Geospatial Analysis and 3D Modelling of Distinct Subprovinces of the Superior Craton

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METAL EARTH

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CANADA FIRST RESEARCH EXCELLENCE FUND

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MERC
Mineral Exploration Research Centre

Metal Earth Objectives I

Key Objectives:

- **Multiscale analysis from craton to deposit** (Superior, Slave) to map the controls on the localisation of mineral deposits using a comprehensive ***"ore system"*** approach.
- **Understand the deeper crust to upper mantle pathways** and their role in controlling the emplacement of ore deposits. 3D/4D imaging with advanced seismic.
- **Transect scale analysis** is required to honour and **interpret the seismic data**. These studies are **expected to generate new exploration targets.**
- **Identification of key patterns** that represent <u>hydrothermal activity</u> are key to this component of the project.
- Evaluating **fertile and apparently less fertile terranes** (similarity and dissimilarity).

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Metal Earth Objectives II

Key Objectives:

- **Obtain a complete 2D/3D and 4D integration** of multiparameter data
- **New technological developments that implement AI systems** to enhance mineral exploration
- **Thematic research** with the aims of:
  - (1) answering craton scale questions on metal endowment and
  - (2) knowledge and data driven **predictive mapping** incorporating new knowledge/data.

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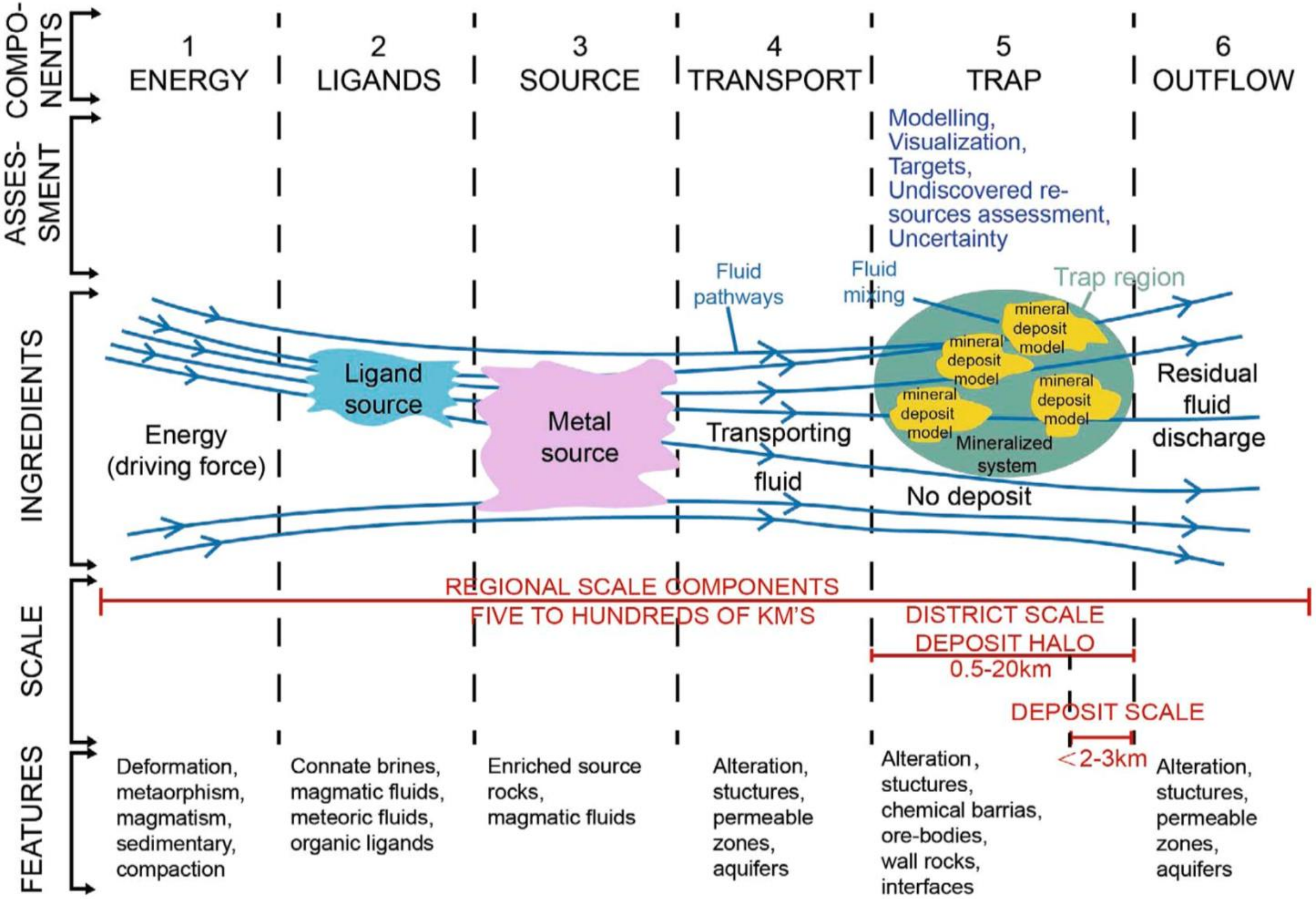
Multiscale Ore System Processes Lead to Giants?



Hagemann et al. 2016

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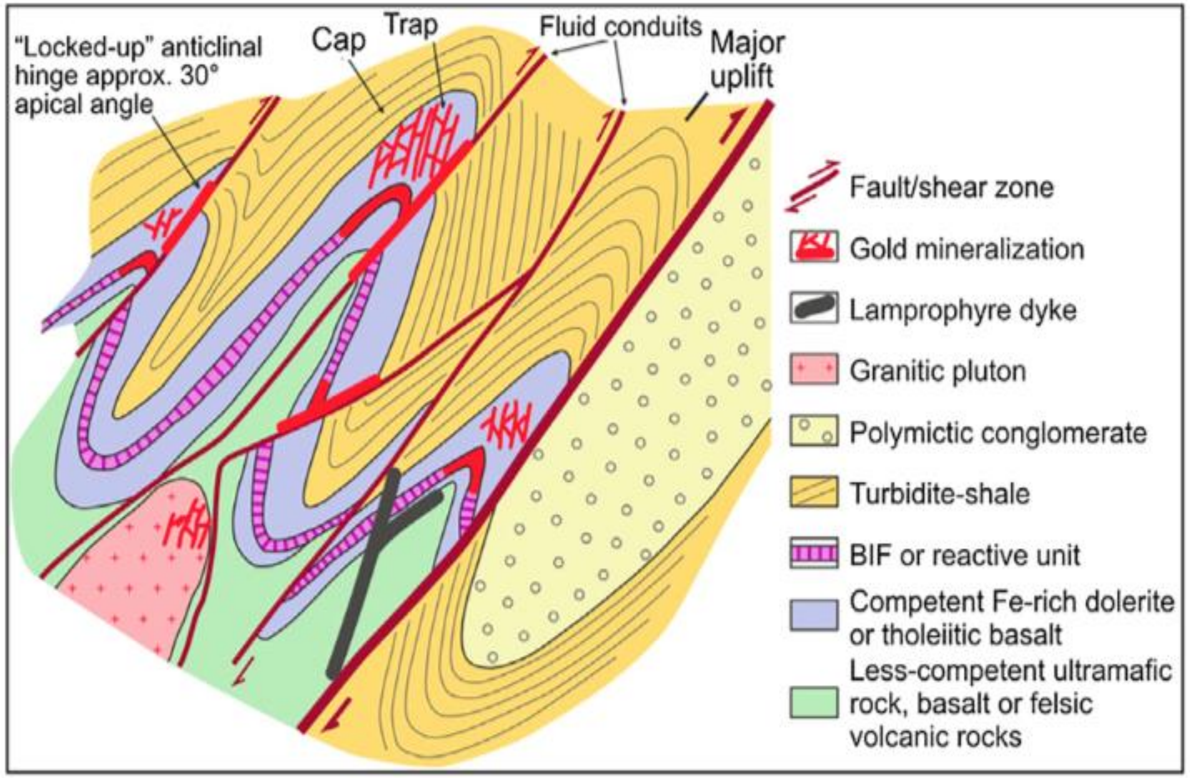
Exploration Models Au Deposits (Conceptual, Local Controls)

Aspects influencing fluid flow, Au traps

- Fault jogs/terminations and intersections especially with favorable host lithologies such as BIF or carbonaceous sequences.
- Presence of lamprophyre (small ultramafic, ultrapotassic assemblages). They are interpreted as being mantle derived magmas. Also an indication of lithospheric structures (mantle-tapping-faults).
- Fold hinge model invoking permeability enhancement together with competency contrasts in lithological units (iron-rich shales vs iron-poor)

Summary of Structural Controls



Groves et al. 2016

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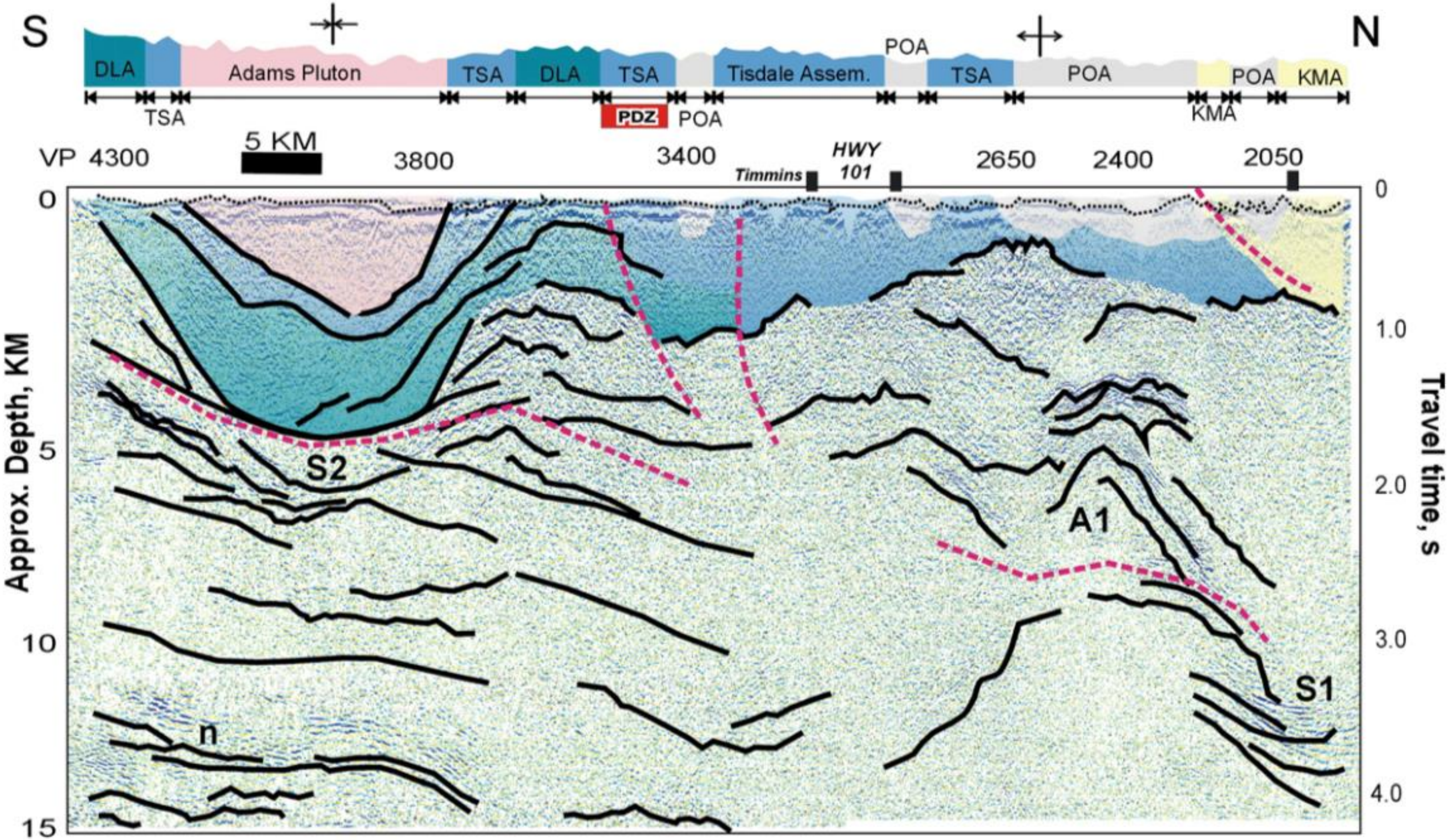
Deep Fluids/Magma Sources and Large Scale Deformation



Abitibi Assemblages

- Timiskaming (2676-70)
  Porcupine (2690-85)
- Blake River (2704-2696)
- Tisdale (2710-03)
- Kidd-Munro (2718-10)
- Stoughton-Roquemaure (2723-20)
- Deloro (2730-24)
- Pacaud (2750-35)

Snyder et al. 2009

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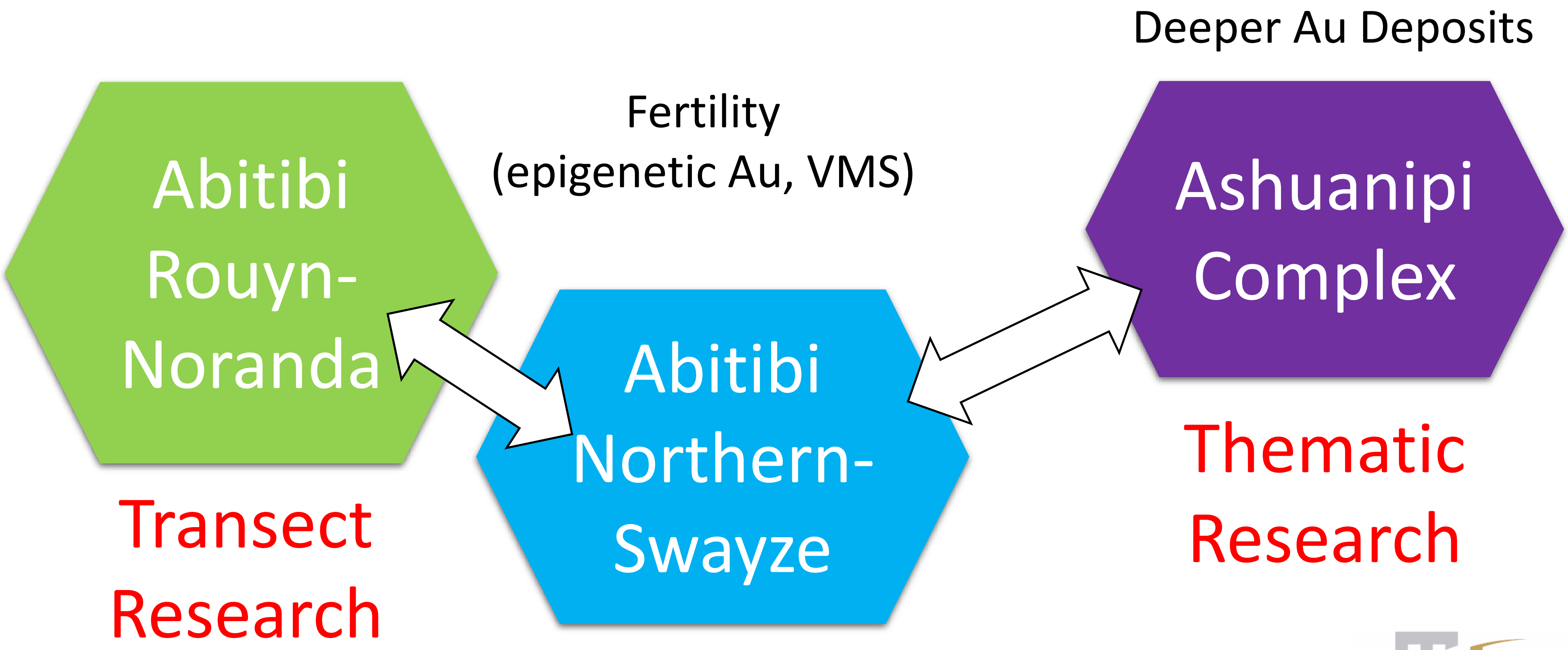
Craton-scale Perspective (Multi-terrane Analysis)

- Focus on three sub-provinces of the Superior craton to understand differences in fertility/mineral endowment and provide integrated datasets for statistical analysis and predictive mapping.



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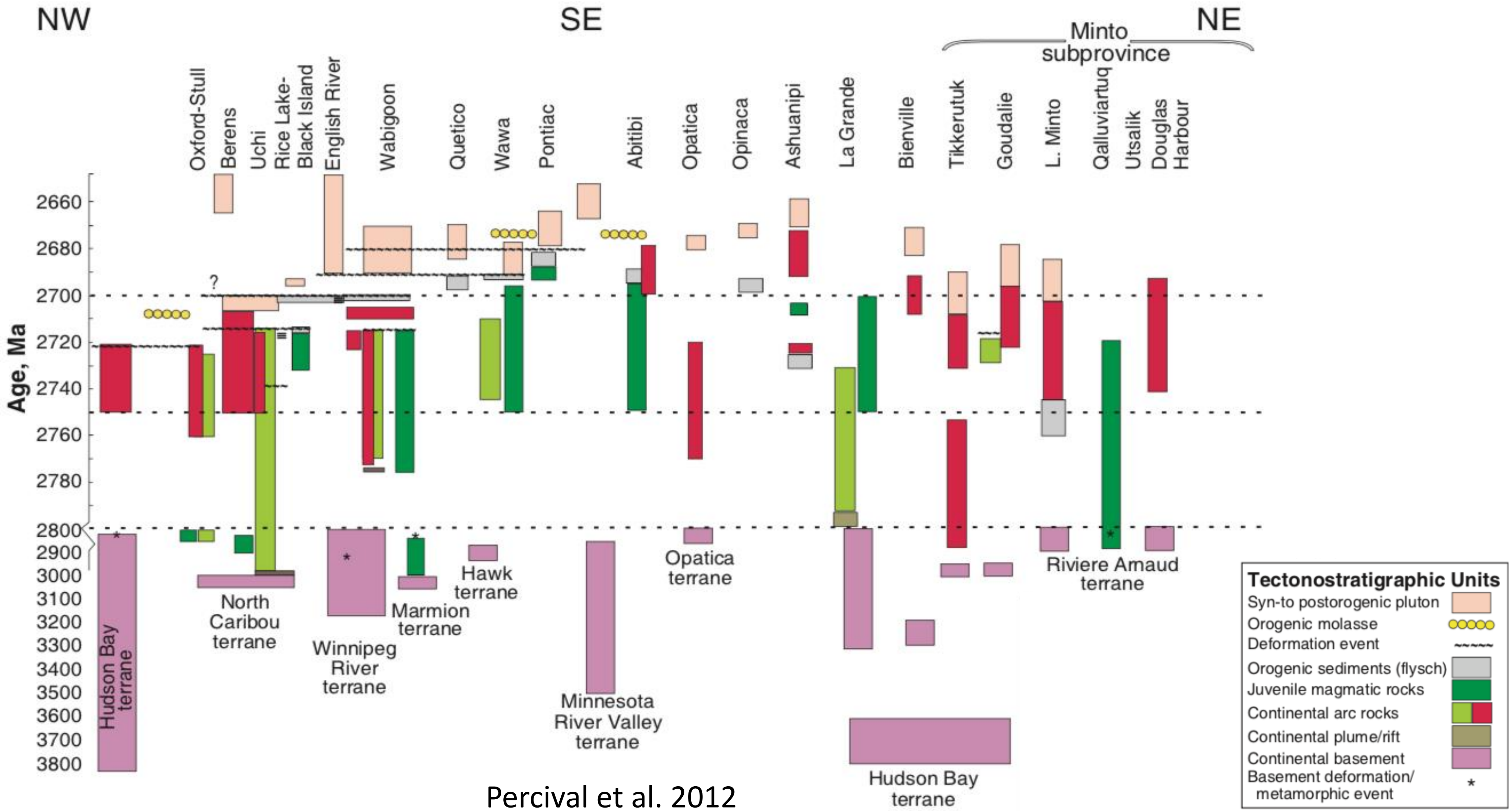
Geology and Tectonic Evolution of the Superior Craton

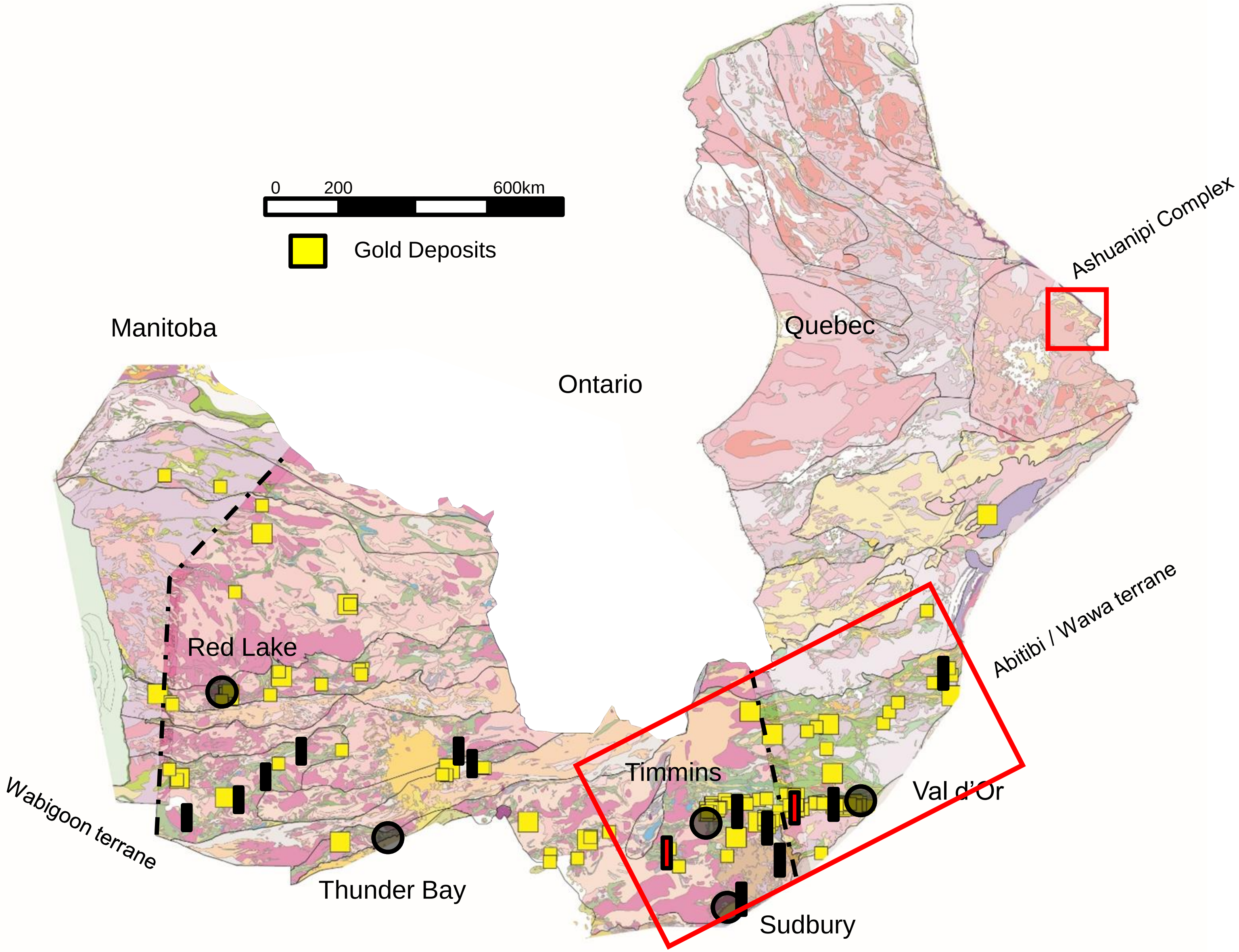


Percival et al. 2012

Superior Craton: Main Project Areas and Au Deposits

Data Analytics Project Locations

- **Abitibi Greenstone Terrane**
  - **3D Modelling (Integration with Seismic and MT)**
    - Rouyn-Noranda Transect
    - Swayze Transect (Northern Swayze)
- **Ashuanipi Complex (Mineral Prospectivity) Predictive Mapping**
  - Southwest of Schefferville along its eastern termination
- **Craton Scale Data-Driven Comparative Analysis**



MSc Projects

Students Involved in Metal Earth (Transect 3D Modelling Research)

- Transect 3 Northern Swayze:

Lawraine Lerato Mogashoa

3D Reconstruction and mineral prospectivity of the Northern Swayze Greenstone Belt

Goals: Information Integration, Structural Interpretation, Analysis of Favorability

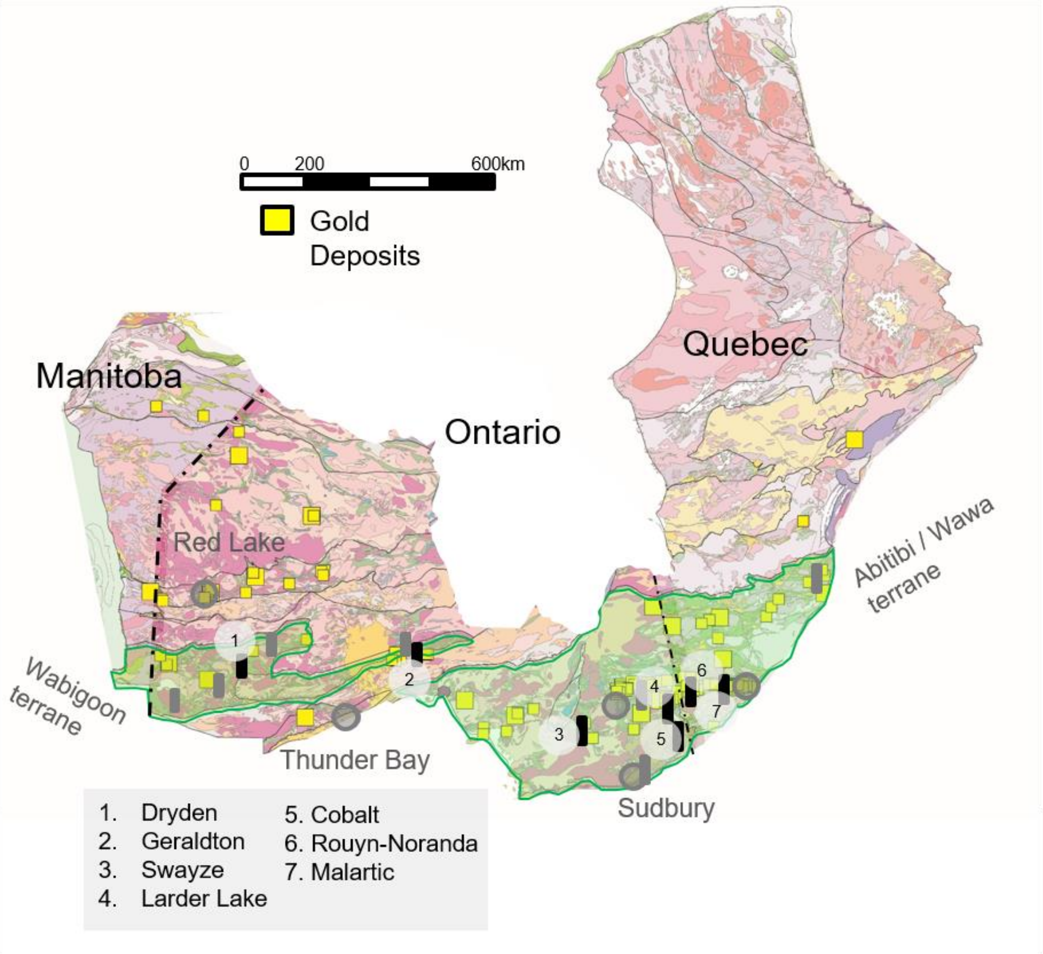
- Transect 6 Rouyn-Noranda:

Sahibzada Hussein Ali

A Revised 3D Reconstruction and VMS Mineral Prospectivity Mapping of the Noranda Camp

Goals: Information Integration, Structural Interpretation, Analysis of Favorability

- Thematic Research Project (MSc): Predictive Analytics for Mineral Potential Determination in the Eastern Ashuanipi Complex.



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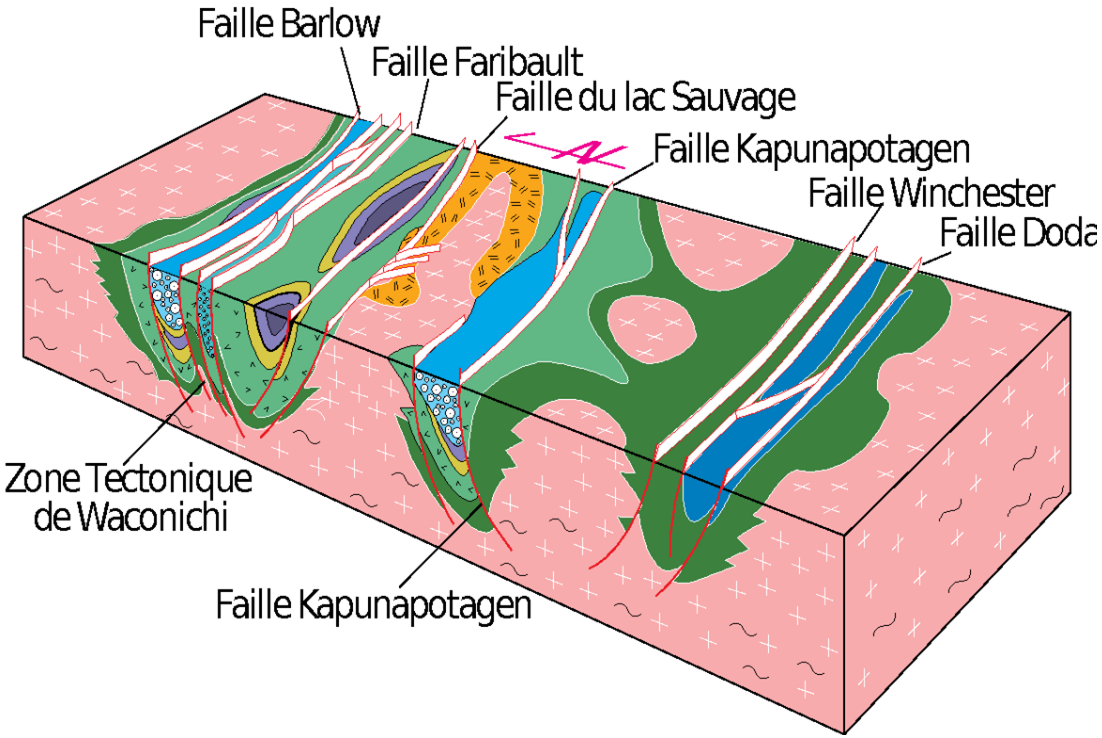
Abitibi (Rouyn-Noranda, Northern Swayze Analytics)

Project Phases

A. Area Selection
B. Geological and Structural Analysis
C. 3D Reconstruction
D. Integration of Geochemical Data
    A. Lake Sediments
    B. Stream Sediments
    C. Till Geochemistry
    D. WR, Other
E. Integration of Geophysical Data
    A. Airborne Surveys
    B. Seismic Transect Profiles
    C. Magnetotellurics

F. Data Analytics
    A. Exploratory Data Analysis
    B. Predictive Analytics (Mineral Prospectivity Mapping)



From Daigneault, 1991

Revealing Key Spatial Associations

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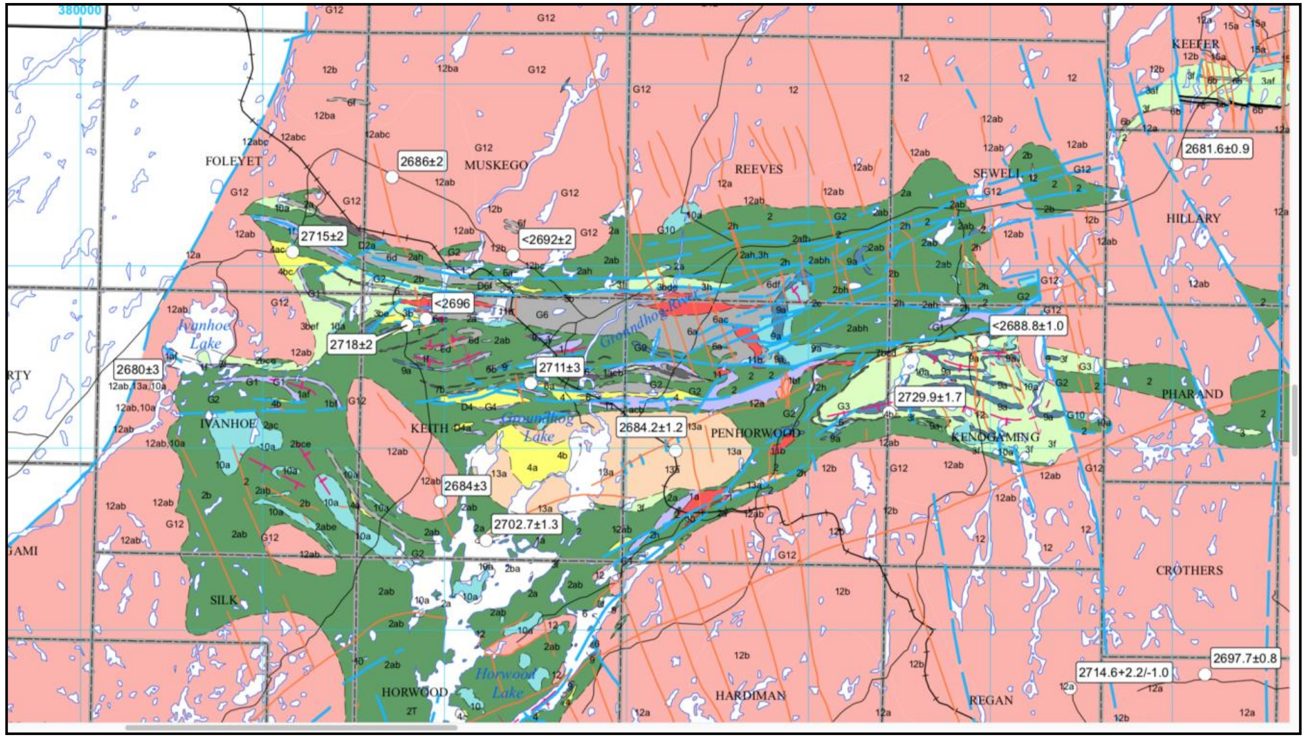
Northern Swayze Greenstone Belt (NSGB) Selected Area

Geological Mapping – Data Compilation

- Ayer 1995 report with structural and geological summary
- Abitibi 2011 compilation
- Abitibi Discovery Initiative
- Metal Earth Data
- Harris et al. GIS prospectivity & lithogeochemical mapping of alteration (1999, 2000, 2001)

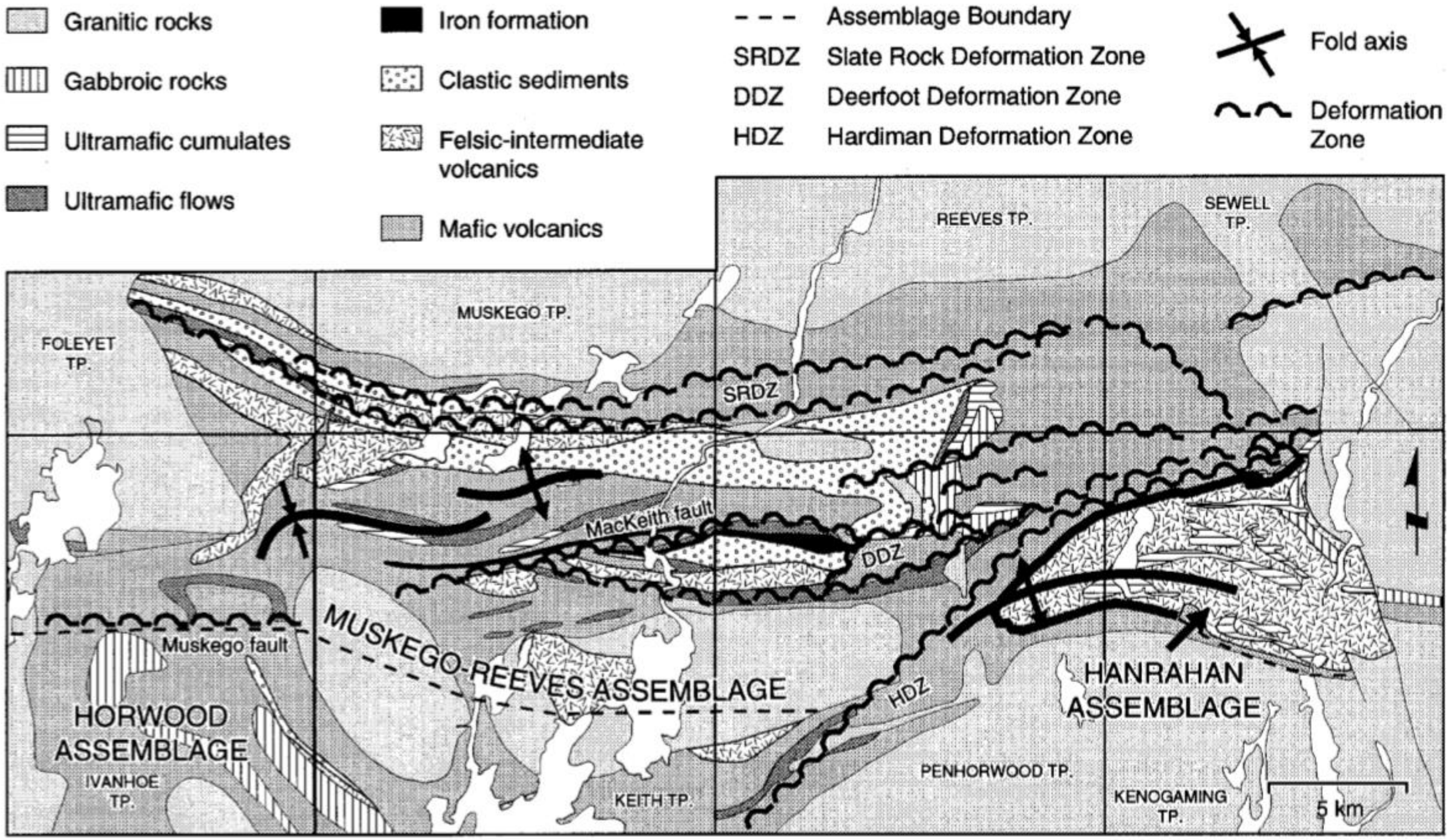


Ayer et al. (2011), Numerous OGS Compilations

- More accurate 3D models capturing key structural trends (bedding/foliations) will support 3D mineral prospectivity analysis (trap detection strategy)

Geology of the NSGB

Key Structural Domains of the Northern Swayze Belt



Ayer (1995)

S-DOMAINS:
- HORWOOD
- MUSKEGO-REEVES
- HANRAHAN

Western termination of Porcupine Destor Shear Zones/Faults

Tight Folding and Hinge Localization

Greenstone/Granite Contacts (competence contrasts)

Ultramafic/BIF assemblages Lamprophyres

NSGB: an Abitibi equivalent although more deeply eroded

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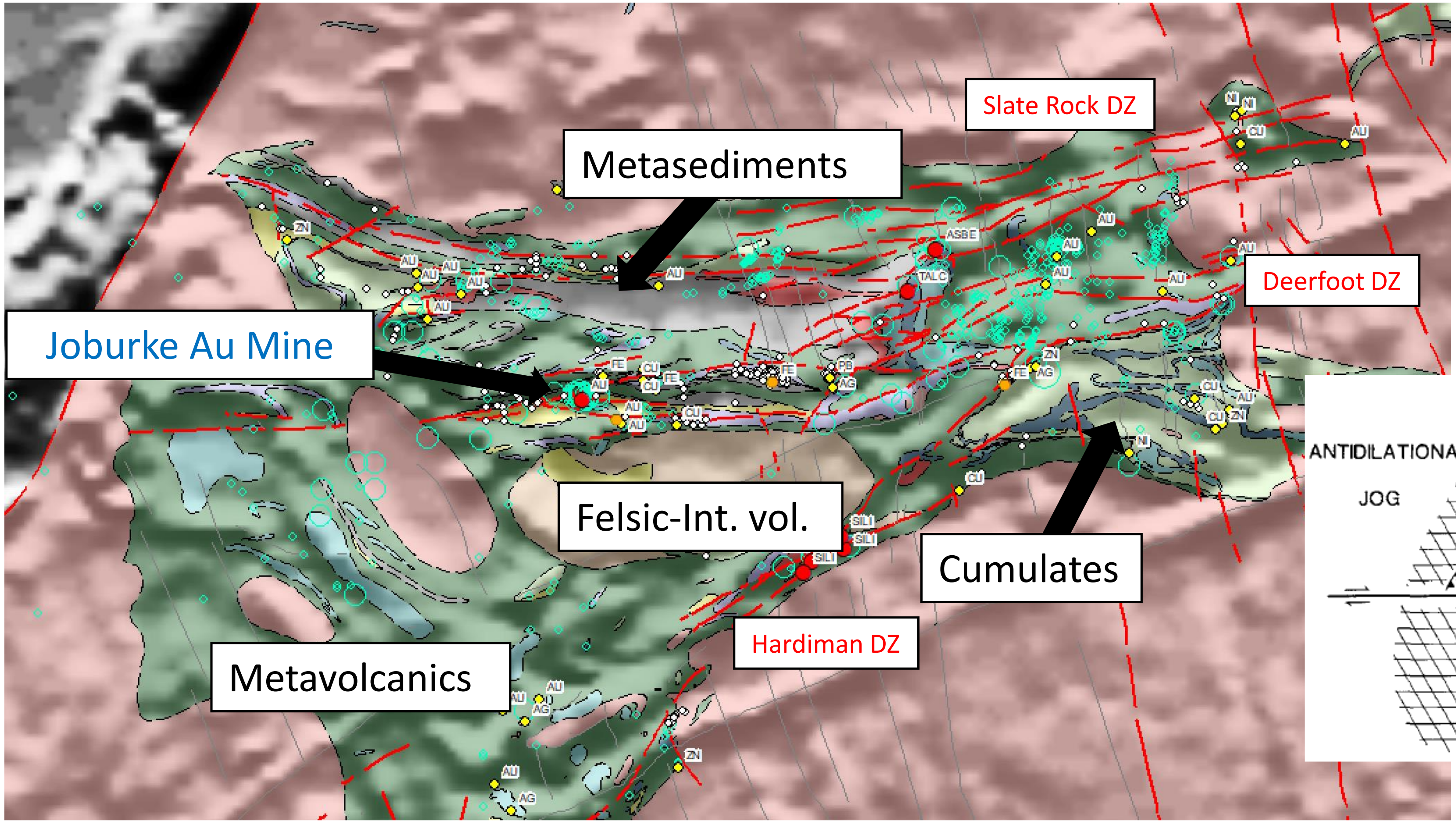
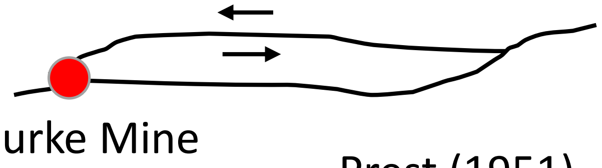
Mineral Deposits, Joburke Mine and Côté Gold Deposit

Different Styles of Deposits but dominantly explored for Au

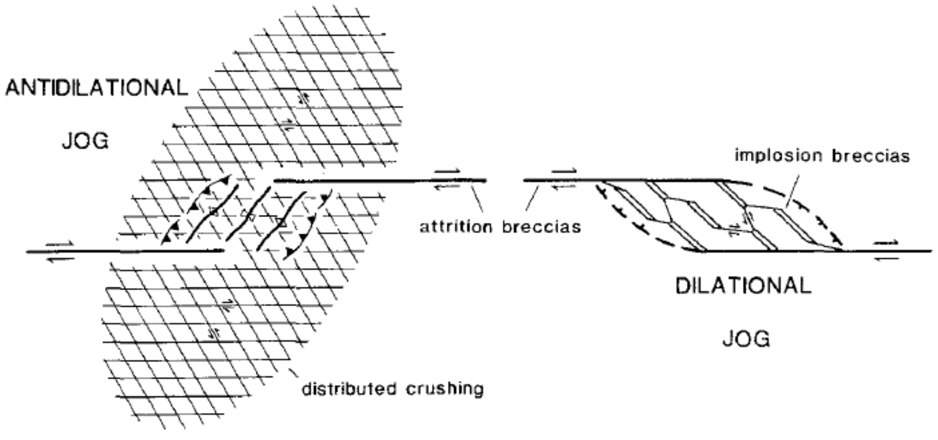


Mogashoa et al. (2019) in prep.

MacKeith Lake Fault (075/60 to 75 N)



Prest (1951)



Sibson (1986)

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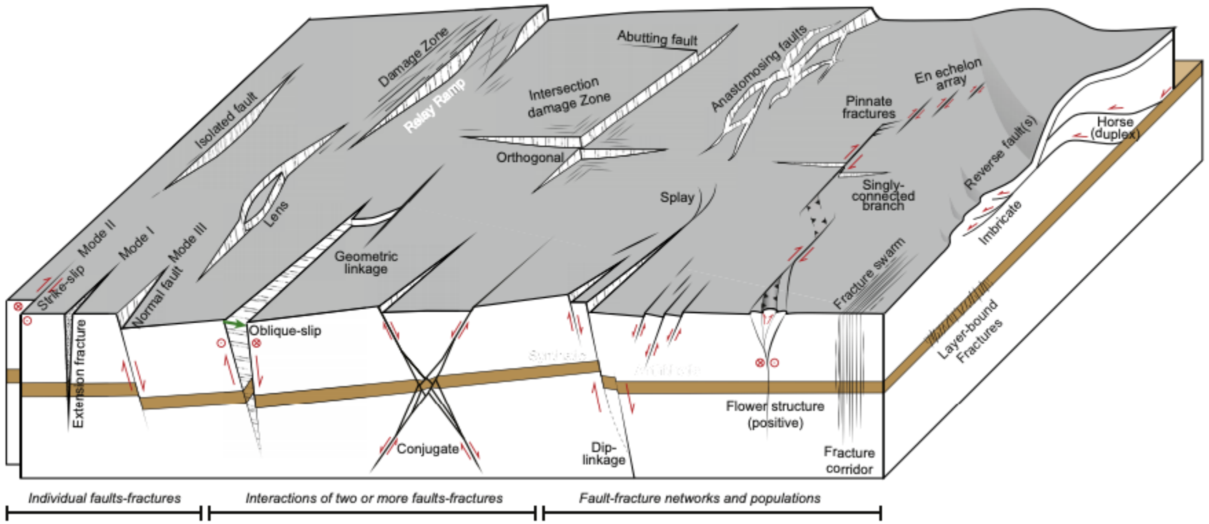
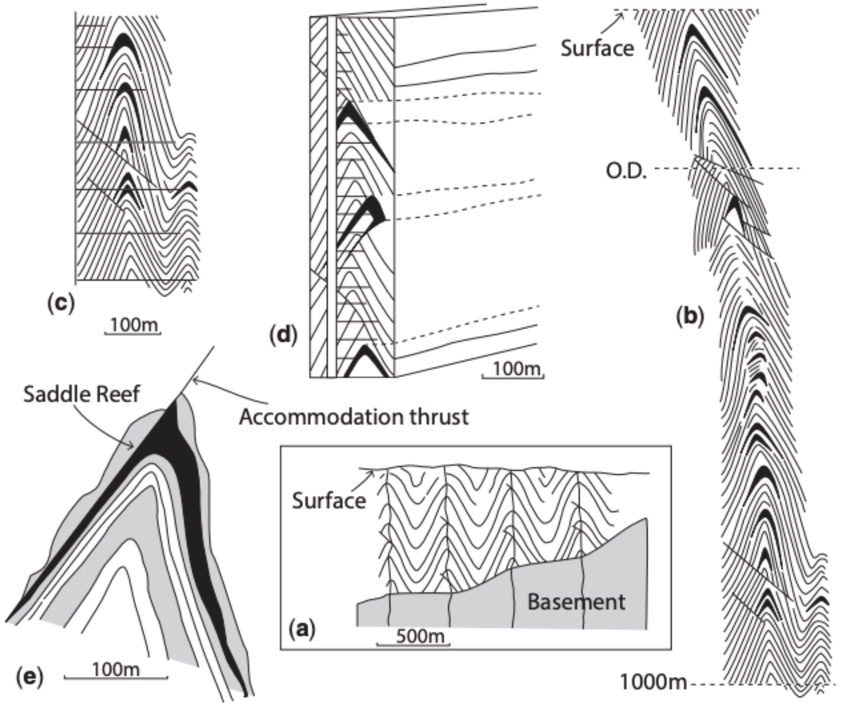
3D Structural Controls

Classification of faults and fracture networks: how do they relate with Au traps?

- Intersections
- Jogs
- Terminations/ tips
- Secondary splays
- Flats
- Anastomosing /Breccia complexes
- Linkages



Peacock et al. (2016)



Cosgrove (2015)

Examine statistical associations with alteration and Au occurrences and their clustering.

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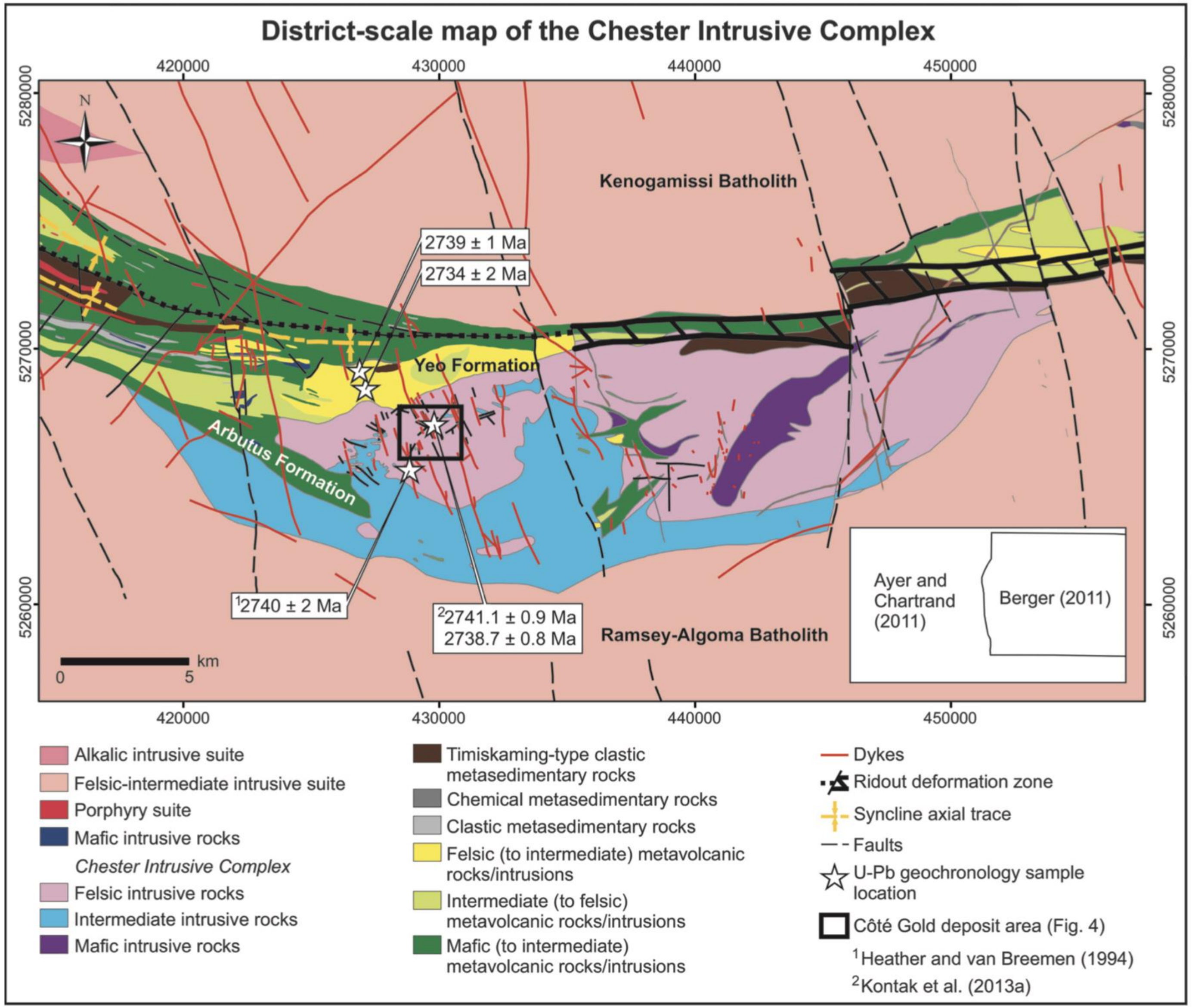
Côté Gold Deposit

Different Styles of Au Deposits

- Economic low-grade high tonnage deposit (approx. 8.65 Moz Au) found away from metavolcanics belts.
- Breccia hosted in sheeted vein complex within Chester Intrusive Complex (TTD low-Al).
- Defines a new metallogenic age (2739-2741 Ma [unusual age!]).
- First world class deposit in the SGB.
- An understanding of intrusive ages and their plausible role as hosts for Au mineralization seems a critical ingredient for discovery in the Swayze.

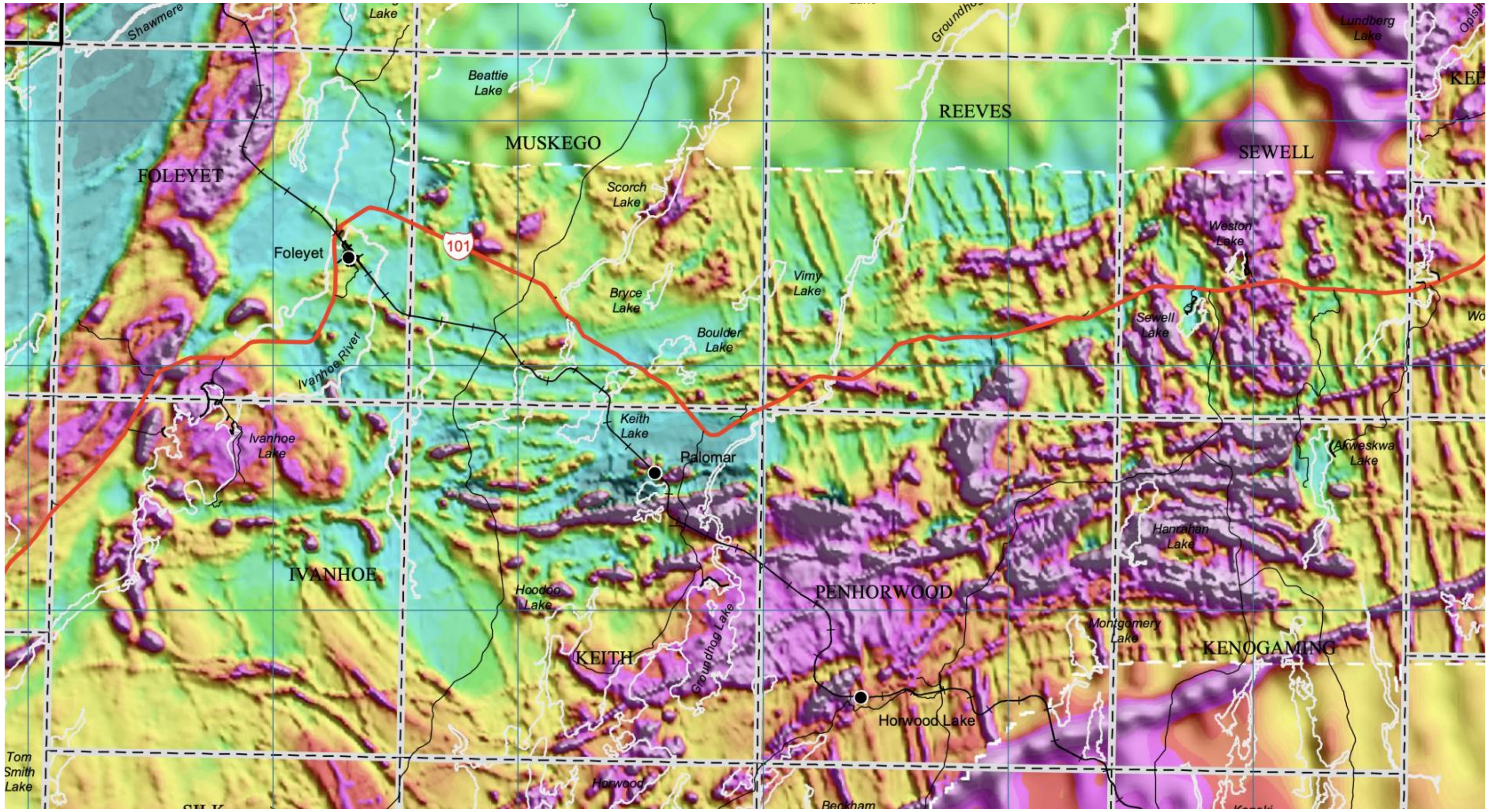


Katz et al. (2017)

Updated Airborne Geophysics, Lithogeochemistry, MT, Seismic

Focus on identification of structural traps in 3D

- **3D reconstruction based on up to date interpretations of geophysical data in conjunction with new ME seismic and MT interpretations.**
- Detecting **optimal traps** using an exploration model that targets Au deposits in greenstones.
- Evaluation of **alternative exploration models** (i.e. intrusions centered).
- Integration of data both **historical compilations and Metal Earth data**.
- **3D Analytics conducted on integrated data.**



Abitibi magnetic supergrid (Ontario Geological Survey 2003)

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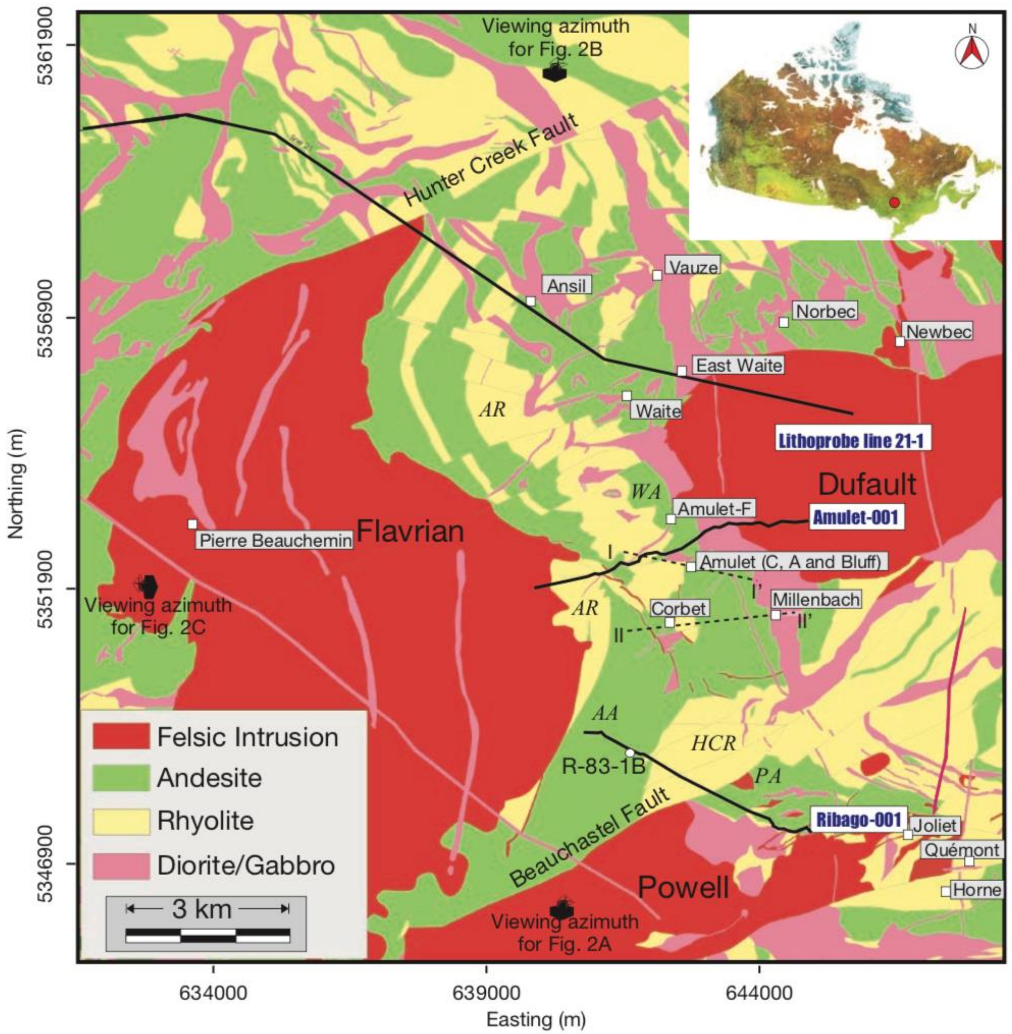
Rouyn-Noranda Selected Area

Key historical aspects of the camp

- District mined since the mid 1920s, regarded as model locality of VMS deposits.
- Giant resources in term of VMS mineralisation. Horne mine is most prominent with the following resource estimate (54 Mt 2.22% Cu, 6.1 g/t Au, 13 g/t Ag; Gibson *et al*. 2000).
- Numerous Cu-Zn VMS deposits of variable style including Cu-rich or Zn-rich systems and also Au-Ag rich accumulations (Horne Mine produced 11.6 million ounces of gold and 2.5 billion pounds of copper).
- Recent Exploration 2016 (Falco Resources): report more than 5,4 (Indicated Resource) gold equivalent million ounces, including 3,4 Moz of gold hosted in 58.3 million tonnes averaging 2.86 g/t Au Eq (1.82 g/t Au; 15.60 g/t Ag; 0.20% Cu; 1% Zn).



Bellefleur et al. 2014

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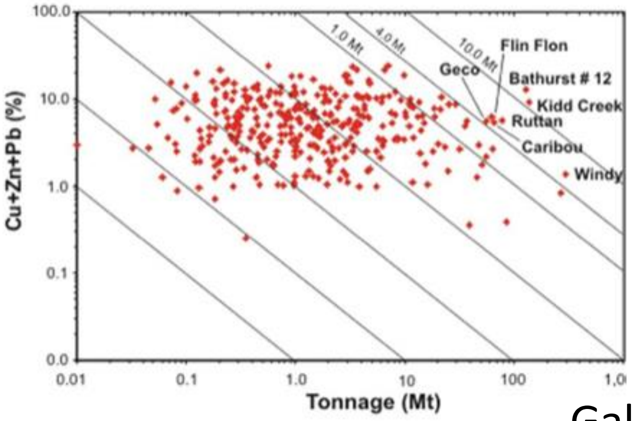
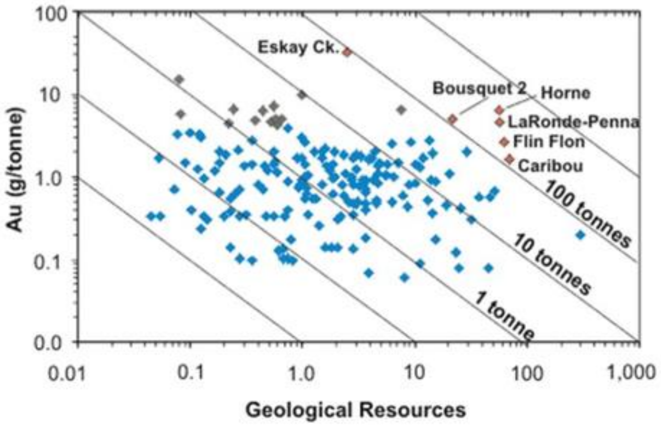
Grade Tonnage of Canadian VMS

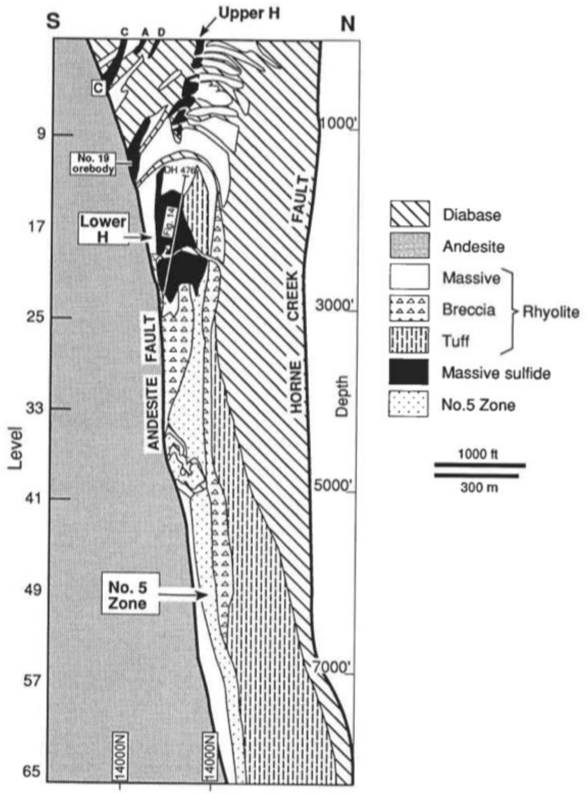
Plots of Cumulative Grade and Tonnage

- Horne stands out as particularly anomalous in term of tonnage and geological resources.
- Most auriferous VMS deposits contain > 4 g/t Au
- Those containing over 1000 tonnes of Au (yellow diamonds) include both auriferous VMS deposits and those with moderate Au grades but large tonnages.
- Data from GSC

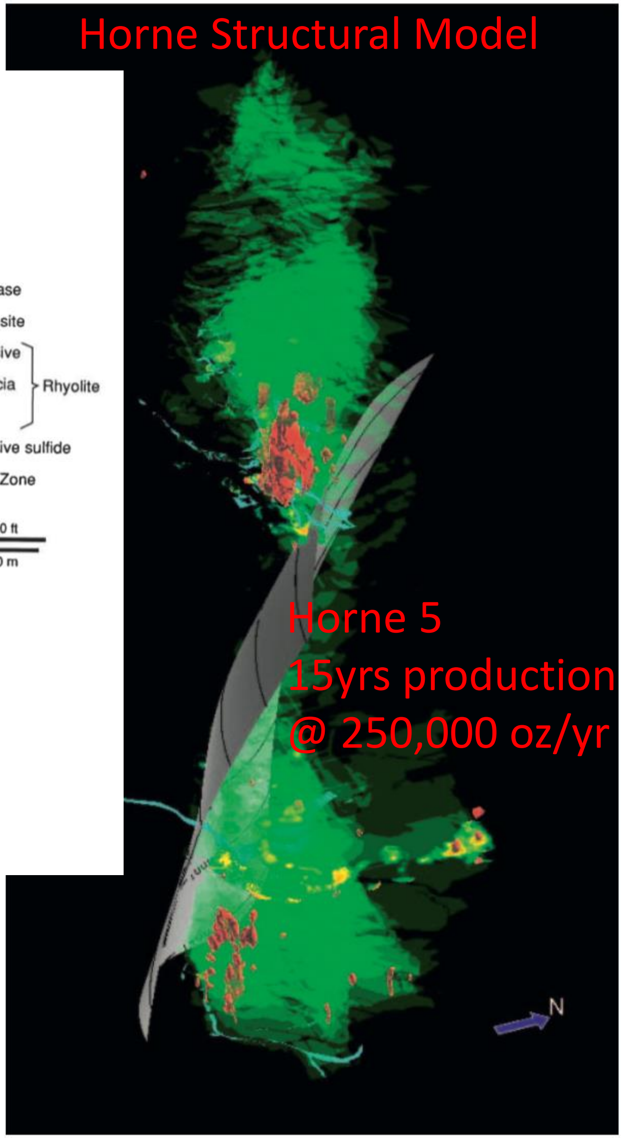




Galley et al. (2006)



Barrett et al. (1990)



de Kemp et al. (2011)

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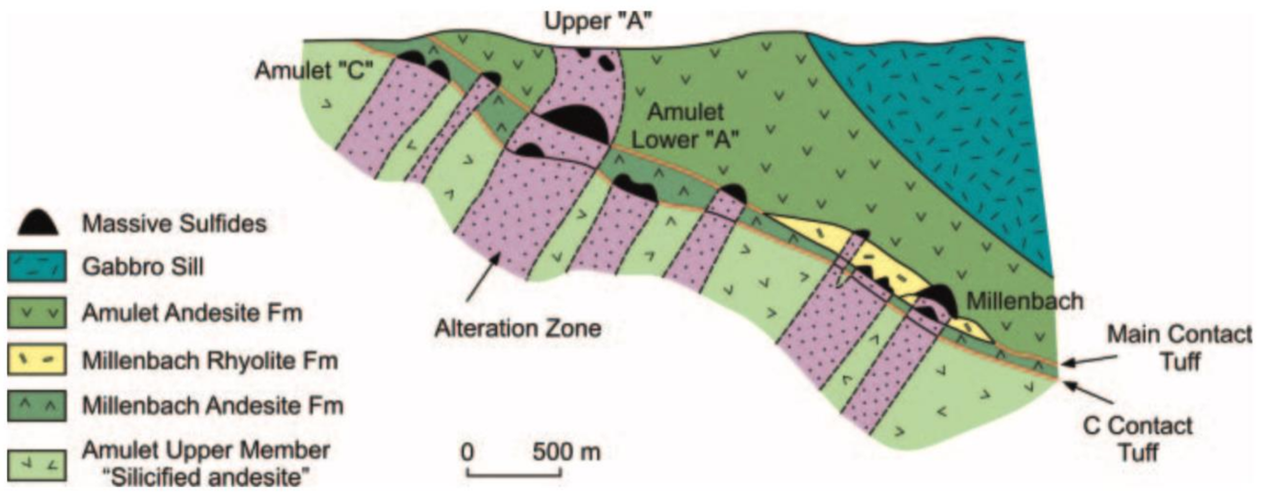
Exploration Model: Volcano-Stratigraphic Control

Cross-sectional distribution of VMS deposit's mounds and alteration plumes

- Plume identification and mapping? Late fault mapping + dikes: enhanced media + 3D modelling



- Fault mapping potentially helpful to unravel buried alteration systems.
- Target interpretation of structures from geophysics and seismic
- Multilevel deposits
- Can extend at depth

Knuckey et al. (1982)

3D Modelling Studies in the Rouyn-Noranda Area

VMS Research on Noranda Camp

- Industry derived models from Xstrata Canada (Regional and Local Mine-scale Models)
- 3D Modelling and geological interpretations improved by usage of two E-W high resolution seismic lines (Amulet and Ribago).
- Focus on the identification of key horizons and reconstruction of distribution of volcanic sequences at depth.
- This work represents the progression of a trend in the industry focused on the identification of deposits at considerable depth (one example that is considered a success is the discovery of an approximately 12 Mt VMS at 1.2 km depth at Halfmile Lake, New Brunswick (Matthews, 2002)).
- Other research conducted on the Noranda camp in collaboration with Xstrata Canada supports the conclusion that 3D modelling was helpful in defining untested targets that resulted in new discoveries such as the West Ansil deposit (Martin et al. 2007).

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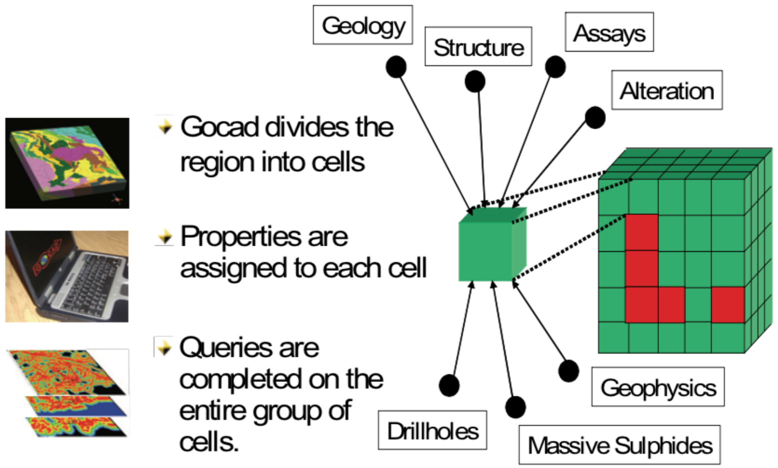
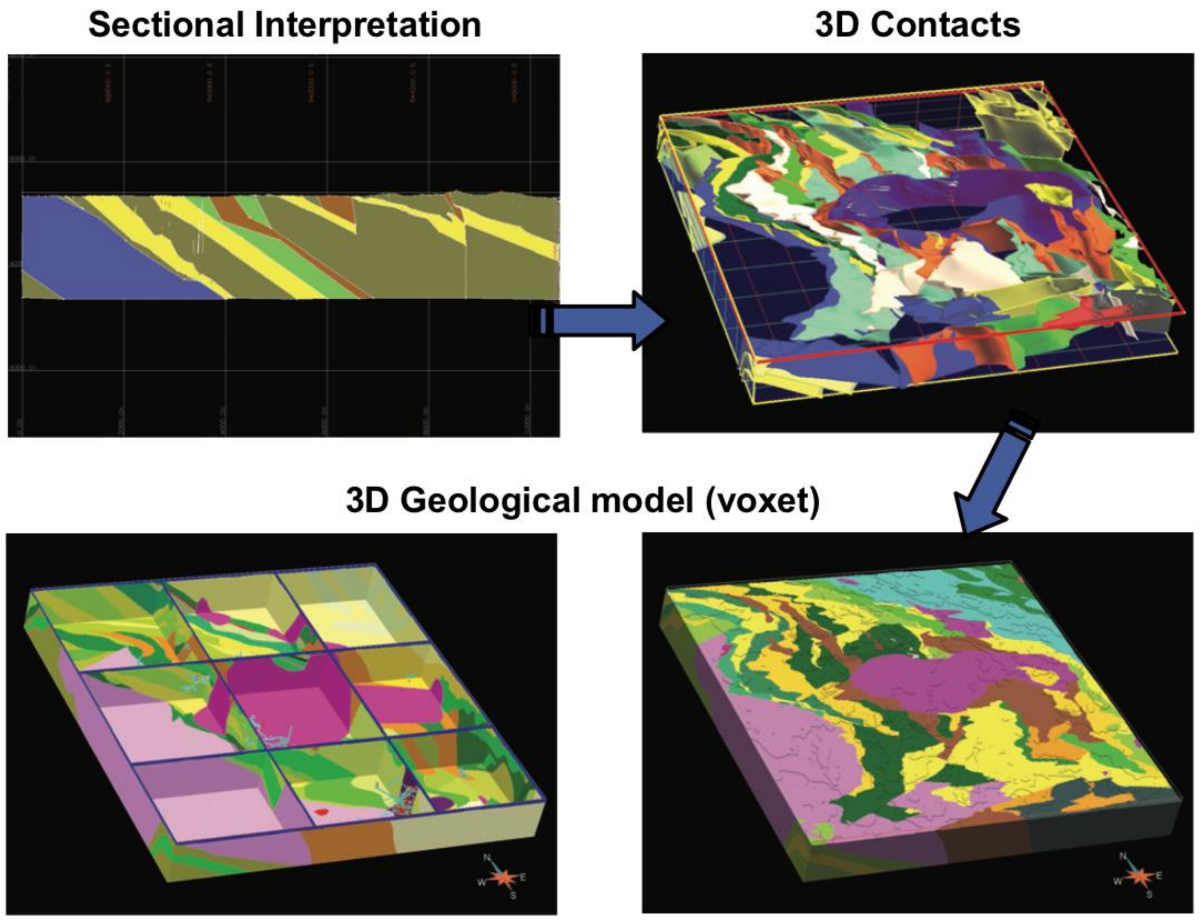
3D Modelling: Probabilistic Analysis and Exploration Targeting

Targeting Scheme

- Locate cells with specific properties:
  - Hosting rhyolite
  - Proximal to synvolcanic faults
  - Cu assay greater than the norm
  - Elevated sericite alteration index values
  - Proximal to EM/Magnetic anomaly
  - Proximal to known VMS



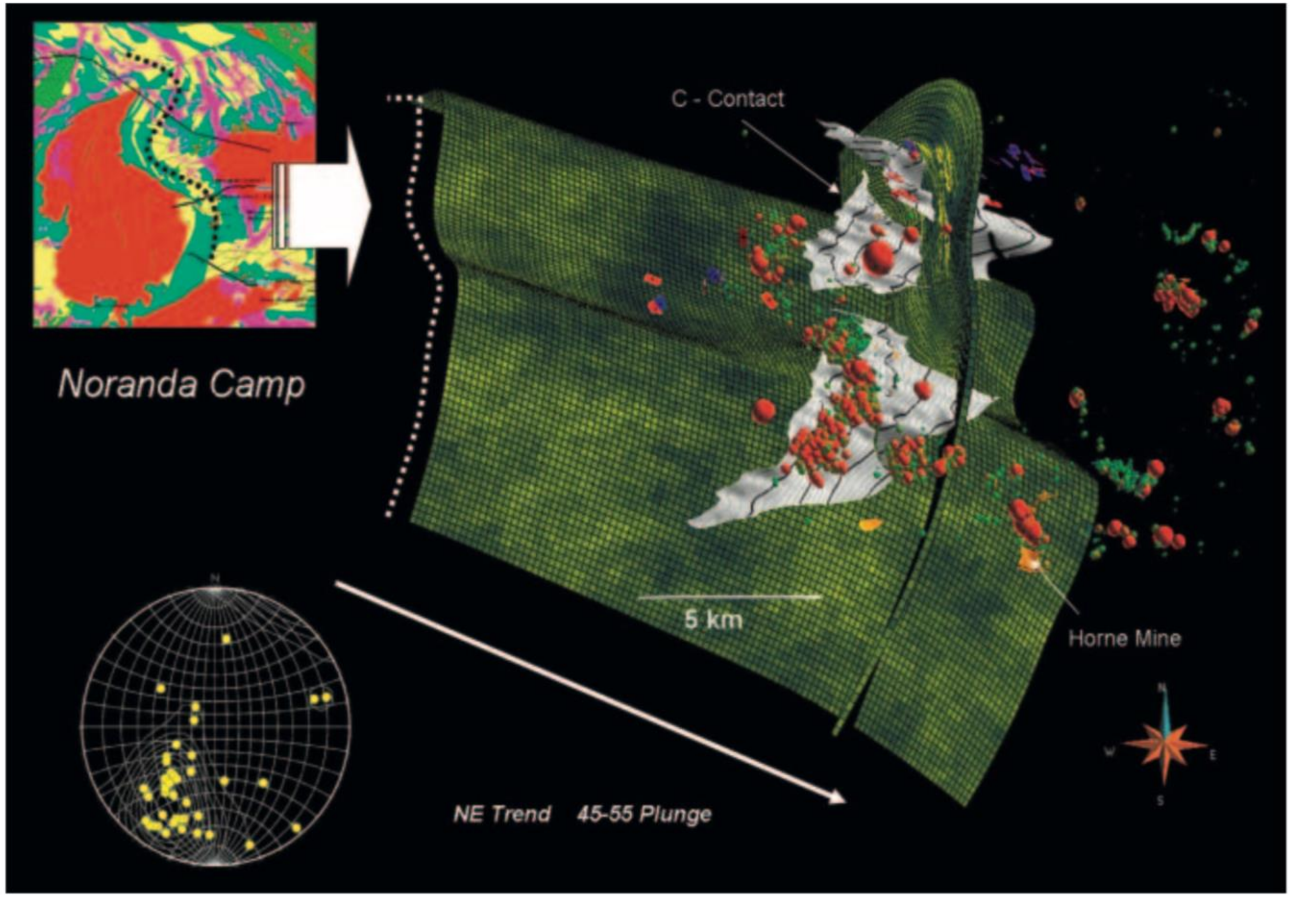


(Martin et al. 2007).

3D modelling: Refined Geometrical Reconstructions

Xstrata Canada Data S-grid 3D Model

- Proposed an s-grid based reconstruction of the felsic unit hosting the orebodies
- Represents a 3d geometry with the rhyolite bodies steeply dipping easterly.
- C-contact appears cut by high-angle faulting that causes a 3 block subdivision (later displacement?)
- C-contact surface folded (45-55 plunge).



de Kemp et al. (2011)

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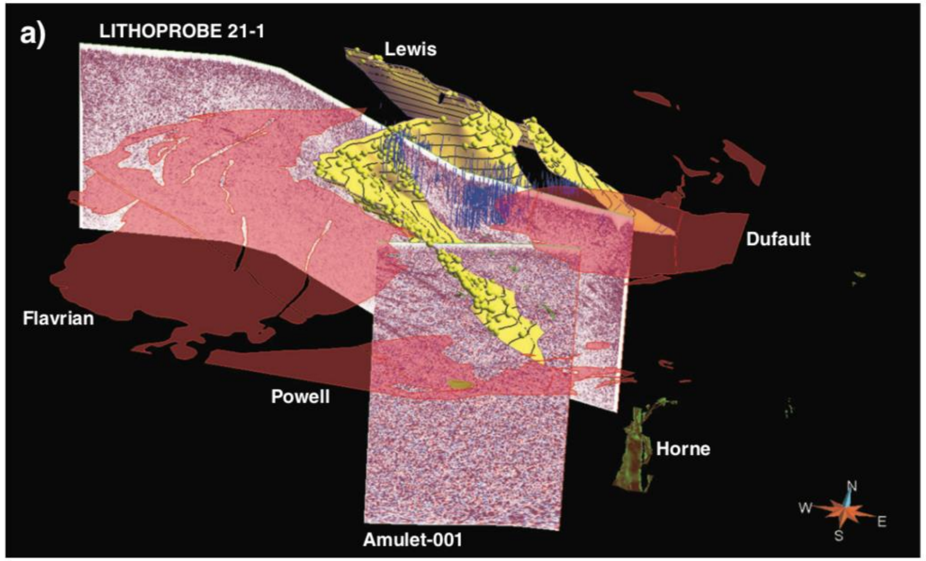
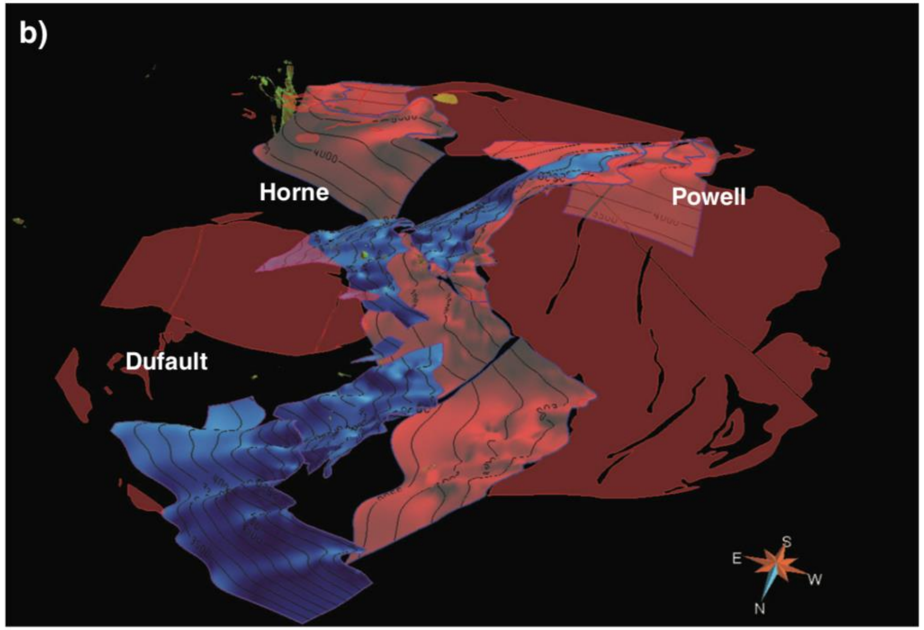
Existing Data Integration Studies

Seismic and drilling integration

- Xstrata Canada holes used to constrain the interpretation of two detailed seismic lines + lithoprobe.
- Reconstructed accurately the position of the C and Main horizons.
- Reconstructions conducted mainly to improve understanding of metavolcanics. Architecture seen as key to unravel mineral deposits in deep locations >1 km.





Bellefleur et al. (2007, 2014)

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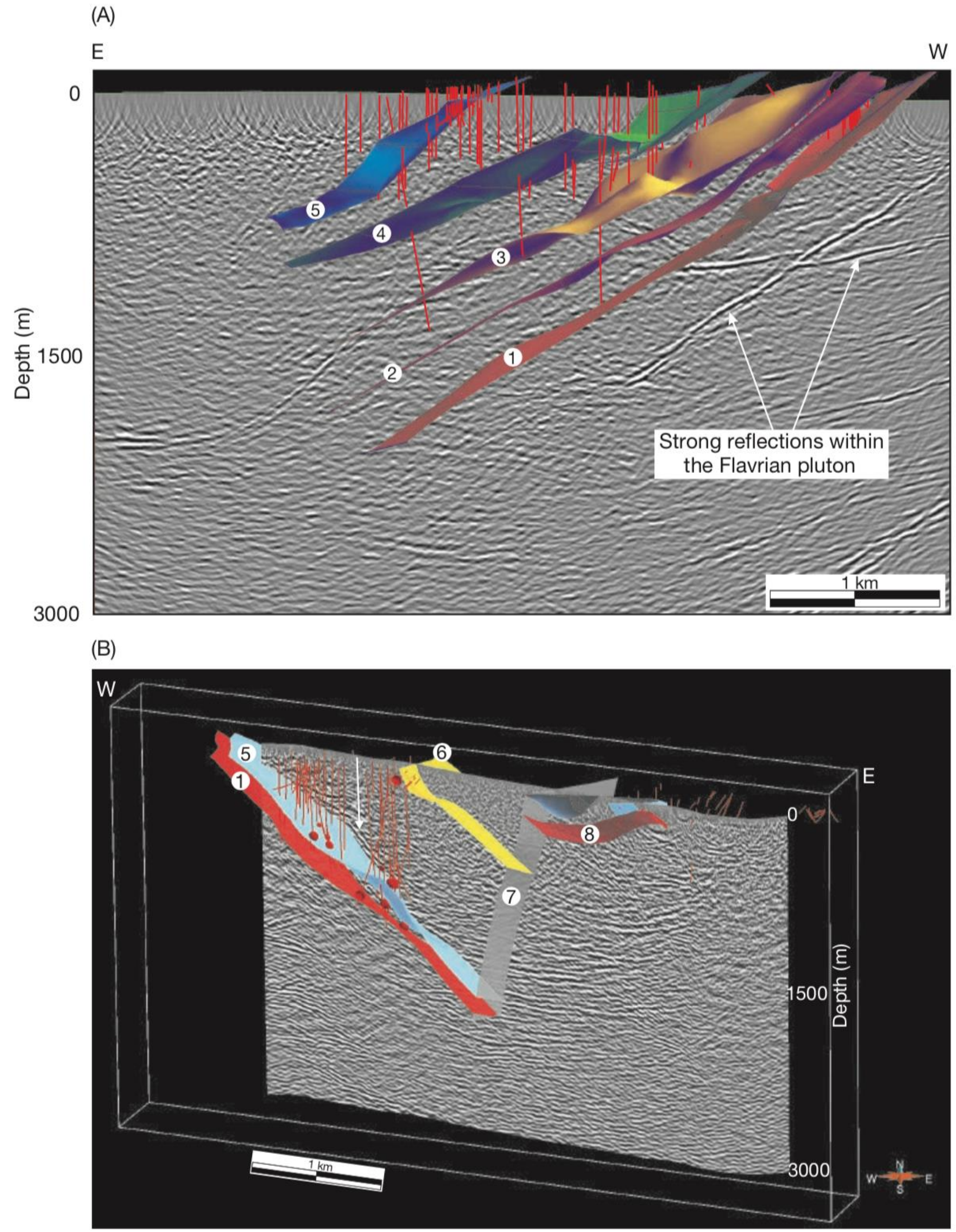
Seismic Interpretations Examples

Amulet Seismic Profile Interp.

- Volcanic sequence contacts (Blake River Grp) interpreted in the seismic data with a younging of the strata directed northeasterly.
- Reprocessing of two lines to emphasise shallow structures. Contacts Andesite/Rhyolite. Five main contacts detected although discontinuous reflections.
- Preservation of diffraction signals (direct detection of VMS). Not observed in the two lines.
- Boreholes and physical rock property data used to validate the seismic lines interpretations.

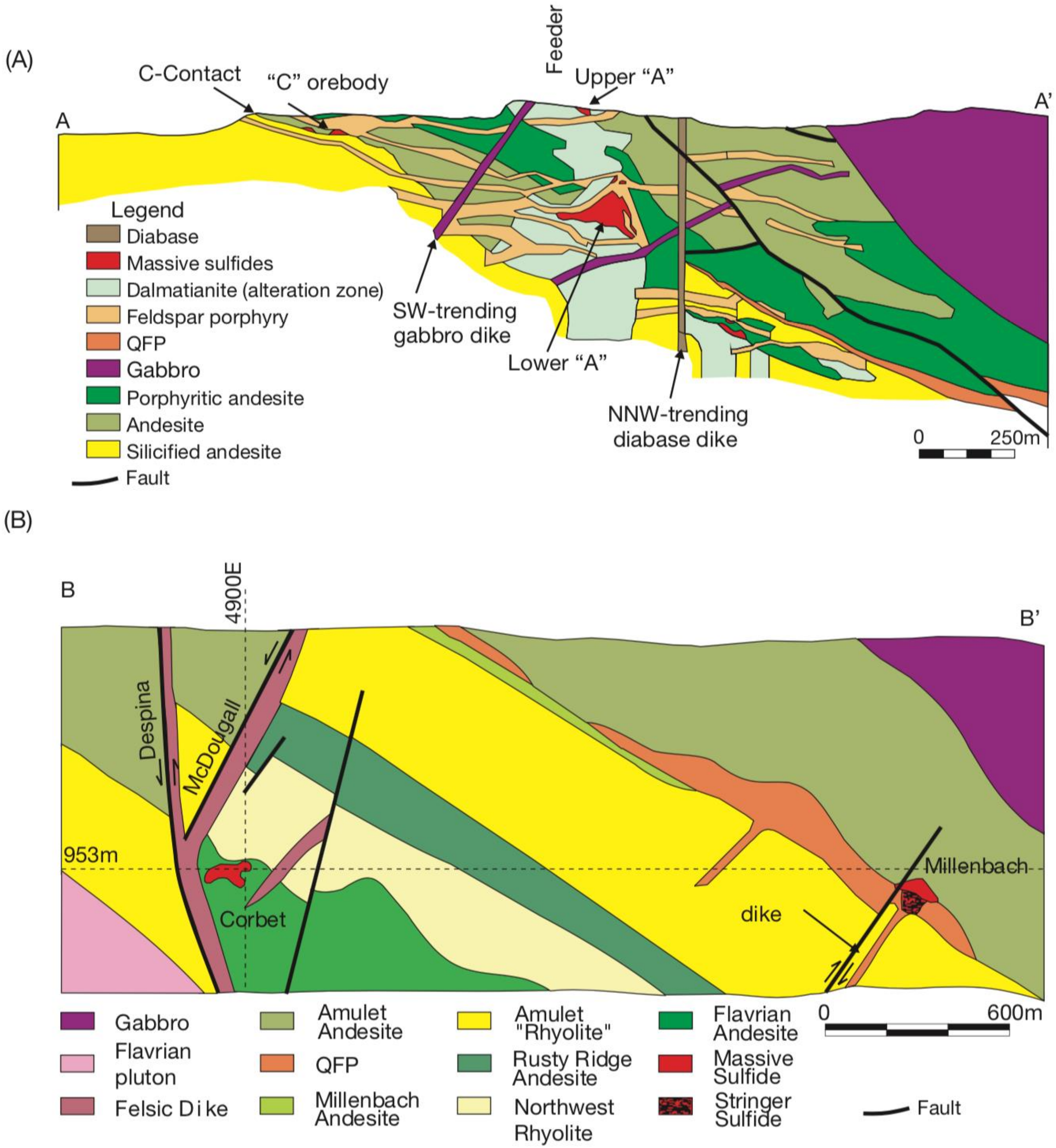


Bellefleur et al. (2014)

Geological Interpretations

Key Implications

- Can we predict the location of new deposits using seismic surveys alone? Heavily dependent on the processing (Deep Moveout - DMO).
- Integration critical. Need access to TGI-3 model and/or Falco drill-holes ~15000 listed.
- The orientation of ME seismic line may lead to identification of reflections that match with existing interpretations of geological features.
- Imaging of alterations systems (feeders) if their orientation is at shallow angle (effect of folding may also be evaluated, potential upgrading?).
- Mapping of Andesite/Rhyolite and also Silicified-Rhyolite vs Rhyolite contacts (C contact, Ribago).



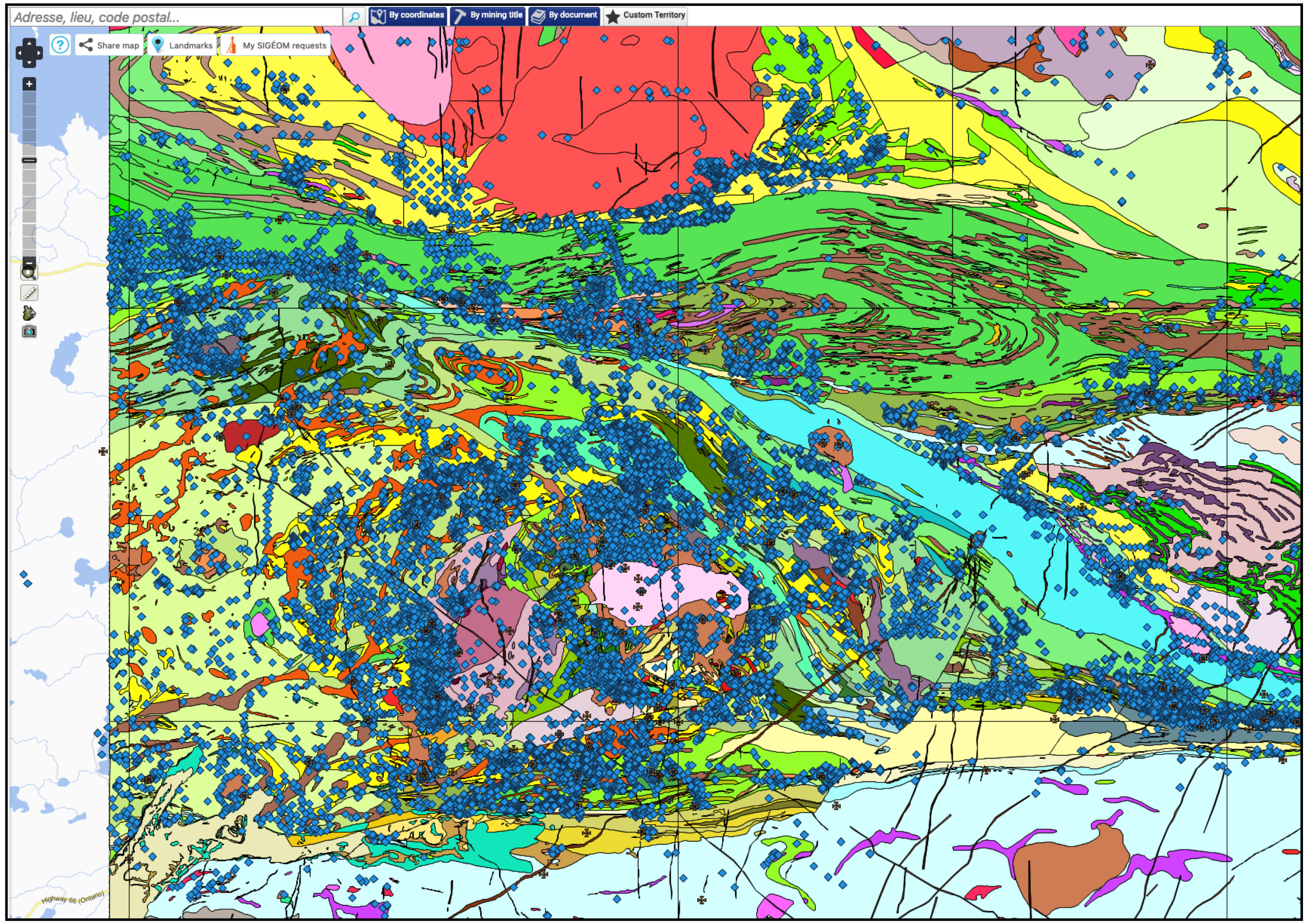
3D Modelling: Geological Constraints

Noranda Camp Geological Mapping

- SIGEOM Data Sources (Geochemistry, Geophysics, Geology).
- GSC (seismic lines: Amulet, Ribago, Lithoprobe).
- Metal Earth R1 Seismic and MT

OBJECTIVES:

- Integration of available seismic lines with the ME seismic R1 and relative interpretation.
- Falco Resources Drillholes (Volcano Strat. Constraints).
- Integration of extensive lithogeochemical data collections (including oxygen isotope ratios).
- Integration of existing interpretations concerning the structural orientation of folded metavolcanics.



SIGEOM Geodatabases (Geochemical sample locations and recent geological interpretations.

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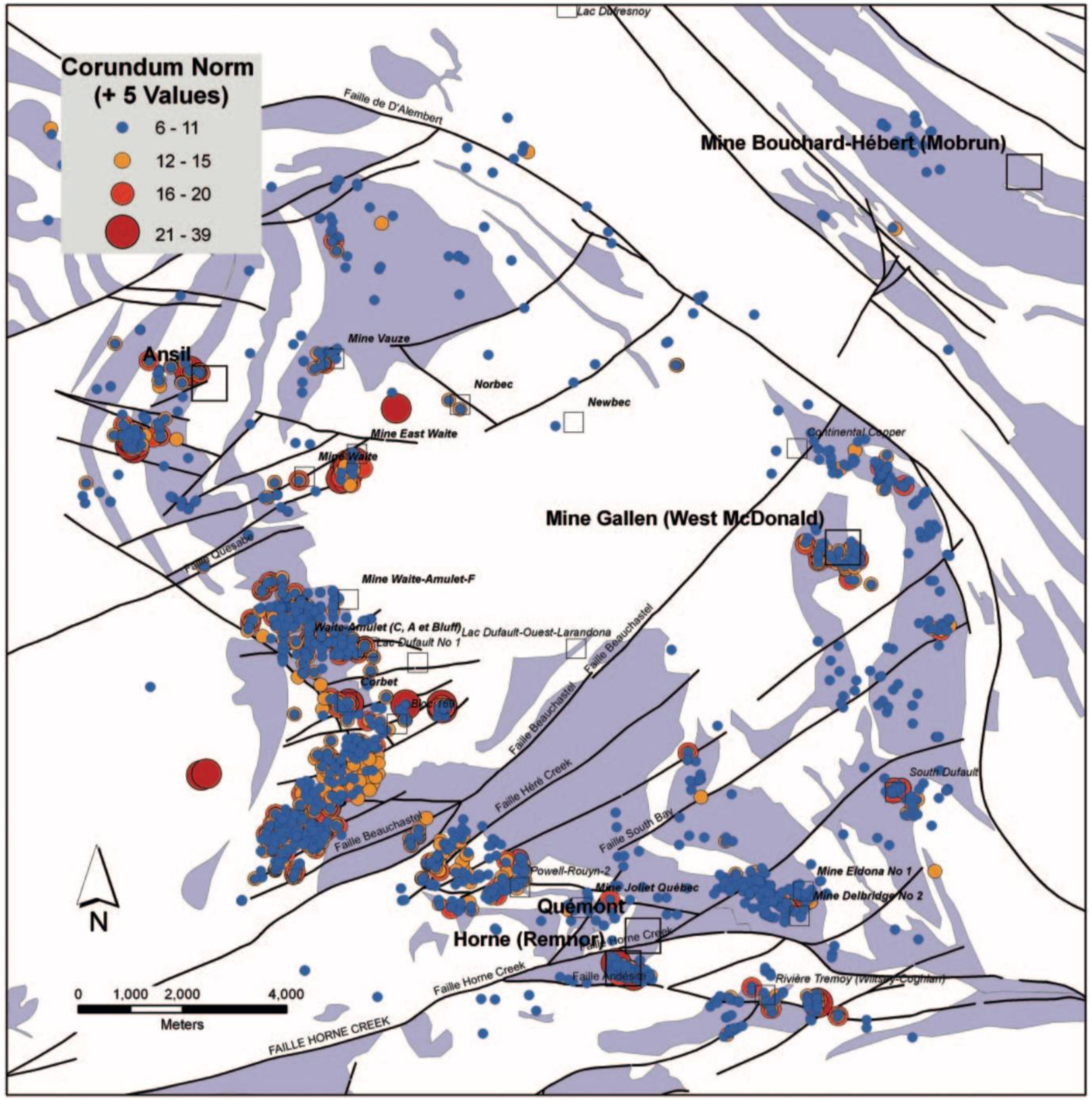
Lithogeochemical Data

Mapping Hydrothermal Plumes/Alteration

- Intersection of favorable horizons with upflow zones – Targeting method.
- Lithogeochemistry used to detect up-flow zones.
- Numerous Alteration Indexes considered (e.g. normative calculations, and mass gains and losses, see Martin et al. 2007-Ishikawa AI).
- Study of association of revised fault interpretations and alteration indexes appears critical given the new data and improved geophysical surveys.
- Possible comparison with NSGB in term of alteration and structure. Scale of footprints and their relationships with master faults.



de Kemp et al. (2011) >5 corundum normative (calculated): alteration indicator

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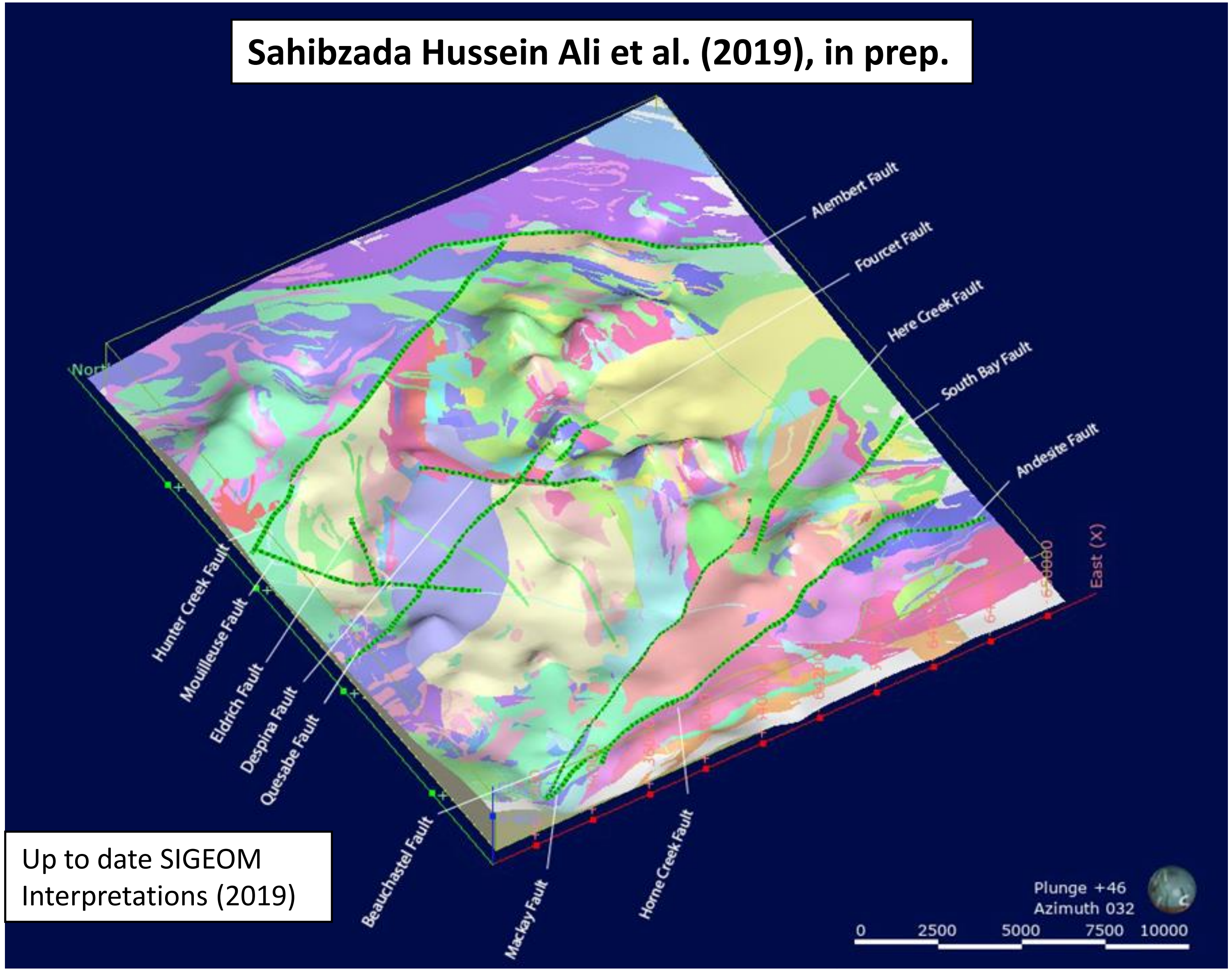
Preliminary Results: Noranda Camp 3D Reconstruction

Use of implicit modelling strategy, for preliminary 3D modelling

Initiated 3D compilation of Noranda Camp

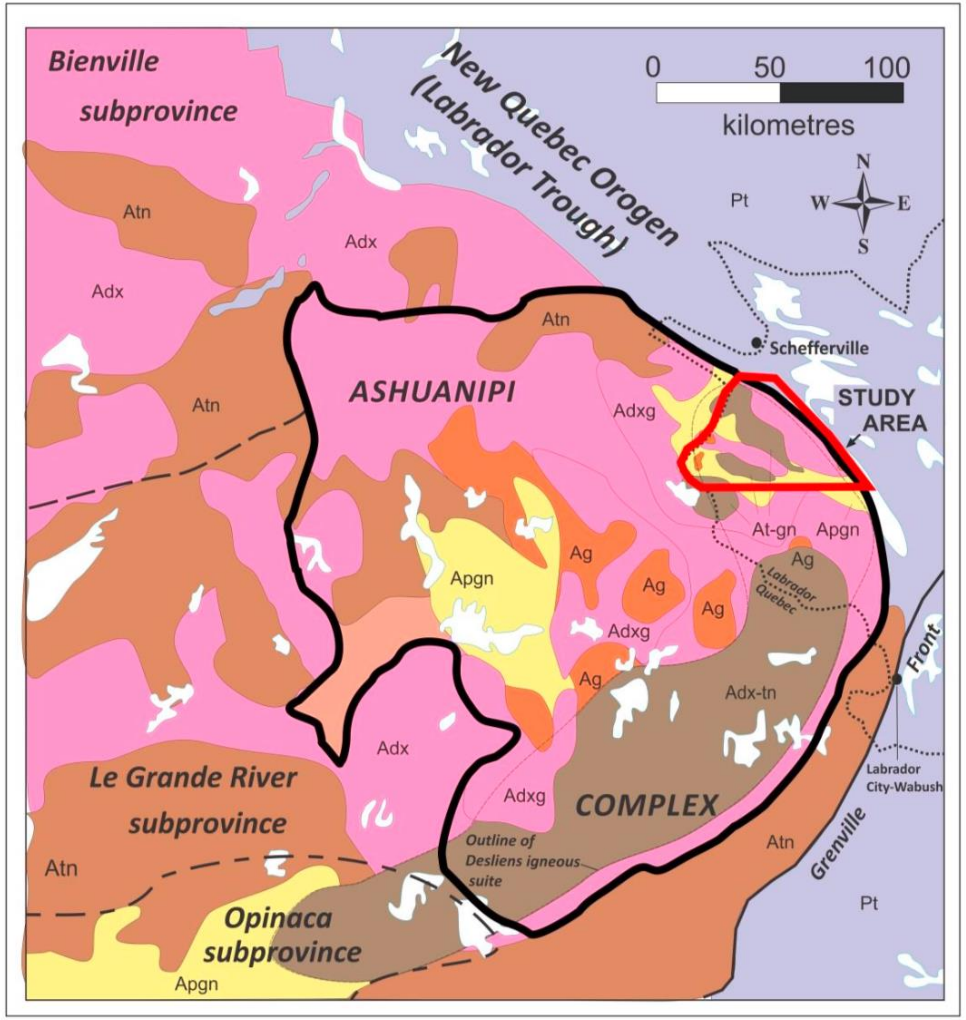
- Review of existing studies
- Structural Interpretations
- Modelling of Topographic Data
- Modelling of Key Faults in the Area
- What's New: inclusion of last 10yrs of information to form a multidisciplinary (integrated compilation of the camp)



Proposed Thematic Project: Au Deposits in Granulitic Terranes

Mineral prospectivity mapping in the Ashuanipi Complex

- Large under-explored properties.
- Potential for discovery of new gold district.
- Initial identification of gold targets supports data-driven mineral prospectivity and other data analytics.
- New data: GSC OF 8348 lake sediments and geophysical surveys (McCurdy et al. 2018).
- Comparative analysis with metavolcanics dominated terranes, where major thrusts exhume amphibolite and granulite facies (e.g. boundary between the Abitibi and Wawa terrane, Borden Gold deposit).



Modified after Wheeler et al. (1996)

Proterozoic

Pt	Undivided supracrustal rocks of the New Quebec Orogen (Labrador Trough)

Archean (3.1-2.65 Ga)

Ag	Undivided granitoid intrusions
Adx	Undifferentiated diatexite
At-gn	Tonalite-diorite intrusions - Desliens igneous suite (Percival, 1991a)
Atn	Granulite facies gneiss
Apgn	Metasedimentary gneiss; paragneiss

Van Nostrand (2016)

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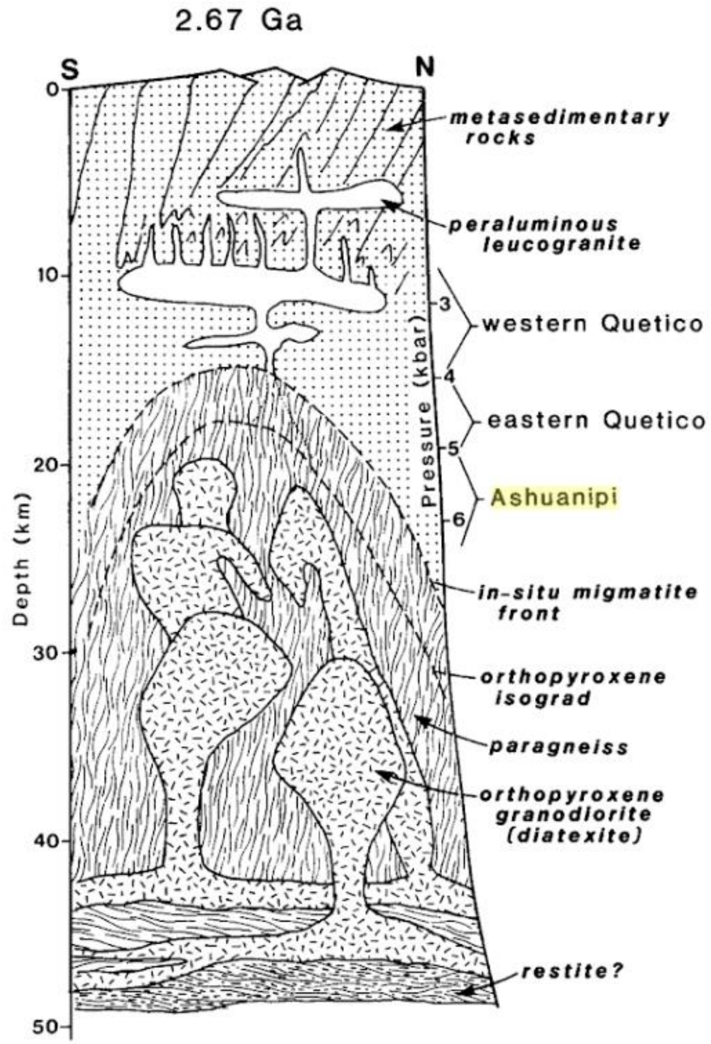
Ashuanipi Complex – Mineral Prospectivity Mapping

Au in deeper settings (20-25 km depth): distinctions

- Deposits hosted in <u>metasedimentary assemblages</u> instead of being dominantly found in metavolcanic rocks.
- Different tectonic setting if compared with Abitibi granulite terranes (Percival, 1990).
- Higher temperatures and pressures (600-700 degrees) at 5-6 kbars, leading to crystallization of garnet, cordierite, sillimanite phases with banding.
- Occurrence of partial melting causing formation of leucosomes and migmatitization.



Percival (1990)

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Lode Au Deposit Model

Exploration Vectors

- Part of the Ashuanipi complex is represented by gneissic assemblages that were likely deposited in a forearc or accretionary wedge (Percival 1990) a favourable setting for porphyry Cu–Mo–Au, epithermal Au, polymetallic (Sn, W) skarn, and orogenic Au mineralization.
- Key controls are similar to greenschist hosted lode gold deposits. Expected exploration potential to increase with Fe-rich metasedimentary rocks.
- Increases in Ca and K and decreases in magnetic susceptibility toward mineralisation have been proposed as vectors for Au deposits found in high-grade terranes (e.g. Glenburgh deposit in Western Australia; Roche et al. 2017). However the <u>alteration is difficult to map</u>.

Au-Source

Iron Content

Addition/Depletion of Ca-Al-K

Magnetite Destruction

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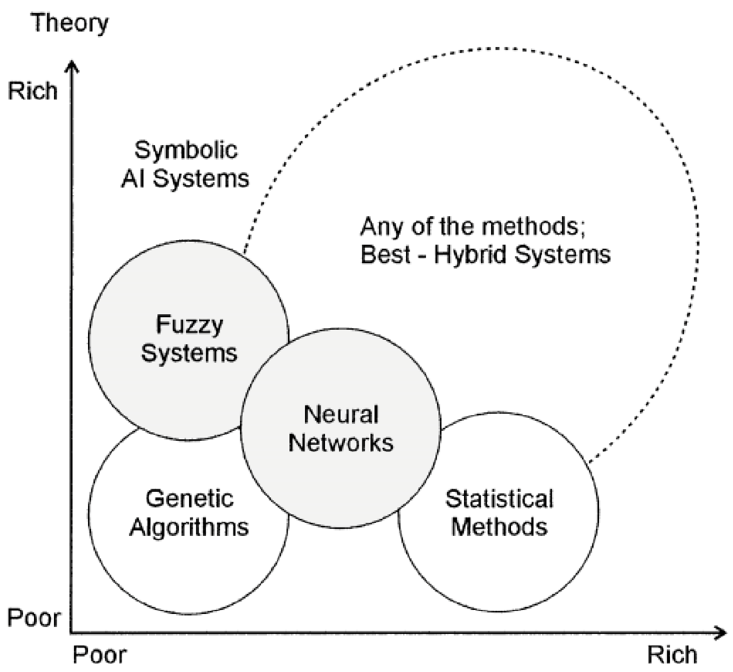
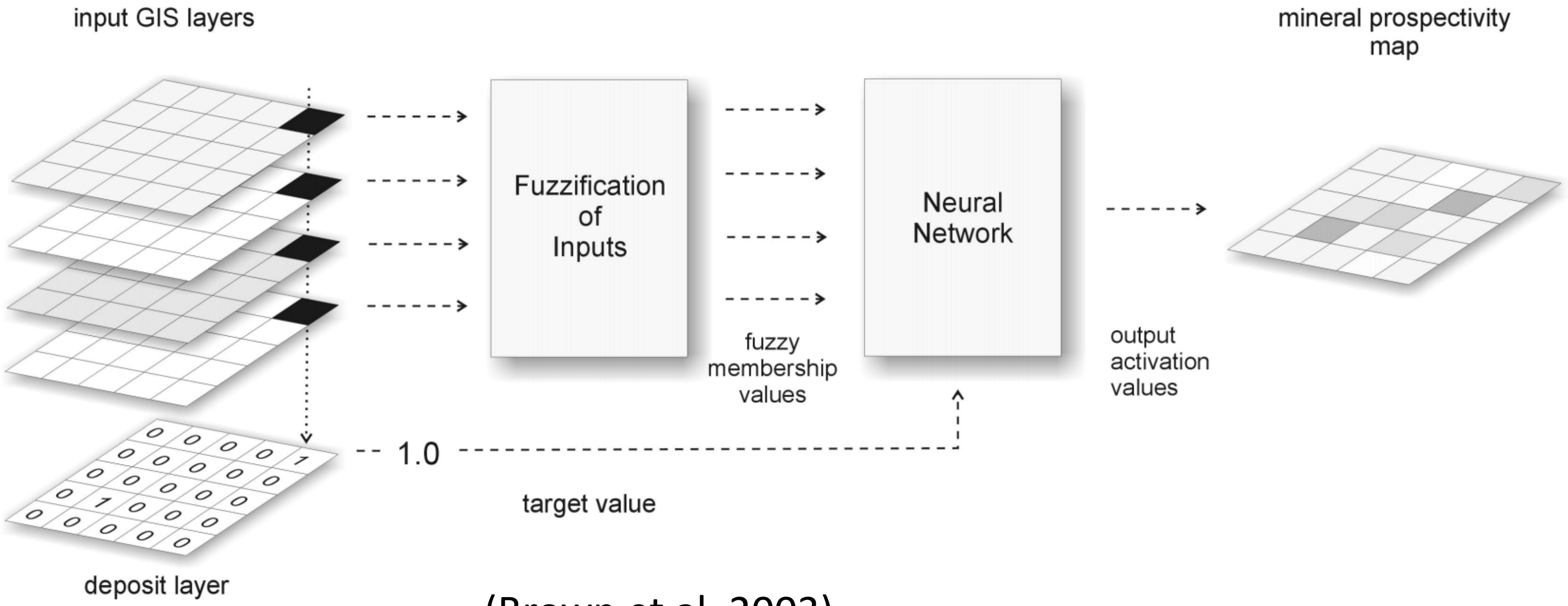
Data Analytics Workflow(s)

Hybrid Approach to Data-driven Analysis

- Various techniques proposed to construct a mineral prospectivity map



(Kasabov, 1996)



(Brown et al. 2003)

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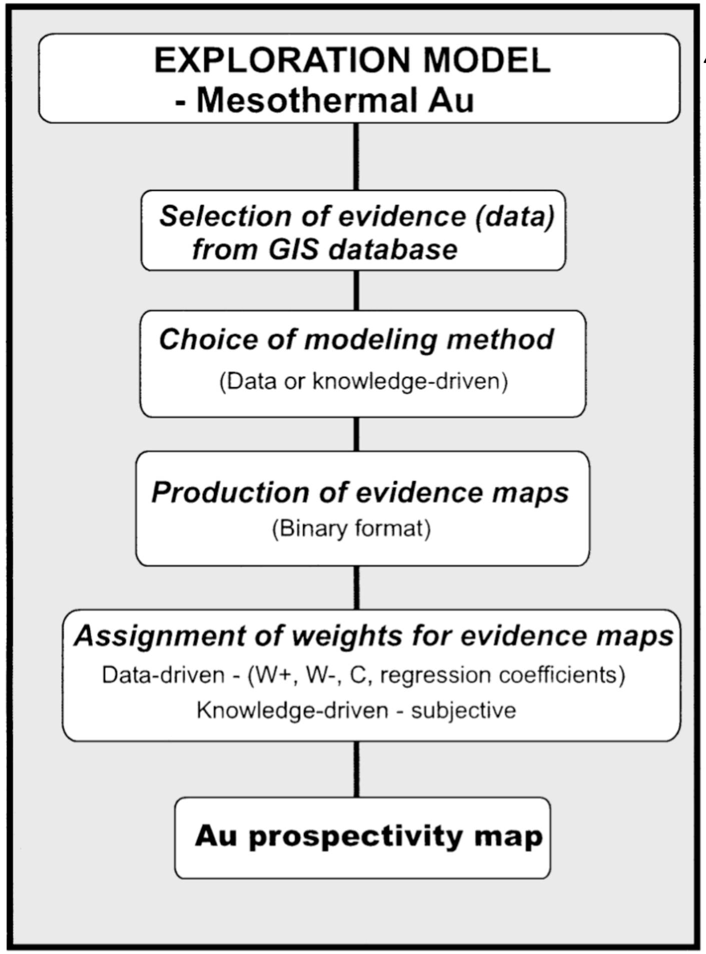
Data Sets Considered

List of compiled GIS information

- **Geology:**
  - Bedrock Formations (mainly No
  - Structural Data (Foliation, Folding, Faulting)
  - Lineament Extraction from SRTM data
- **Geochemistry:**
  - Lake Sediments (Updated 2015)
  - Alteration Indexes Calculations (e.g. Hashimoto, ACNK)
- **Geophysics:**
  - Available High-res Mag Surveys (partial coverage, 2011, 2012)
  - Regional Magnetic Survey
- **Remote Sensing:**
  - Landsat 8 analysis involving generation of band ratios to enhance mapping of iron-oxides and clays
- **Mineral Occurrences:**
  - Mineral Occurrence Data System



Harris et al. (2001)

Algoma-type (BIF hosted)

Hybrid methodology of integration

Hybrid methodology of statistical weighting

New prospectivity mapping, updated data repository for analytics

<ins>Focus on lake sediment geochemistry</ins>

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Labrador Lake Sediments Metadata

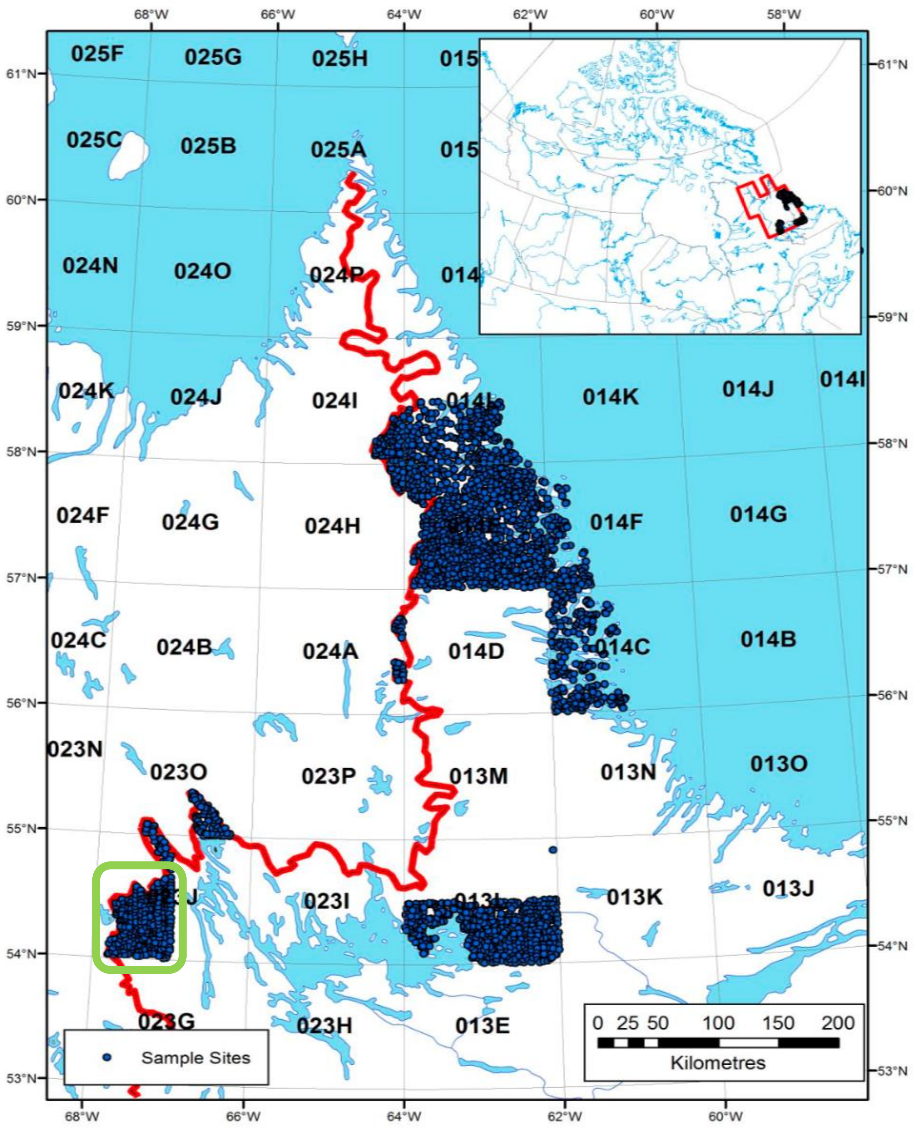
Lake Sediments Data (Metadata and QA/QC)

- Data subject to re-analysis in 2015 (ICP-MS), Original LS (1 sample per 13 km^2) collected in 1982, 83, 85. 2075 samples. Total of 65 elements (2015).
- Samples were re-analyzed by Instrumental Neutron Reactivation (GSC OF: 2037, 2647, 2690, 2691) + ICP-ES (2012) on selected elements (OF:LAB1602)

<u>QA/QC Procedures (2015-re-analysis)</u>

- Accuracy, Precision, ANOVA (Garrett, 2016).
- Results indicated potential issues with the following elements:
  - **Pt, Au, In, Ge and Te**

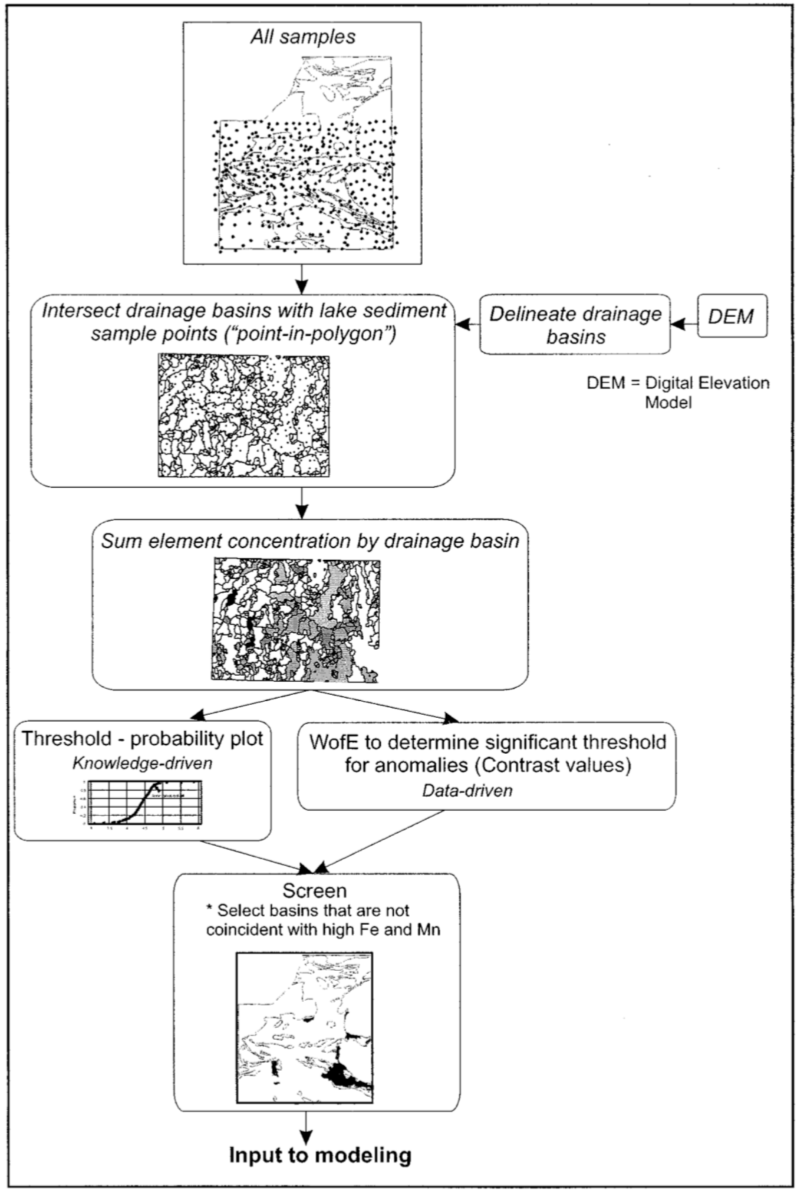
Lode Au Deposits-pathfinders: **(Au) Ag, As, W, Sb, Te +/- Cu, Pb, Mo** (McQueen, 2005)



Labrador Lake Sediment Data: Processing Steps

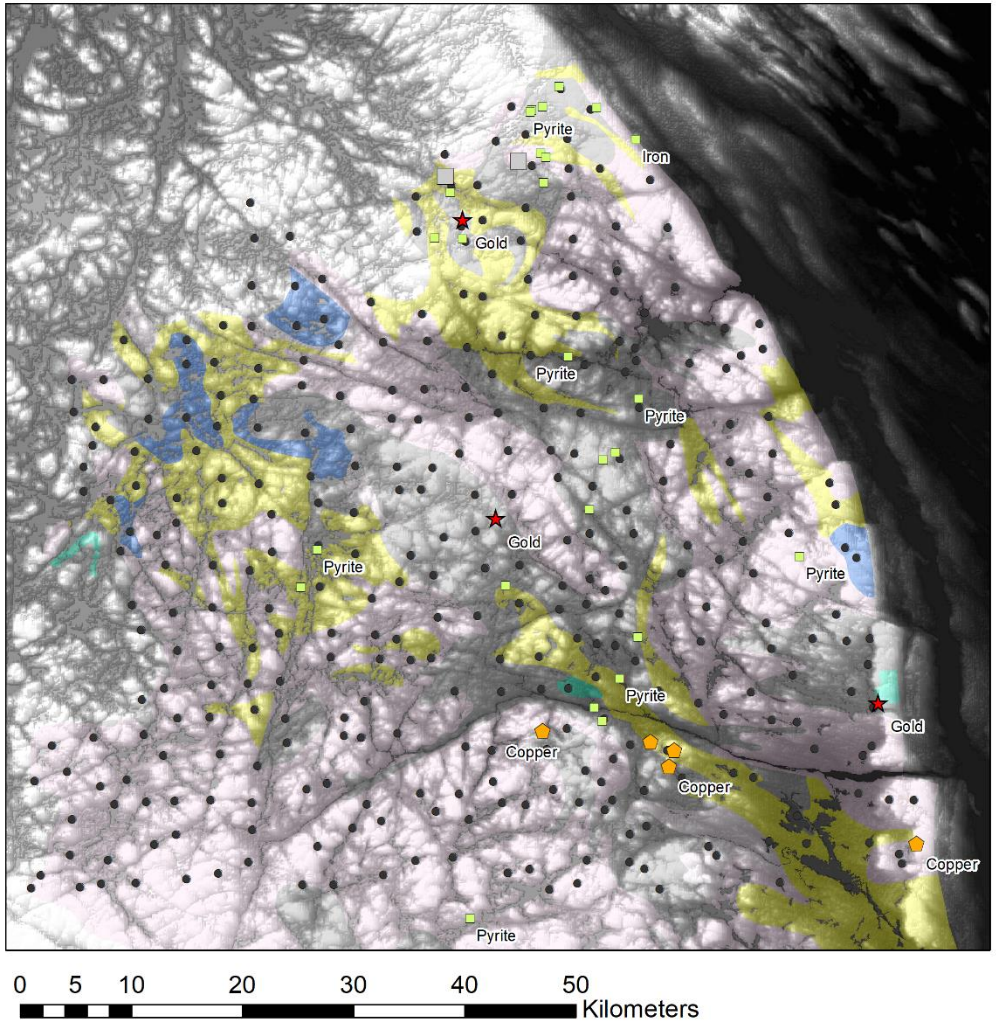
Sample Locations & Catchment Analysis

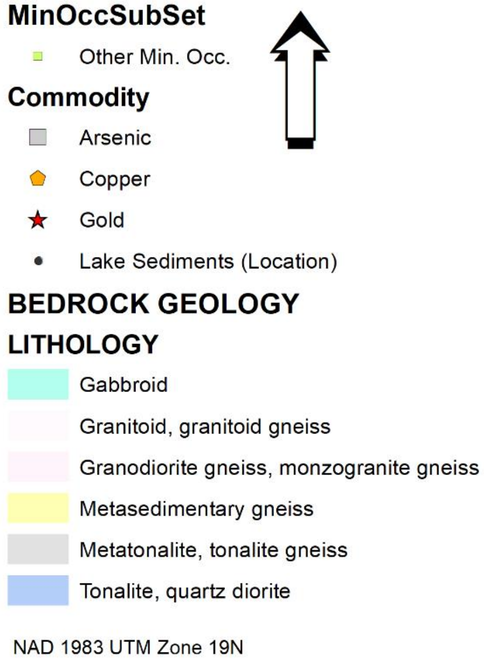
- Determination of areas of influence (Catchment) to constrain the siting of potential sources (see Harris et al. 2001).
- Sample selection and determination of pathfinders.
- Development of drainage GIS analysis based on SRTM data (90 m resolution-void filled).
- Sum of element concentration by drainage basin.
- Quantization of resulting distribution and catchment reclassification to obtain multiclass layers for subsequent fuzzy analysis.

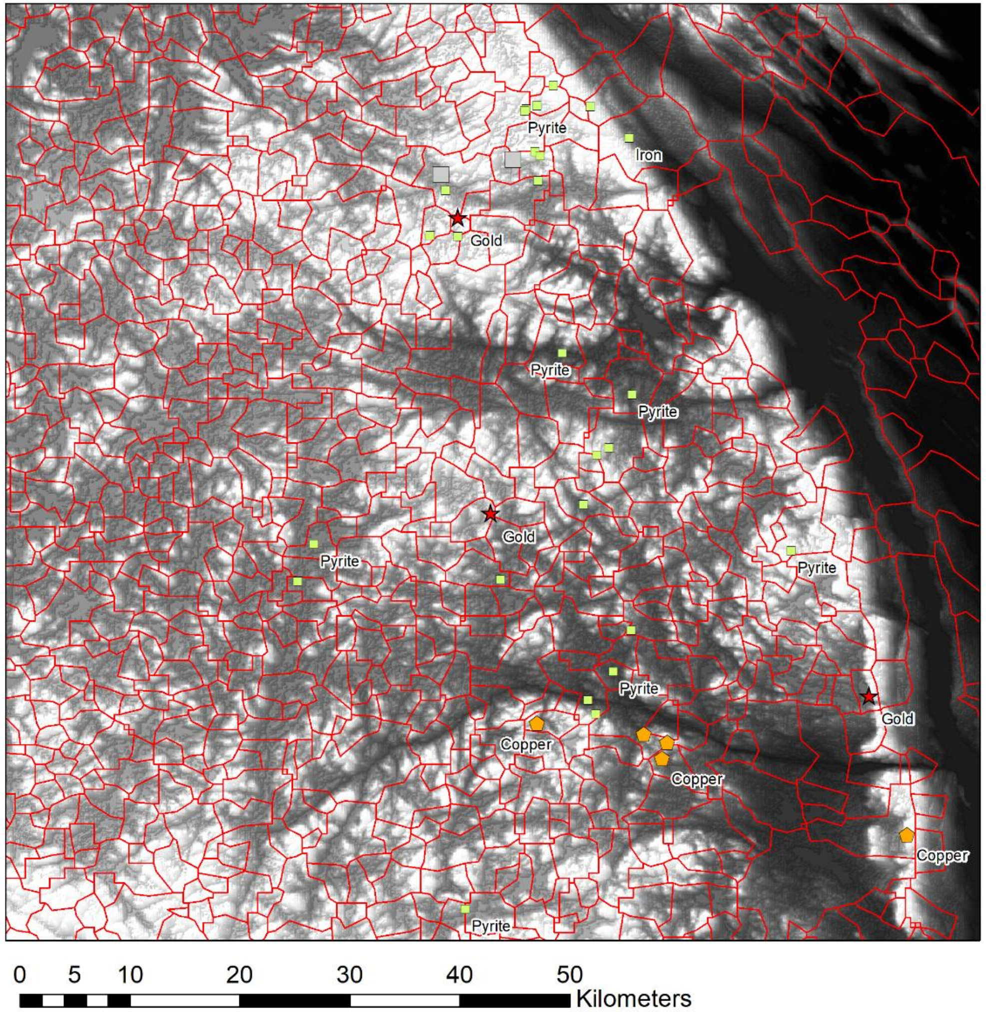


Labrador Lake Sediment Processing I

Occurrences, Lake Sediments, SRTM and Geological Mapping



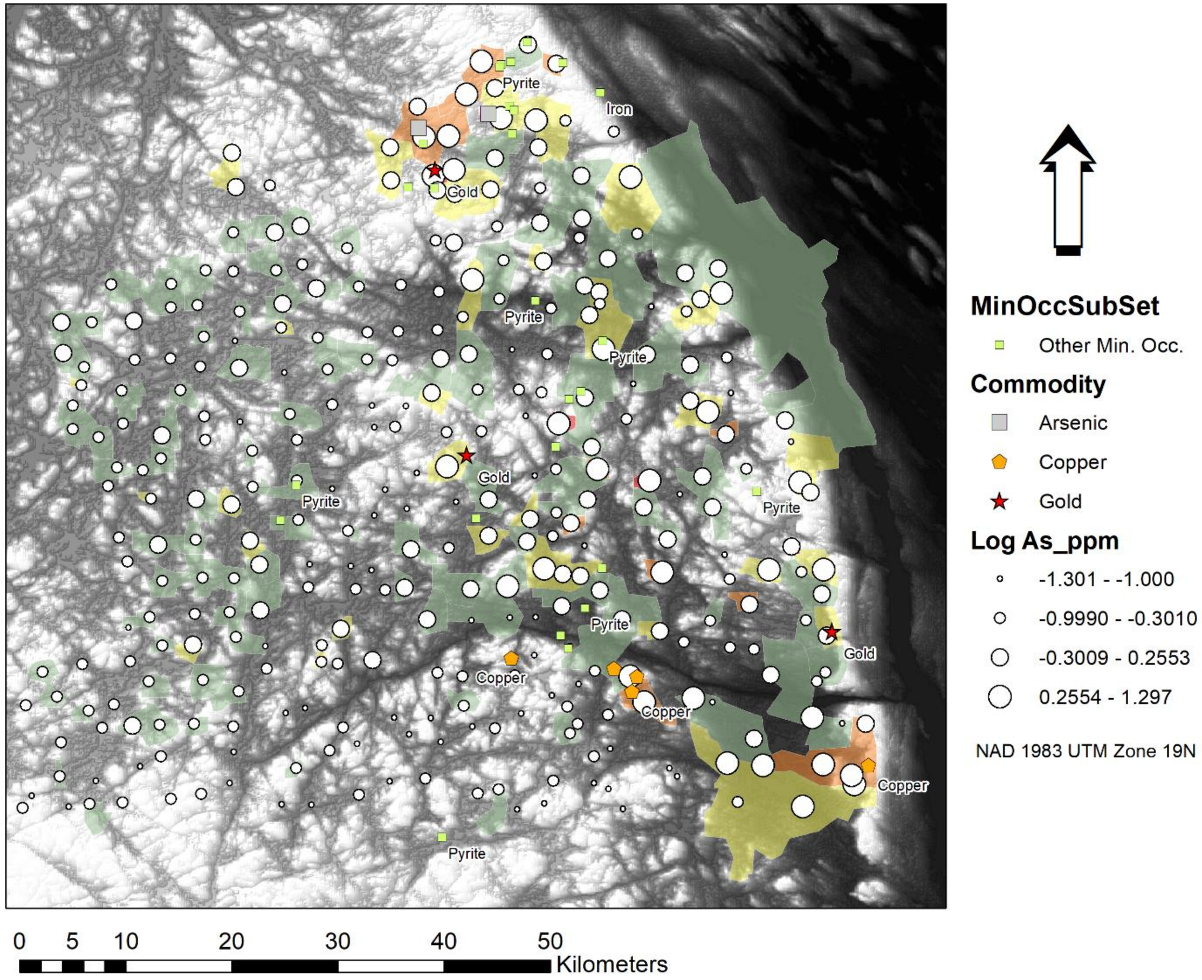


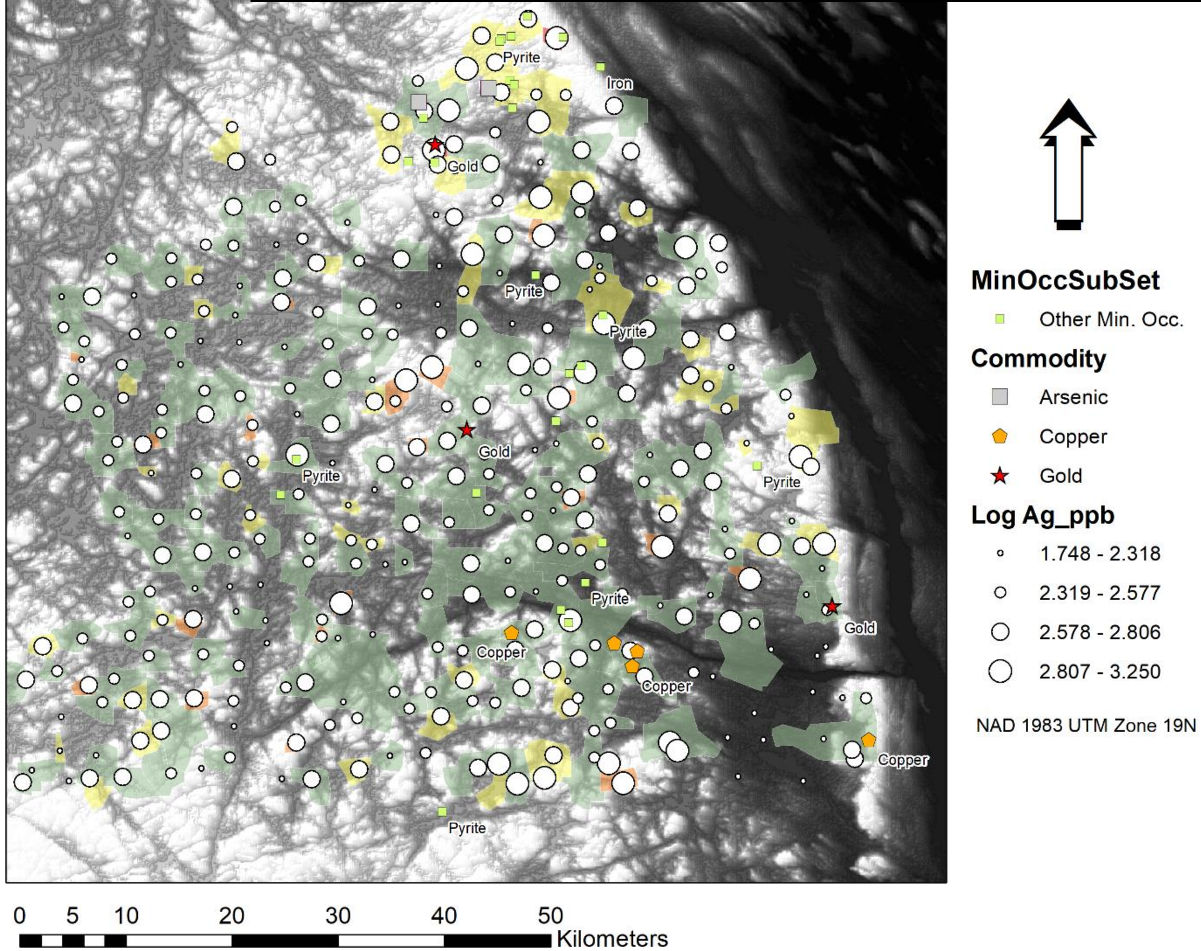


Labrador Lake Sediment Processing II

Testing the predictive capacity of catchment interpolations

Pathfinders For Lode (Algoma-Type) Au





Feltrin (2019), in prep.

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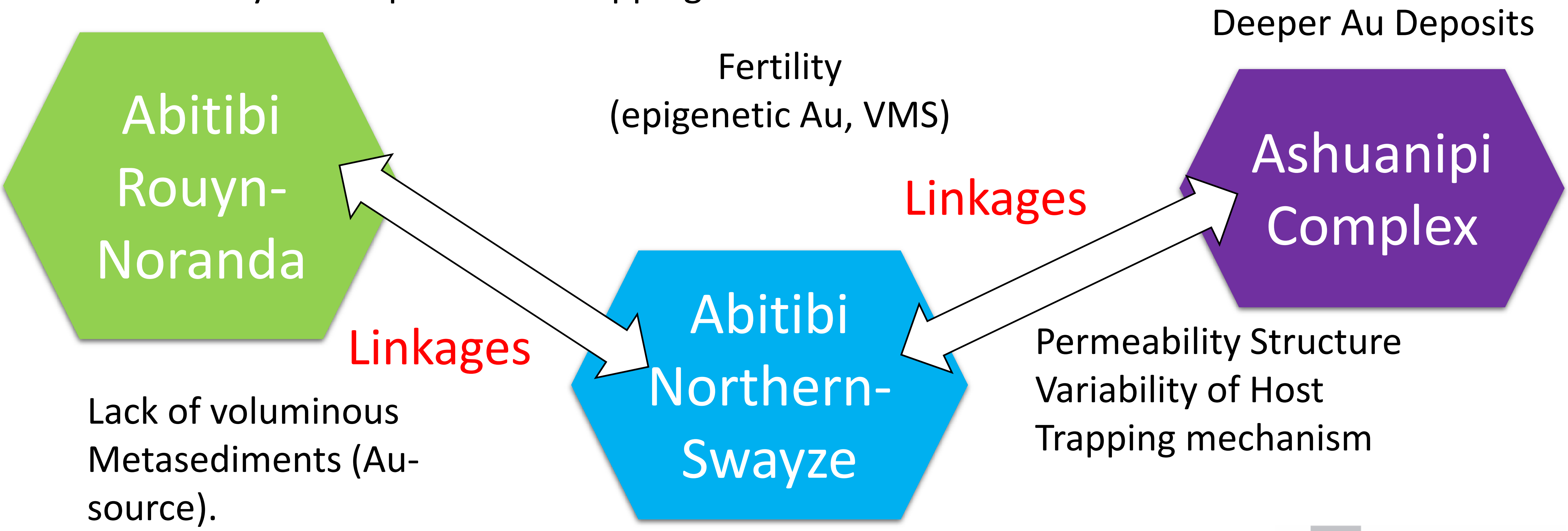
Summary

- Focus on three sub-provinces of the Superior craton to understand differences in fertility/mineral endowment and provide integrated datasets for statistical analysis and predictive mapping.



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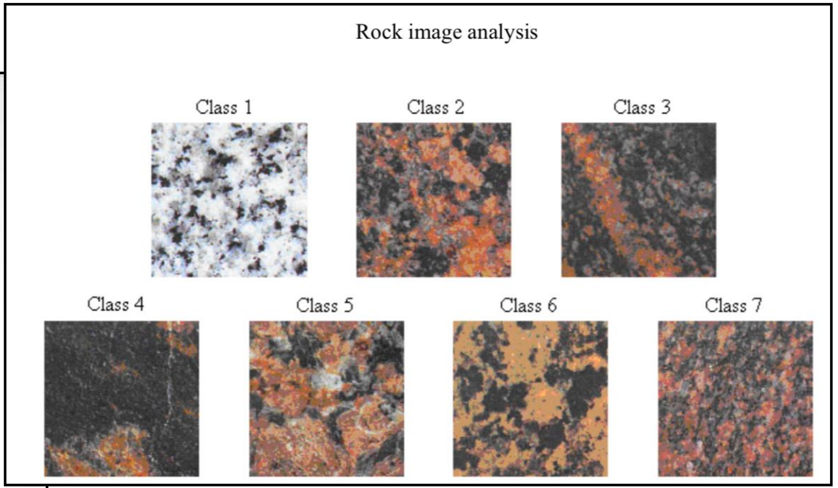
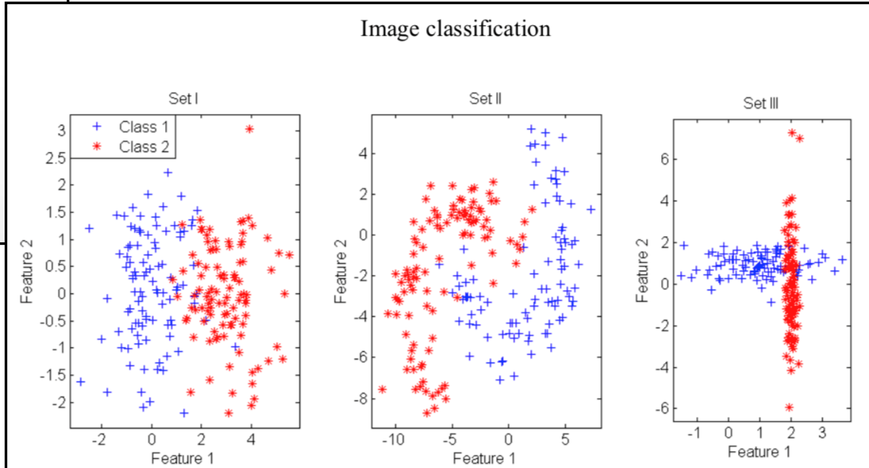
Drones and Machine Learning

ML processes to detect structure and mineralogy in rocks using a drone?

OBJECTIVES:

- Identify a drone that is suitable for experimentation.
- Evaluate the capacity of the drone of being automated to collect systematically imagery.
- Evaluate possible classification and rock recognition strategies.





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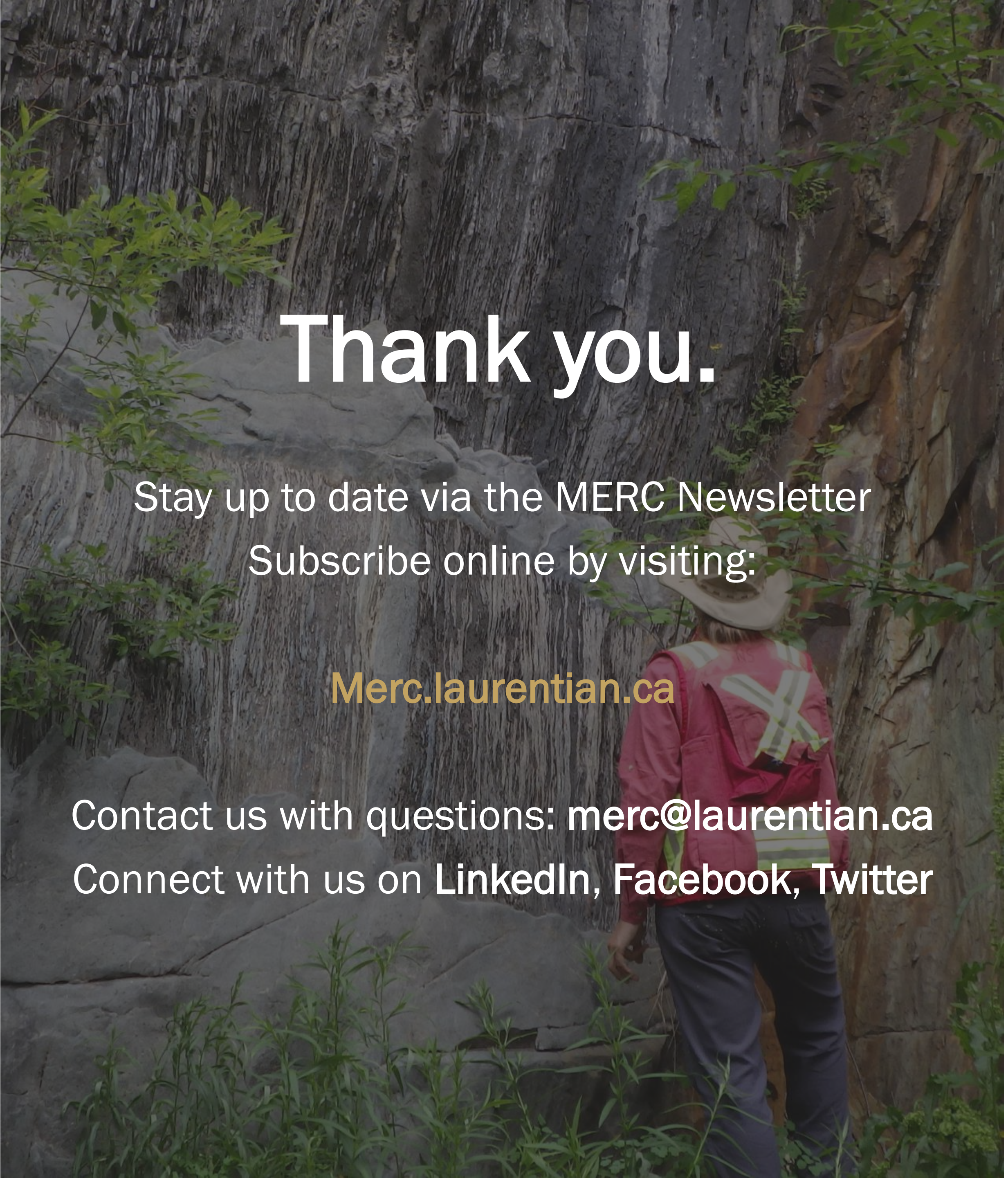

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