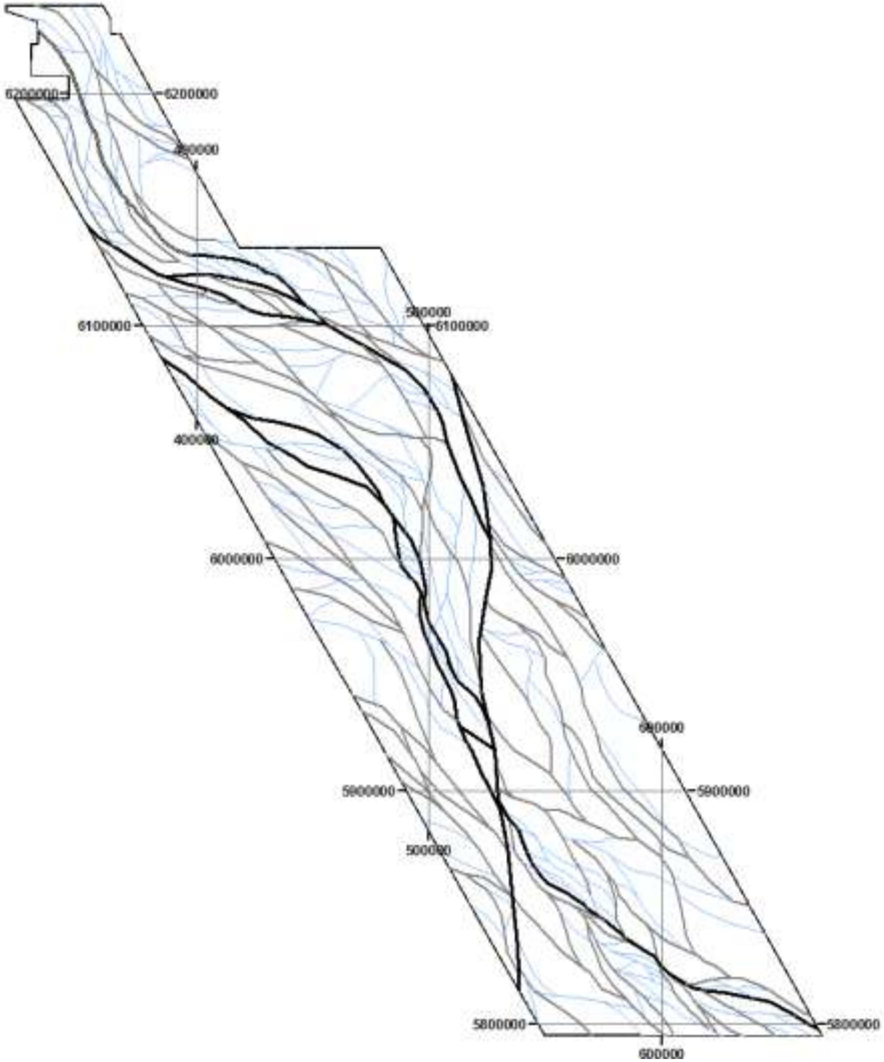


Quest Area Form Lines

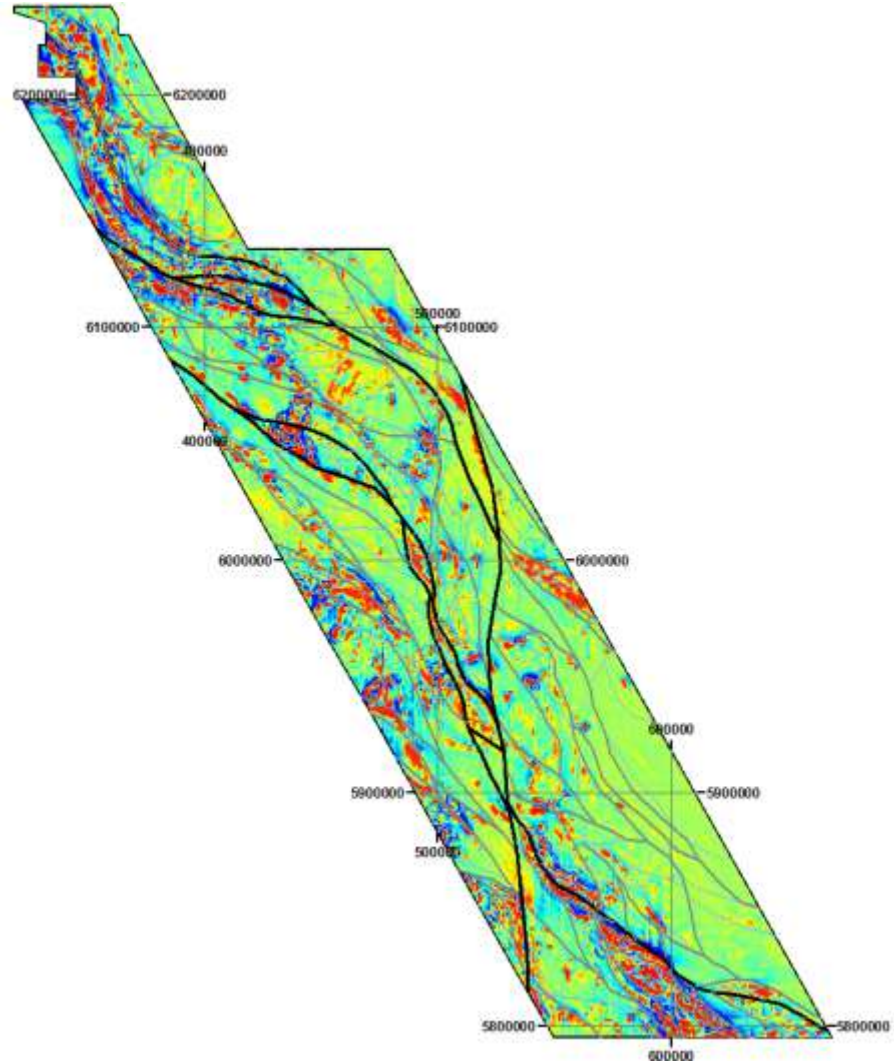


Quest Form Lines Vs. Mapped Geology

Quest – Fault Mapping



Quest Area Faults

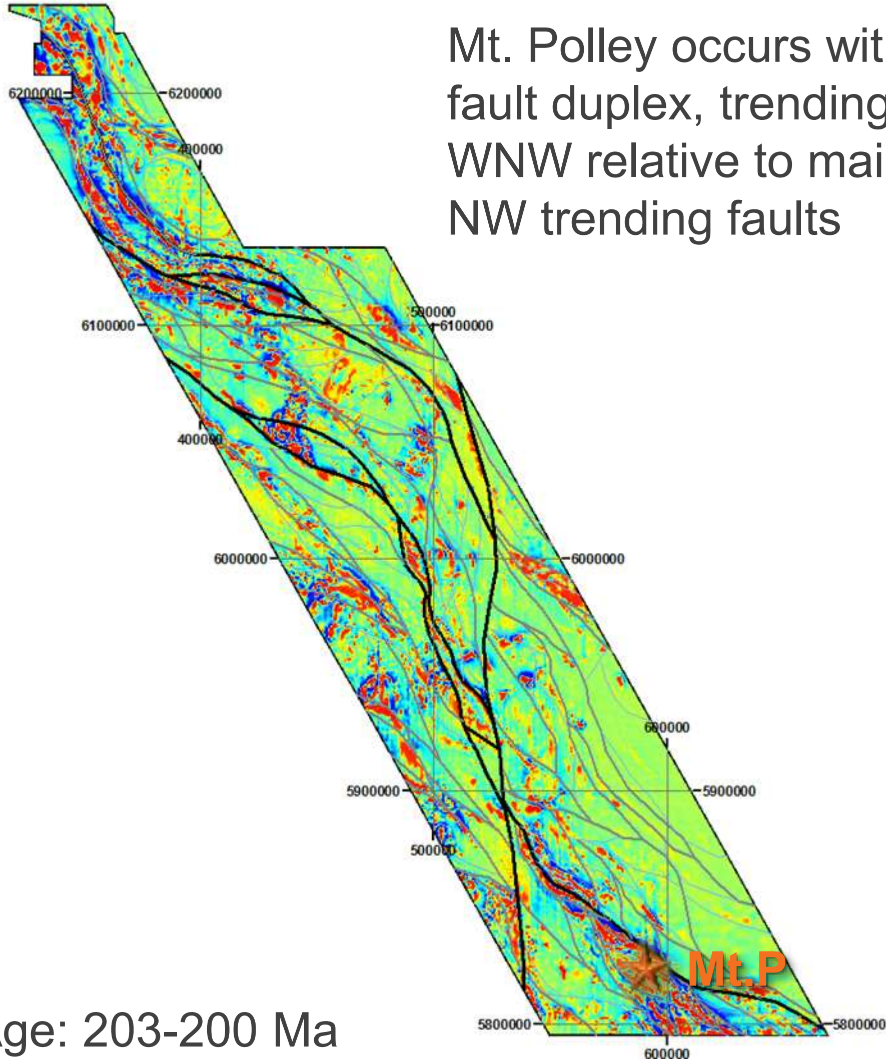


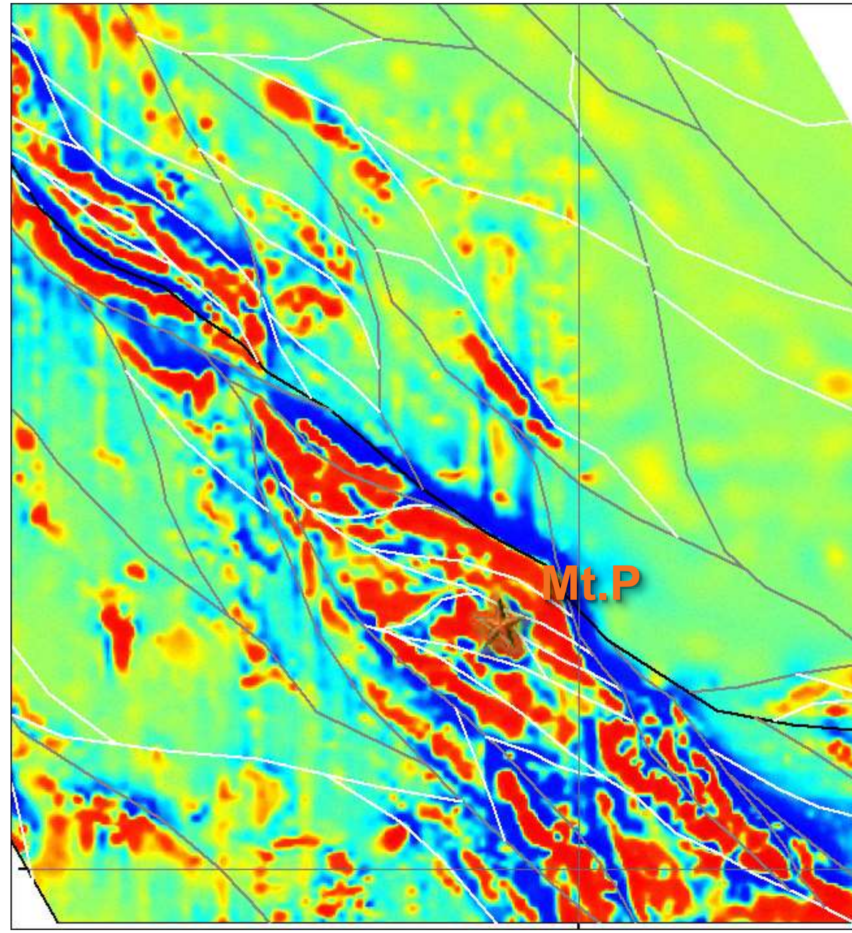
Quest Faults with GSC 1VD magnetic grid

Quest – Mt. Polley Setting

46.2 mt @ 0.34% Cu, 0.29 g/t Au, 0.95 g/t Ag

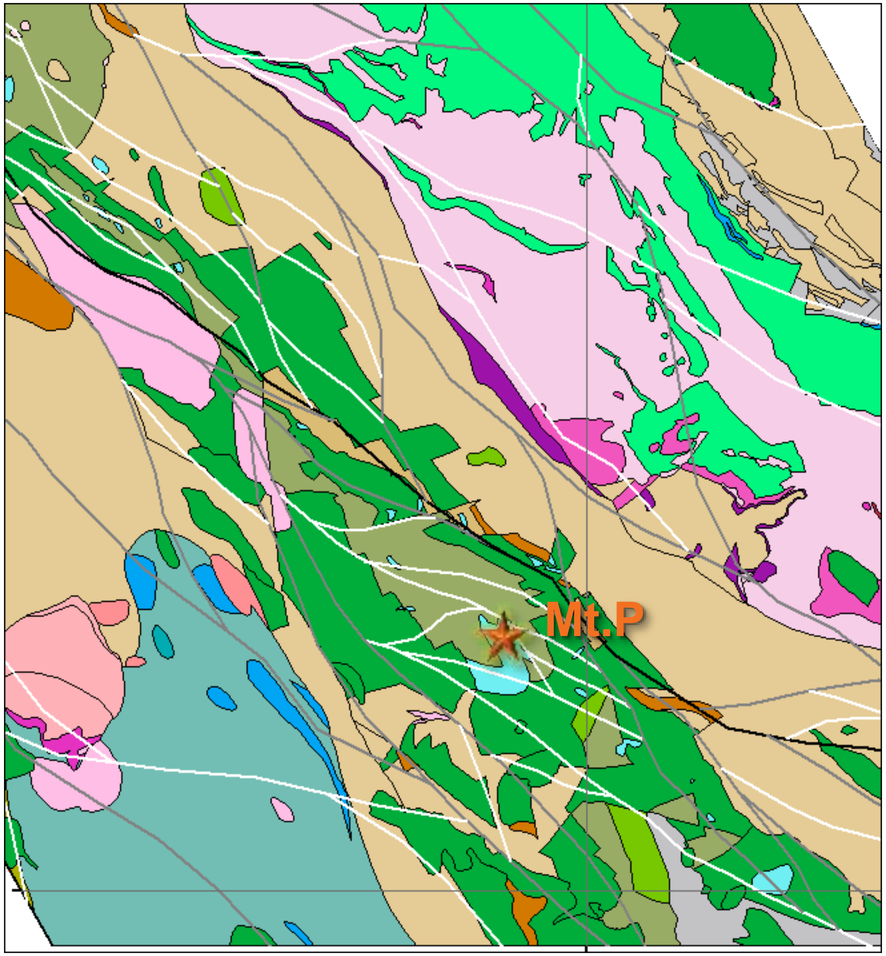
Mt. Polley occurs within a fault duplex, trending WNW relative to main NW trending faults

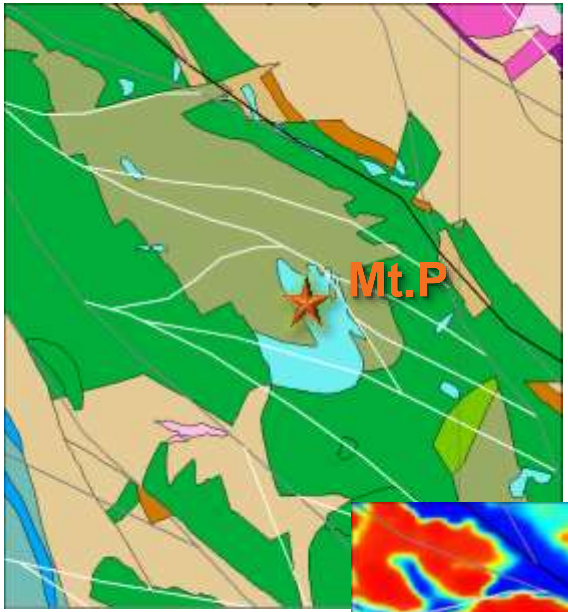


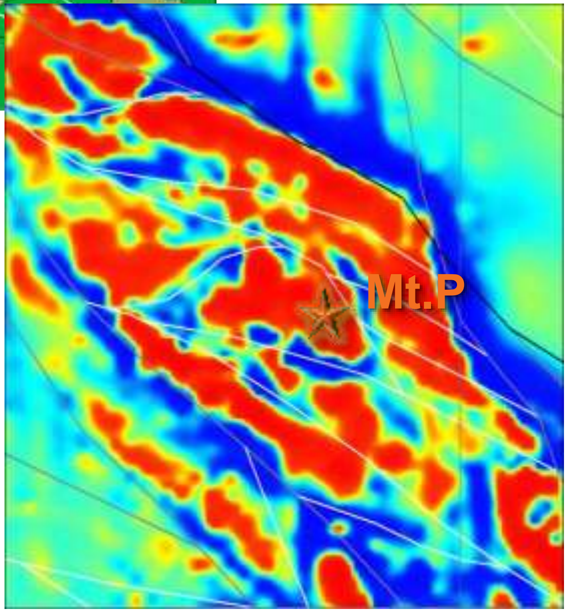


Age: 203-200 Ma

Quest – Mt. Polley Setting

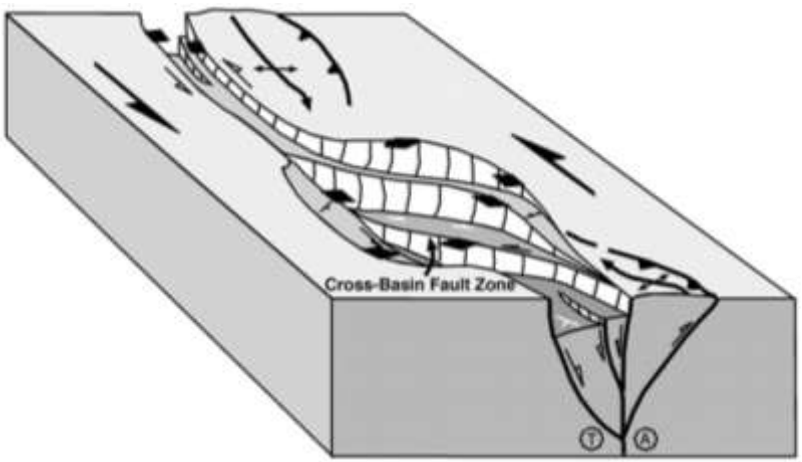


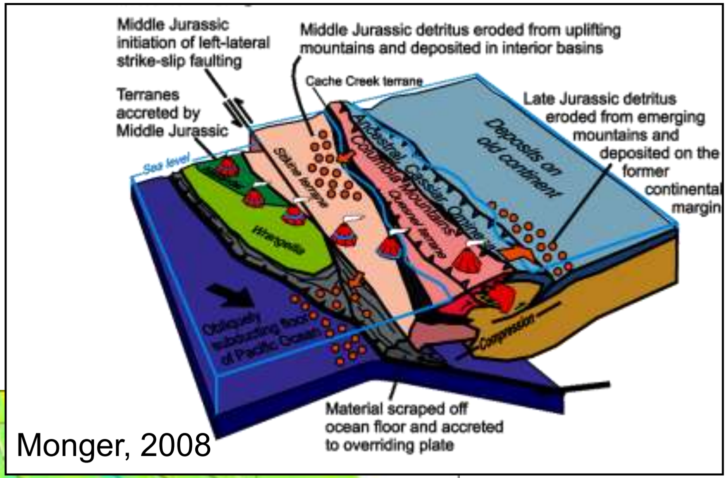




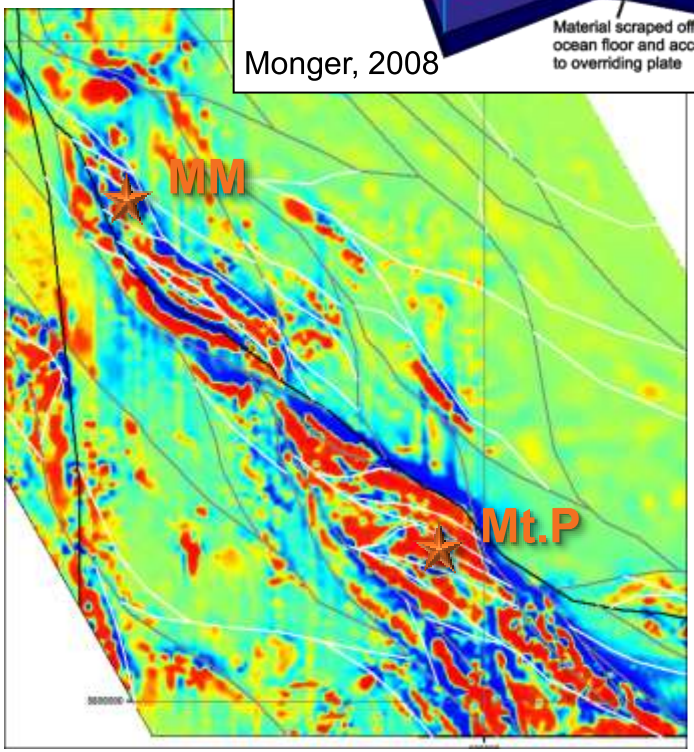
Split in Mt. Polley syenite-monzonite intrusion related to fault network

Quest – A Tectonic Model?





Monger, 2008



Reverse-sinistral transpression creating WNW or E-W pull-apart structures

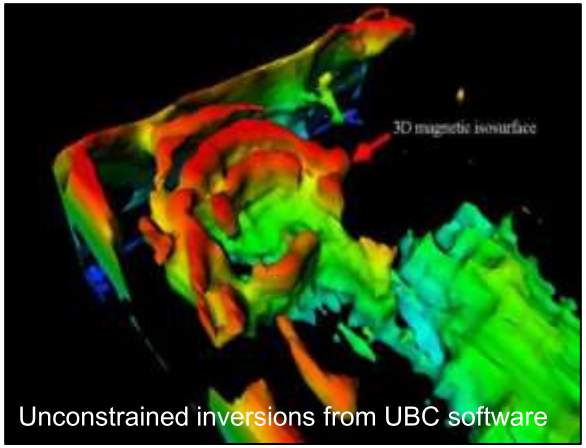
The Way Forward – Digitizing

http://www.wacom.com

The Way Forward – Data Integration

3D Geophysical Inversion:

Most gridded potential field data sets (magnetics, density or EM) can be directly used to constrain 3D geological models. (3D Geomodeller & GOCAD).

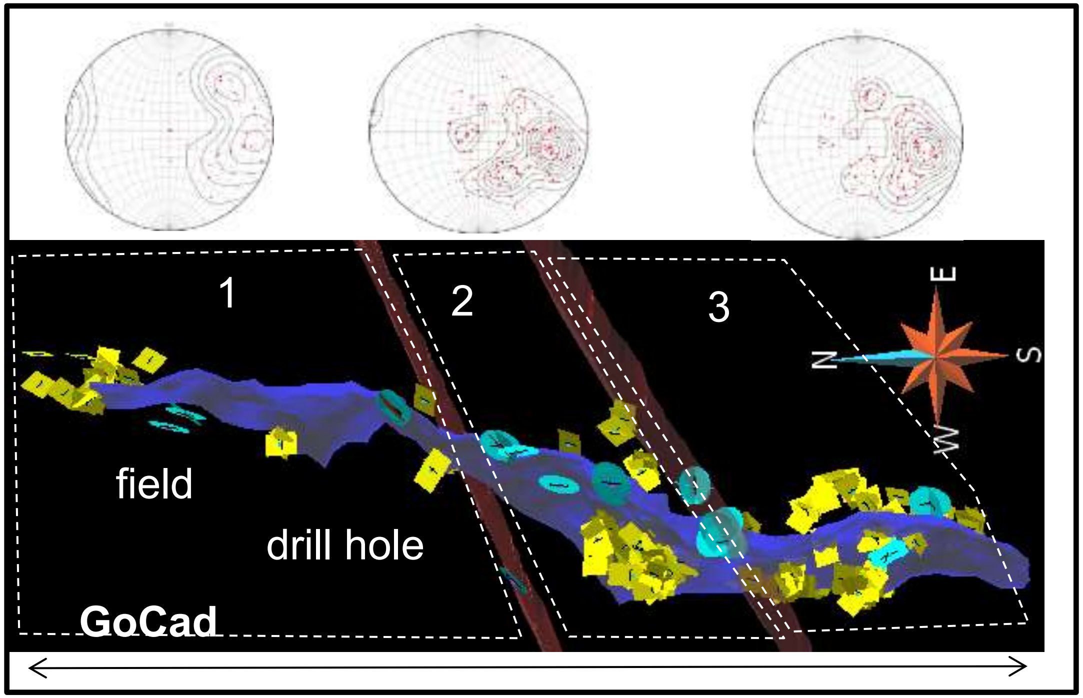


3D GIS:

Spatial data analysis, domaining and querying.

Structural Data:

Wireframes created from planar measurements. Stereonets!



Conclusions

To produce an accurate, applied geological interpretation:

- Think geologically – process/controls when defining geological elements from aeromagnetic data;
- Focus your interpretation with an understanding of potential controls on the distribution of mineralization first;
- Incorporate reality – structural settings/geometries, known geological relationships in the area (e.g. stratigraphic relationships);
- Define your geological and structural history; and
- Incorporate multiple datasets, e.g. existing geological mapping, drillhole data.