Upper-Crustal Architecture of the Eastern Sudbury Ni-Cu-PGE Camp by 3-D Integration of Geology and Geophysical Datasets

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PDAC Short Course – Mar 04, 2023

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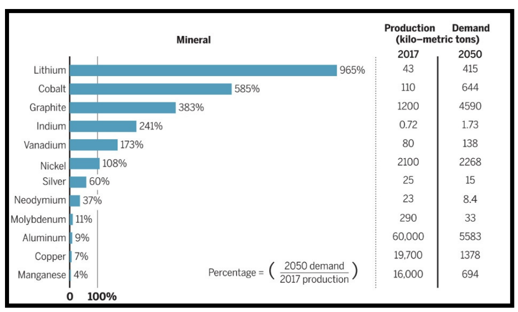
MINERALS & METALS EXPLORATION – GLOBAL PERSPECTIVE

Why it is important:

- United Nation's mission of **Net Zero emission** (carbon neutrality) by 2050
- **Clean energy transition**: Deploy technologies such as wind, solar, electrification (e.g. electrical vehicles) and geothermal power
- **Minerals and metals** are essential to achieve this clean energy transition.
- Over the next 30 years, production of minerals and metals needs to increase by **500% average**



Growth in mineral needs for low-carbon technology (Courtesy: Sovocool et al., 2020. https://www.greencarcongress.com/2020/01/20200105-sovacool.html)

What are the exploration challenges:

- Existing near surface resources are **getting depleted & less new discoveries**
- Discoveries are getting **deeper** and less **accessible**
- **Discovery to production ratio** is very poor
- Lack of skilled geoscientists, **particularly Geophysicists**

What are the solutions?

- Paradigm shift in **exploration techniques**
- Developing the **Mineral system concept** (Australia is leading)
- Import ideas from **oil and gas industry**
- **Advanced technologies** (3D and 4D modelling)
- Train future generation of **geoscientists**

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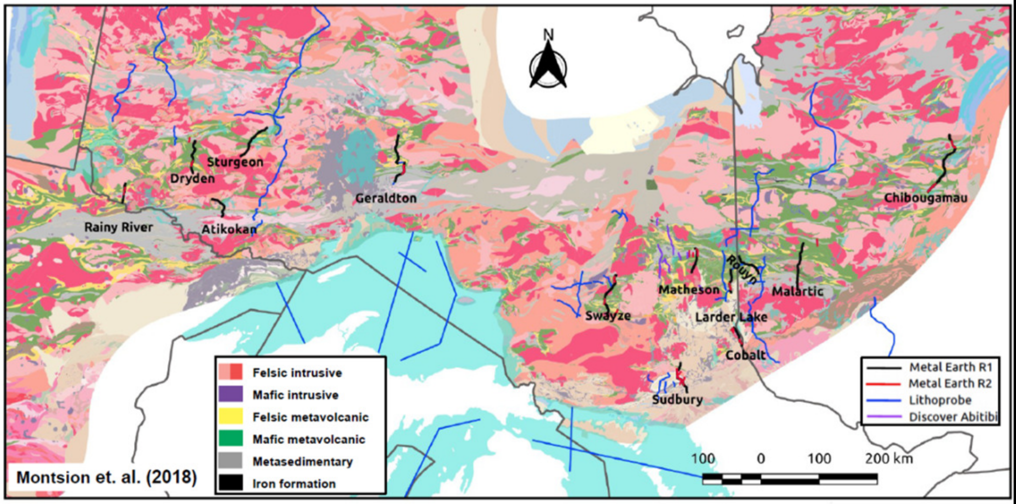
METAL EARTH PROJECT (CANADA) – A BRIEF OVERVIEW

- Metal Earth is a **Laurentian University** led collaborative research project, **partially funded by Government of Canada for seven-years, with total funding of $ 104M**, with an objective to improve our understanding of **metal endowment in Precambrian rocks of Ontario.**
- There are total **13 transects** within Superior Craton across **Abitibi and Wabigoon Subprovinces**.
  - Some **metal endowed**
  - Some **non/less-endowed**



Lithological Map of Superior Province and Seismic Transects

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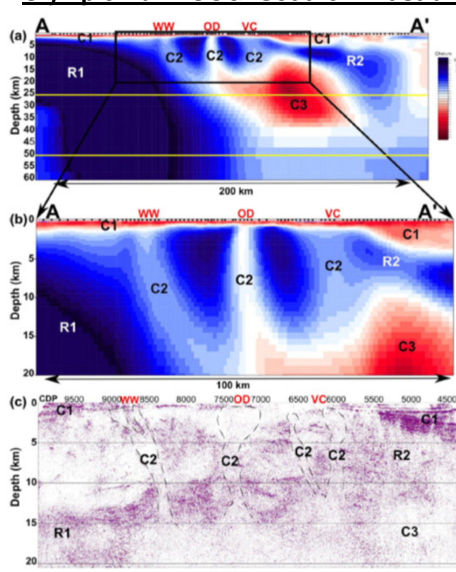
METAL EARTH PROJECT (CANADA) – A BRIEF OVERVIEW

Core Objectives:

- **Integration** of multidisciplinary geological and geophysical data.
- **Image ore and non-ore systems** and controls
  - full crust-mantle scale,
  - district scale
  - deposit scale
- Compare transects cross-section to establish differences between **endowed and less-endowed greenstone belts.**

Olympic Dam IOCG- Southern Australia magmatic mineral system



MT and seismic over the Mesoproterozoic Olympic Dam IOCG

Are similar features evident in endowed and unendowed greenstone belts?

(Heinson et al., 2018) Scientific Reports

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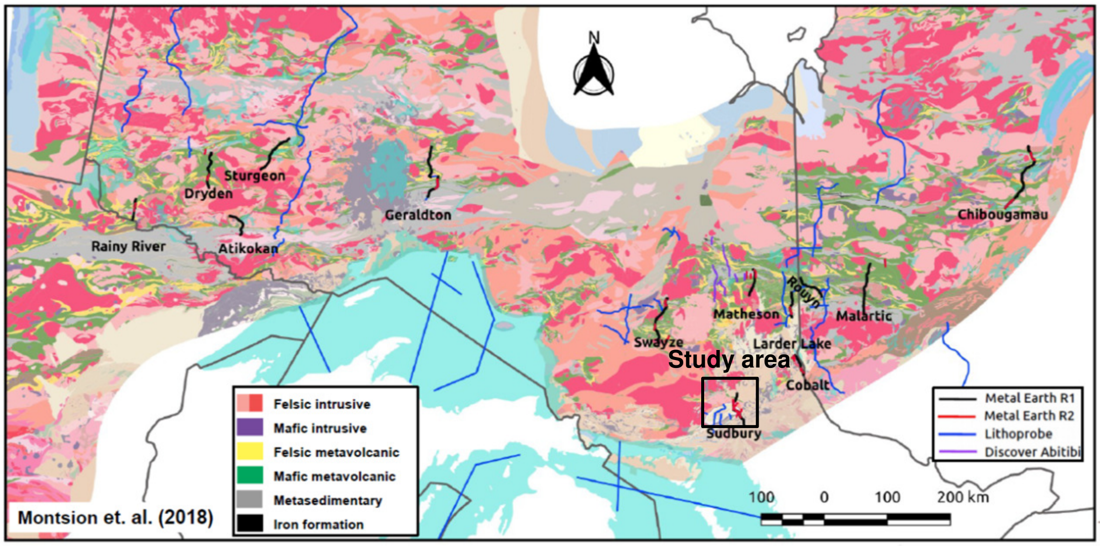
METAL EARTH PROJECT – SUDBURY TRANSECT



Lithological Map of Superior Province and Seismic Transects

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METAL EARTH PROJECT – SUDBURY TRANSECT

Sudbury Project Research & Funding Partners

Software	Industry	Government organization
EMERSON; Mira Geoscience ...modelling the earth; SEEQUENT; Adobe; esri	VALE; SUDBURY INTEGRATED NICKEL OPERATIONS A GLENCORE COMPANY	Ontario

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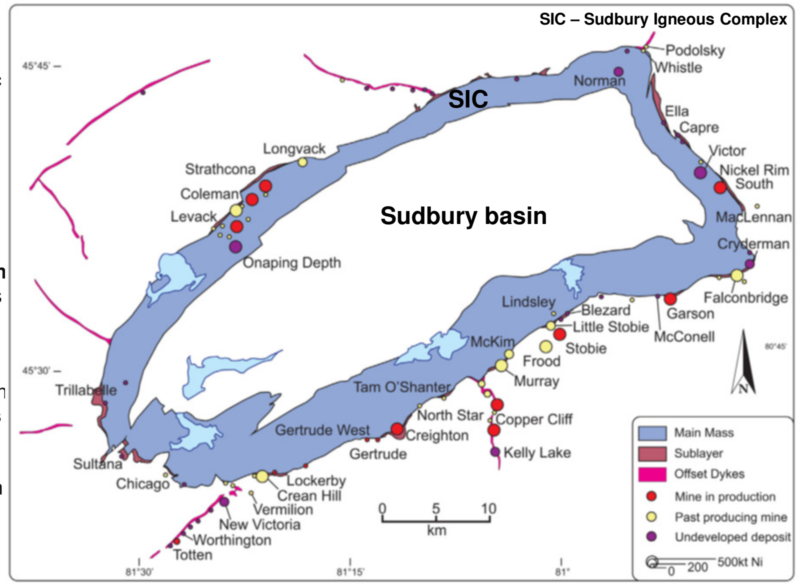
HISTORICAL PERSPECTIVE – SUDBURY BASIN

- Sudbury basin is known for world class **Ni-Cu-Co-PGE-Au deposits** and therefore its has enormous economic and social impact on not only Sudbury region, but also on the economic development of Canada.
- Many of these deposits occur along the rim of **Sudbury Igneous complex** (SIC) and associated offset dykes.
- In the Eastern part of the basin, apart from **Nickel Rim South, Falconbridge and Garson deposits**, there is no other significant deposits discovered that are economically viable for Mine production.
- Its high time to look into Eastern Sudbury basin more carefully with **latest technological tools** available in the market.
- In search of new deposits or targets, One such research initiative taken up by **Metal Earth project** in collaboration with local companies **Vale & Glencore**.



(Lightfoot, 2017)

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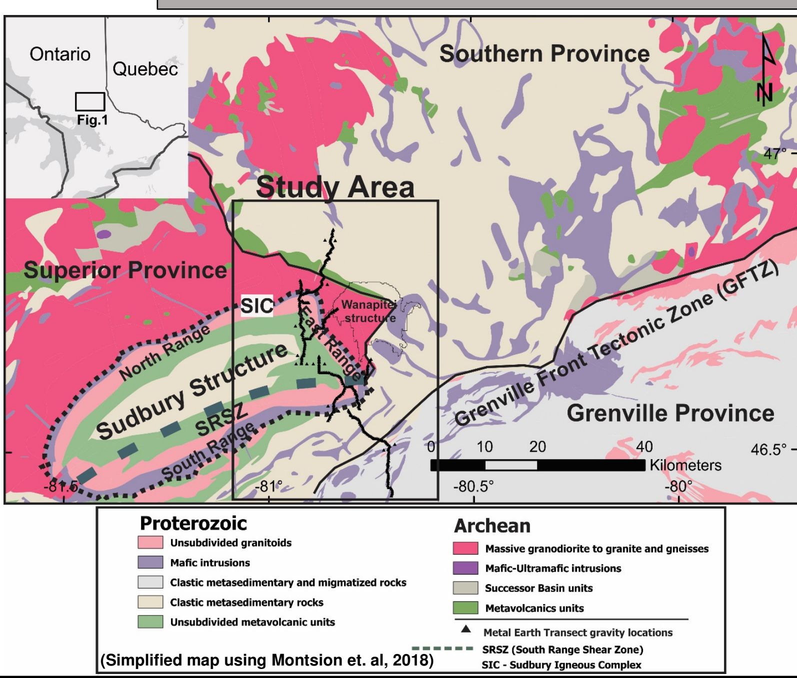
GEOLOGICAL BACKGROUND – SUDBURY TRANSECT



(Simplified map using Montsion et. al, 2018)

- Sudbury Impact crater formed at around 1.85 billion years ago.
- The current structure overlies on Archean rocks (granite and gneisses) to the North and on Proterozoic rocks (meta-sedimentary) to the south.
- The current study area lies in the eastern part of impact crater
- South Range Shear Zone (SRSZ) passes through the middle of the study area.
- Grenville Front Tectonic Zone (GFTZ) lies to the south of the study area.

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ANTICIPATED OUTCOMES – SUDBURY TRANSECT

Research outcomes:

- A complete interpretation of the **upper crustal architecture** over the Eastern part of the Sudbury impact structure
- To identify **new targets/potential zones of mineralisation** by **3D integration and interpretation** of various geological and geophysical datasets (e.g. surface geology, potential field, magnetotelluric, seismic sections, petrophysical and other geophysical data), and subsequently, an interpretation of the overall crustal scale geology and associated mineralizing structures of the Eastern Sudbury basin.
- To build a robust **3D geological model of upper-crust (10 km) of the Eastern Sudbury basin** which will help in **constraining mineralized (Ni, PGE and Cu) structures**, their orientation and volume and also helps to **identify sources of mineralization** and **pathways**
- The research methodology can be utilized to study **other similar ore deposit models** worldwide.

Possible future outcomes:

- To **guide exploration companies** for exploration of **new deposits** and develop **new mines**
- Contributing to provincial **economic development**
- Contributing to Canada's vision of achieving **Net-Zero emission** by 2050.

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SUDBURY TRANSECT – PREVIOUS 3D GEOLOGICAL MODEL

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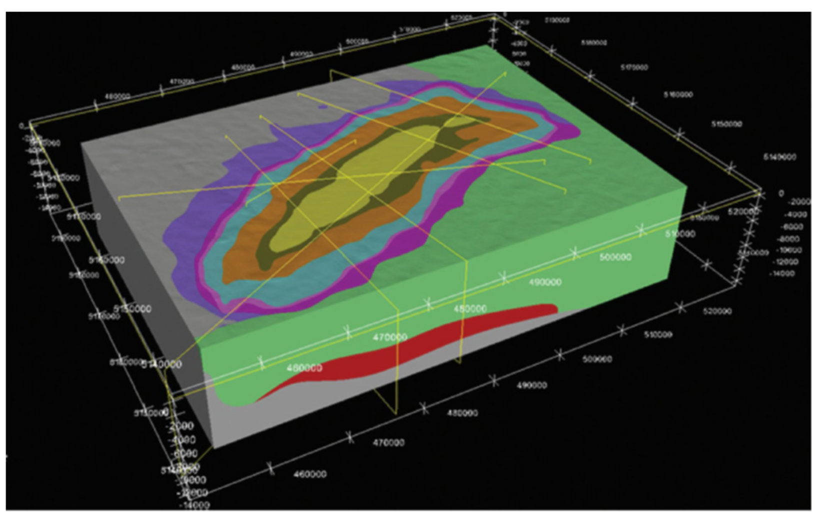
Why new model ?

New data, new approach and new AOI (area of interest)



Previous model (Olaniyan et al., 2015)

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RESEARCH TEAM – SUDBURY TRANSECT

Metal Earth Team:

Rajesh Vayavur (**Research Associate – Geophysics**)

Rasmus Haugaard (**Research Associate - Geologist**)

Ademola Adetunji (**Research Associate – Magnetotelluric**)

Saeid Cheraghi (**Research Associate – Seismics**)

Mostafa Naghizadeh (**Research Associate/ Former Professor – Seismics**)

Richard Smith (**Professor – Geophysics**)

John Ayer (**Associate Director MERC, Metal Earth Project**)

Ross Sherlock (**Director MERC, Metal Earth Project**)

Vale & Glencore Team:

Kevin Fenlon (**Geophysicist - Vale**)

Lisa Gibson (**Manager – Vale**)

Enrick Tremblay (**Exploration Manager – Vale**)

Warren Hughes (**Senior Geophysicist – Glencore**)

Guido Serafini (**Principal Exploration Geologist – Glencore**)

My roles and responsibilities:

- To perform **3D potential field modelling/inversion**
- To coordinate with other team members for **3D integration of various geological and geophysical datasets**
- To build a robust **3D geological model** of the Eastern Sudbury basin

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GEOPHYSICAL METHODS – SUDBURY TRANSECT

Geophysical Method	Measured parameter	Estimated property
Seismic survey	Travel time reflected/refracted seismic wave	Density and elastic moduli (seismic impedance)
Gravity survey	Gravitational field of the Earth	Density
Magnetic survey	Geo-magnetic field of the Earth	Magnetic susceptibility
Magnetotellurics survey	Electrical and magnetic field components	Electrical conductivity

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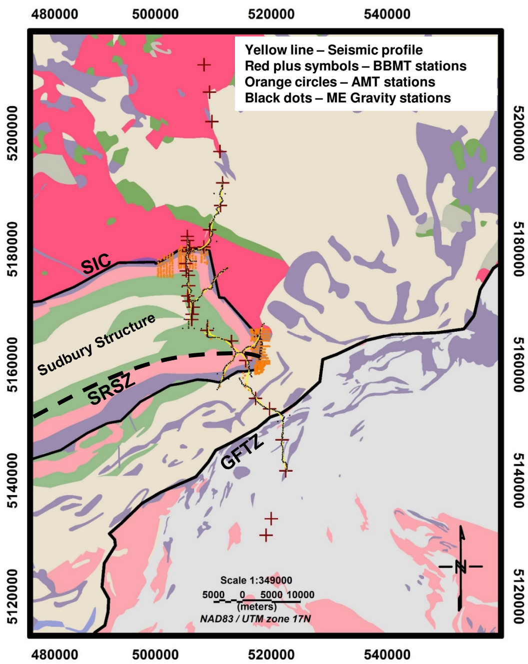
GEOPHYSICAL DATASETS ACQUIRED – SUDBURY TRANSECT



In summers of 2017 & 2018, Metal Earth in collaboration with Vale & Glencore companies (NSERC-CRD grant) collected

- **Seismic data** (Regional **R1** and High-resolution datasets **R2**)
  Five new seismic lines span a length of ~ 60 km extending from the northern Archean terranes to the southern Grenville front. Hi-Seis company processed the seismic data.
- **Magnetotelluric & Audio-frequency Magnetotelluric data**
  (466 AMT & 30 BBMT stations)
- **Gravity data**
  (357 gravity stations acquired)

Other datasets used:

- **Publicly available OGS** (Ontario Geological Survey) aeromagnetic grids, gravity (.csv) data and mineral occurrences database.
- **Vale** provided **3D GOCAD model** of top 5 km of basin

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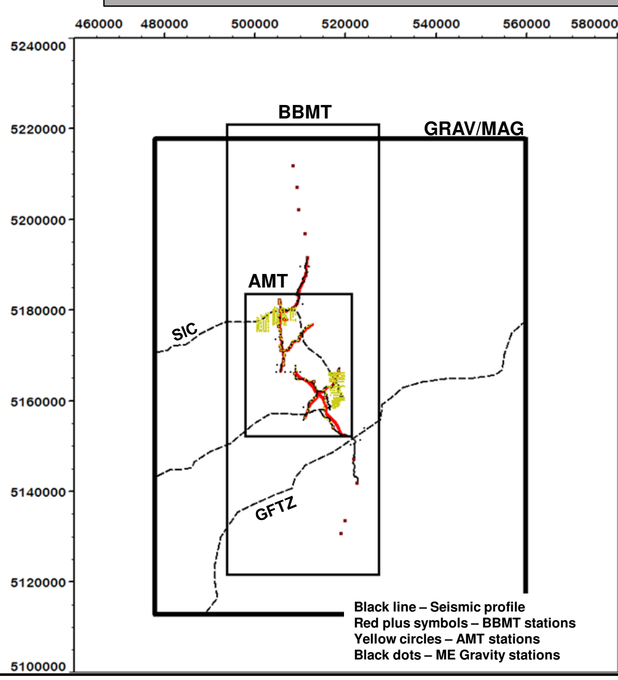
3-D GEOPHYSICAL INVERSIONS – SUDBURY TRANSECT



3-D geophysical inversions carried out at various scales:

- Gravity and Magnetic inversion (15 km depth)
- BBMT inversion (~60 km depth)
- AMT inversion (~15 km depth)

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3-D AMT INVERSION – SUDBURY TRANSECT

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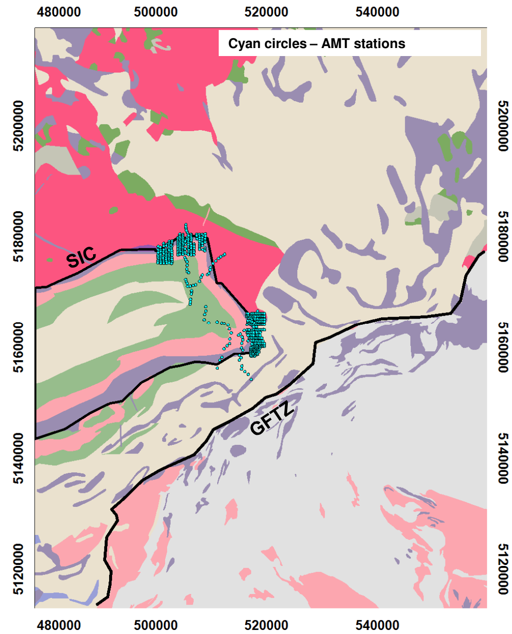
High resolution industry sponsored Audio-frequency Magnetotelluric (AMT) data



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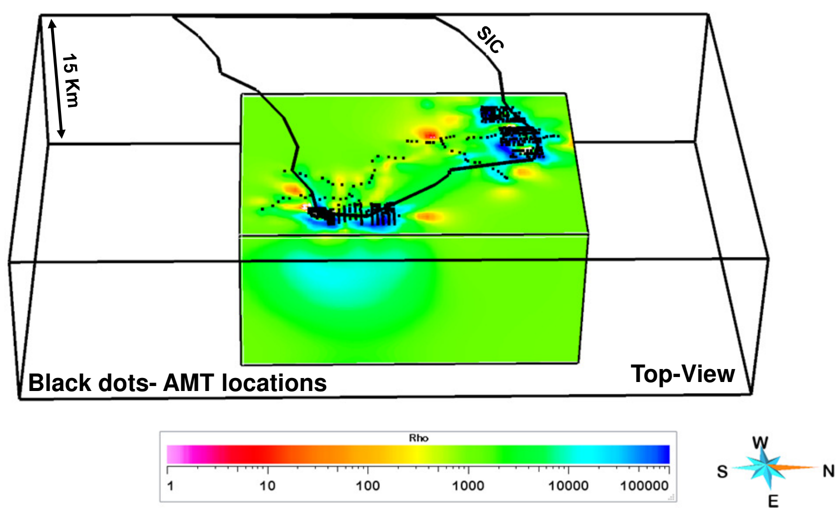
3-D AMT INVERSION – SUDBURY TRANSECT

- **Final Inverted AMT model**
- **Inversion performed by Ademola using ModEM code by (Egbert and Kelbert, 2012; Kelbert et al., 2014)**
- **Starting model used 1000 ohm.m**



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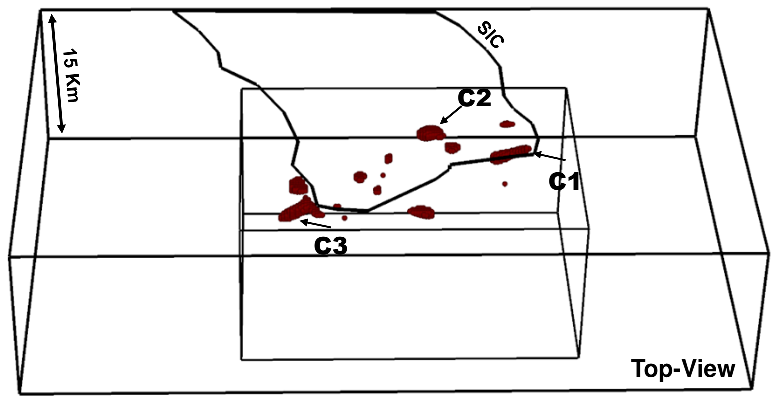
3-D INTEGRATION OF GEOPHYSICAL MODELS – SUDBURY TRANSECT

- C1, C2 & C3 are conductors
- C1 and C3 - High confidence conductors based on dense AMT dataset
- C2 is moderate to high confidence conductor

Research Questions:
- What might be emplacement mechanism?
- Are there any additional deeper sources?
- What are the other structural controls?

Resistivity (1-100 ohm.m) isovolume



Shallow Anomalies Investigation

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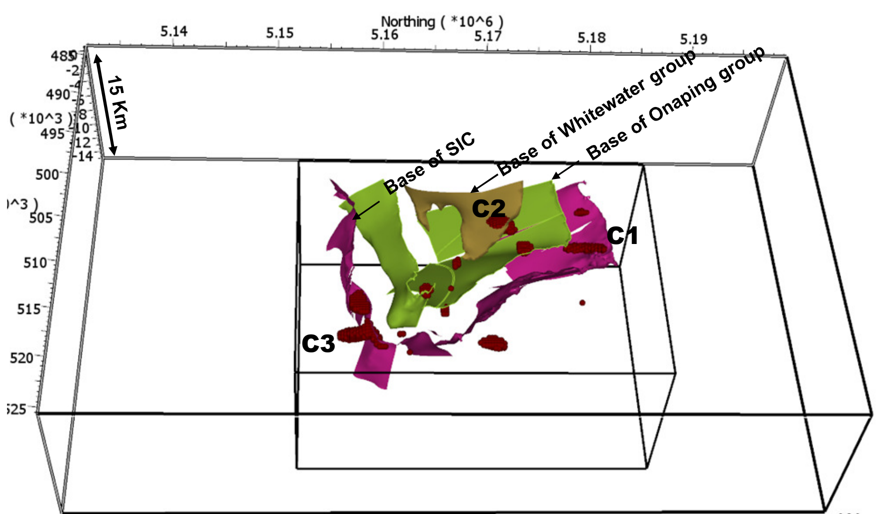
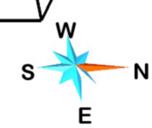
3-D INTEGRATION OF GEOPHYSICAL MODELS – SUDBURY TRANSECT

- C1 conductor lies in the north-east range proximal to the basal contact of the SIC
- C2 conductor lies in east-central area corresponding to white water group of sediments
- C3 conductor lies at south-east range also proximal to the basal-contact of the SIC



Resistivity (1-100 ohm.m) isovolume

Borehole constrained Vale 3D GOCAD surfaces overlaid



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3-D GRAVITY INVERSION – SUDBURY TRANSECT

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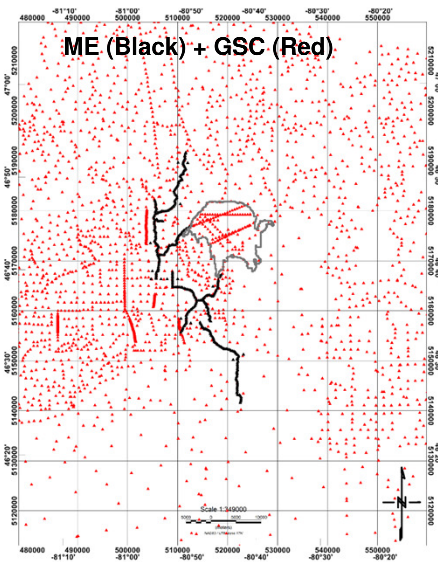

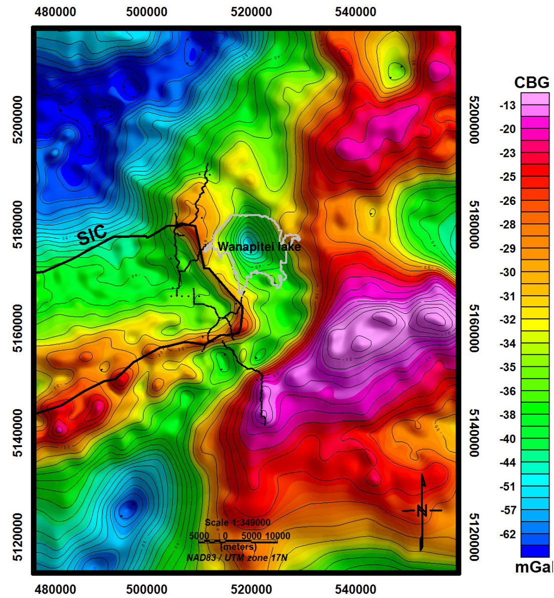

Standard processing of gravity data (Latitude correction, free air correction, Bouguer correction and terrain correction (Correction density – 2.67 g/c.c) – Done by Eshaghi

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3-D GRAVITY INVERSION – SUDBURY TRANSECT

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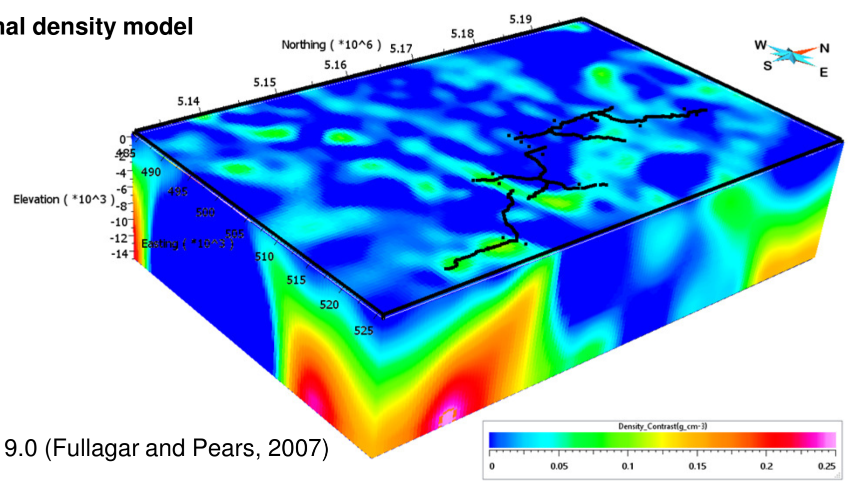
Final density model



Inversion:

VPmg version 9.0 (Fullagar and Pears, 2007)

Final RMS misfit - 1mGal

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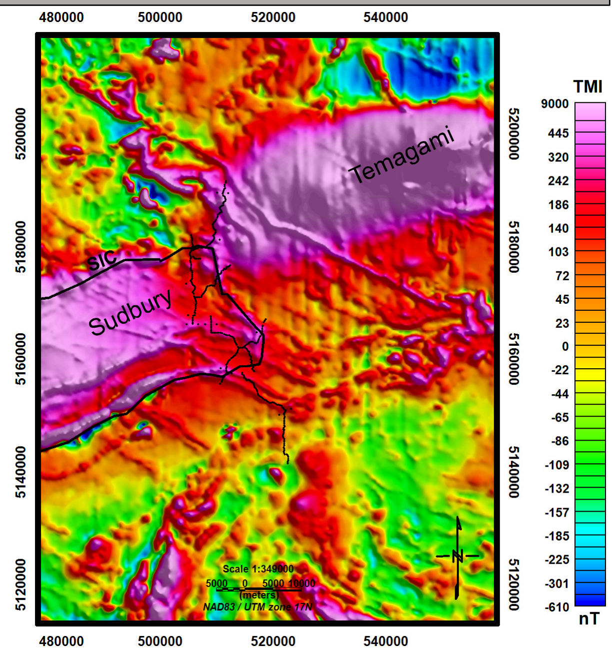
3-D MAGNETIC INVERSION – SUDBURY TRANSECT

TMI -Total Magnetic Intensity grid (GSC regional compilation, 200m line spacing)

- **Reduced magnetic fields in the East Range of Impact crater**



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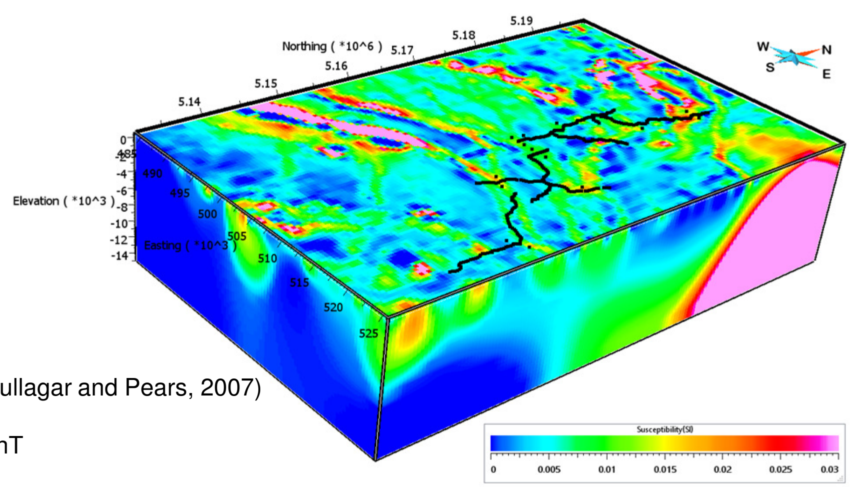
3-D MAGNETIC INVERSION – SUDBURY TRANSECT

Final susceptibility model



Inversion:

VPmg version 9.0 (Fullagar and Pears, 2007)

Final RMS misfit – 7nT

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3-D CROSS-SECTION – SUDBURY TRANSECT

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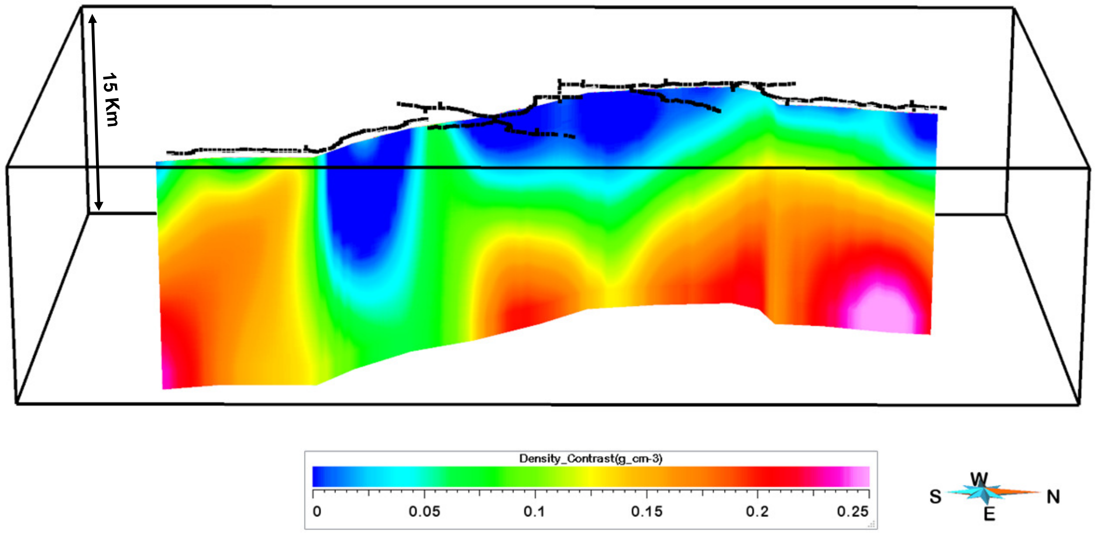
Density Model Cross-section



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3-D INTEGRATED CROSS-SECTION – SUDBURY TRANSECT

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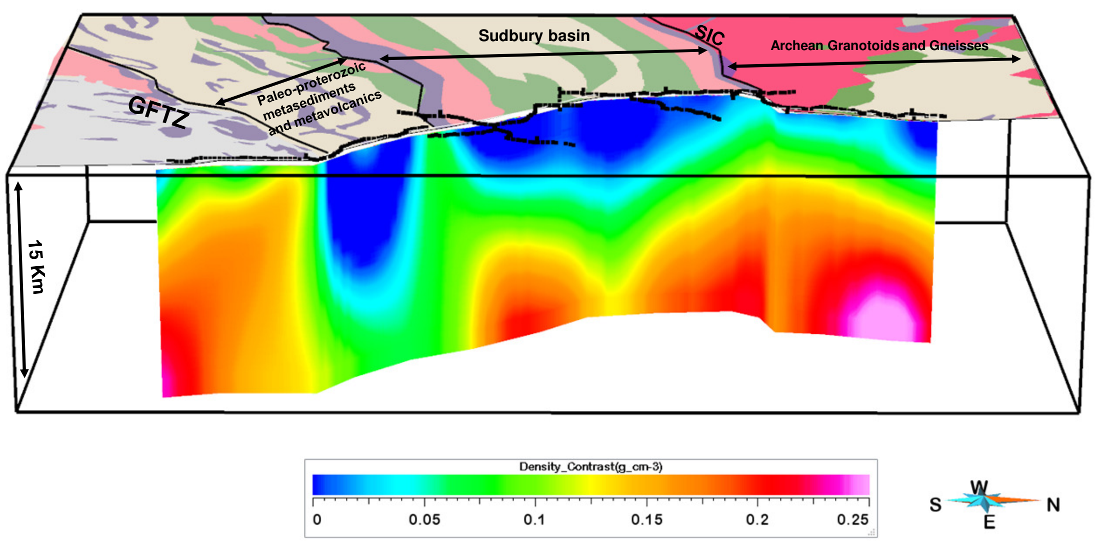
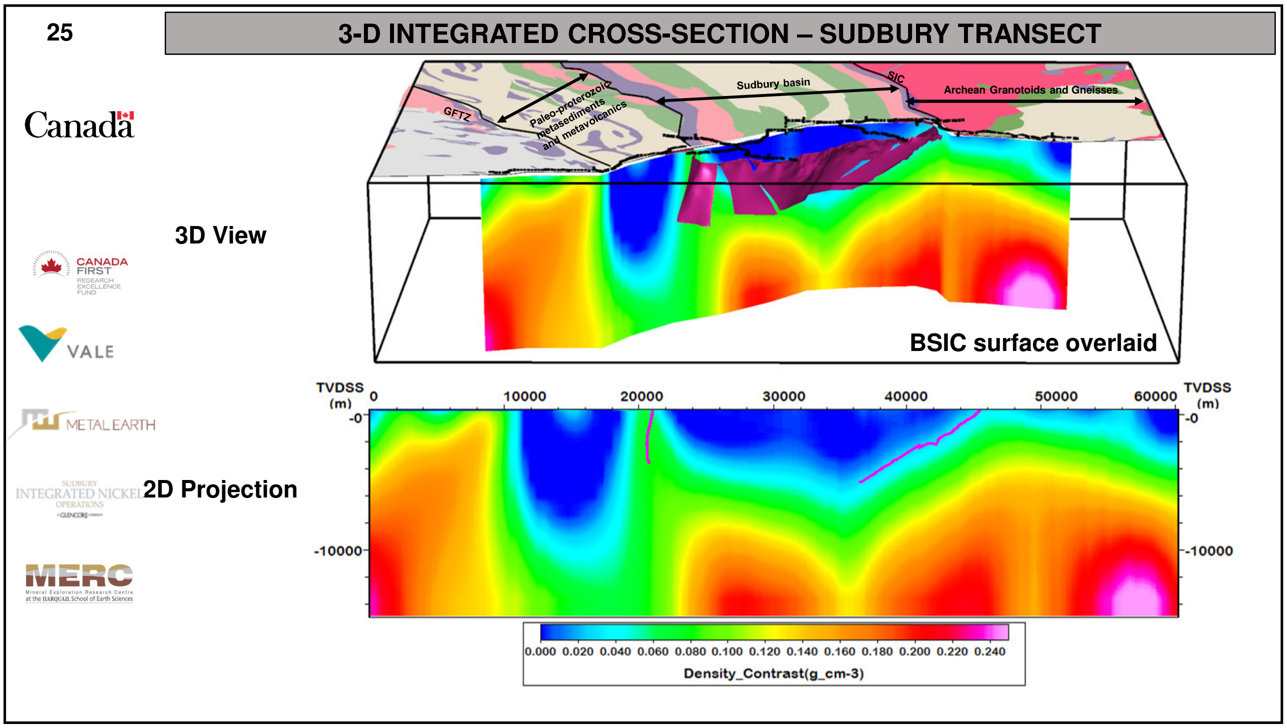
Geology Overlay on Density Model Cross-section

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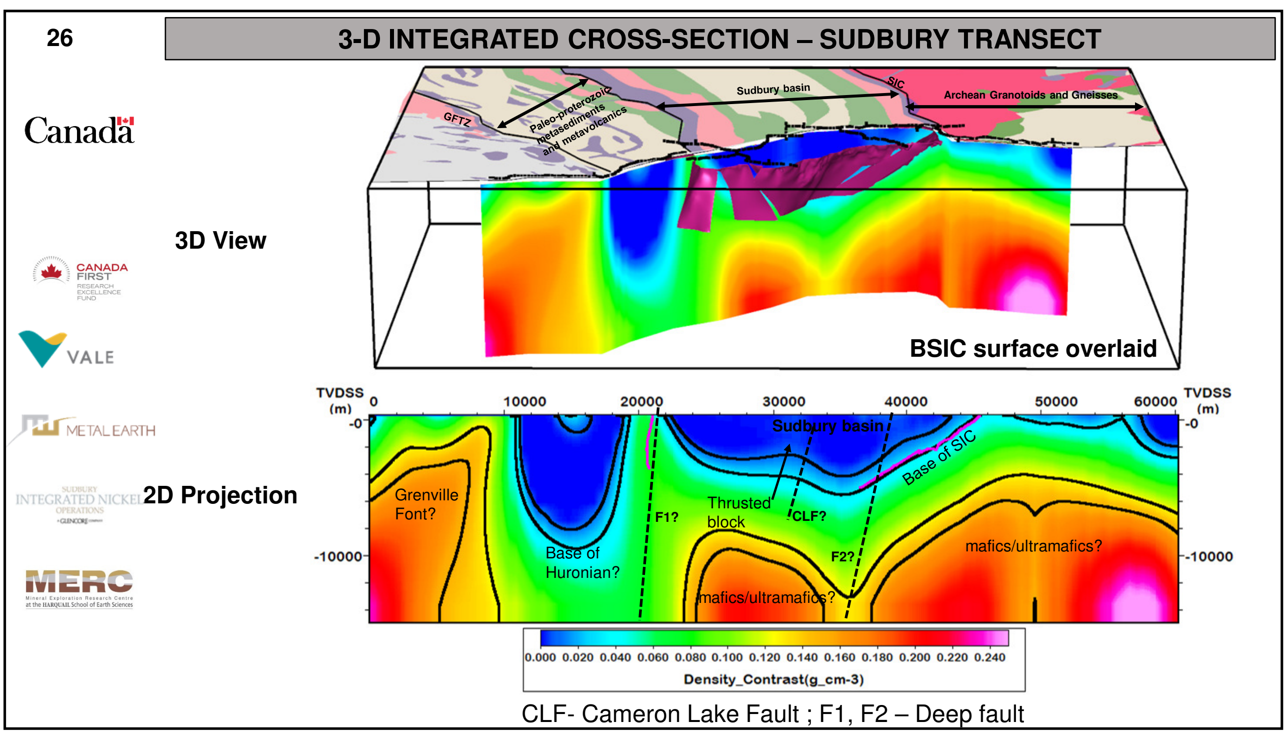
3D View
GFTZ
Paleo-proterozoic metasediments and metavolcanics
Sudbury basin
SIC
Archean Granotoids and Gneisses
BSIC surface overlaid
2D Projection
TVDSS (m)
0
10000
20000
30000
40000
50000
60000
-0
-10000
0.000 0.020 0.040 0.060 0.080 0.100 0.120 0.140 0.160 0.180 0.200 0.220 0.240
Density_Contrast(g_cm-3)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MERC
3D View
GFTZ
Paleo-proterozoic metasediments and metavolcanics
Sudbury basin
SIC
Archean Granotoids and Gneisses
BSIC surface overlaid
2D Projection
TVDSS (m)
0
10000
20000
30000
40000
50000
60000
-0
-10000
Sudbury basin
Base of SIC
Grenville Font?
Base of Huronian?
F1?
Thrusted block
CLF?
F2?
mafics/ultramafics?
mafics/ultramafics?
0.000 0.020 0.040 0.060 0.080 0.100 0.120 0.140 0.160 0.180 0.200 0.220 0.240
Density_Contrast(g_cm-3)
CLF- Cameron Lake Fault ; F1, F2 – Deep fault

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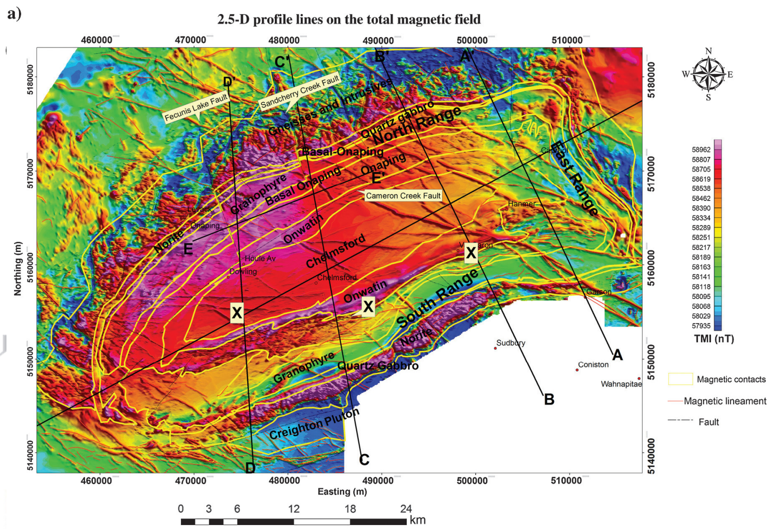
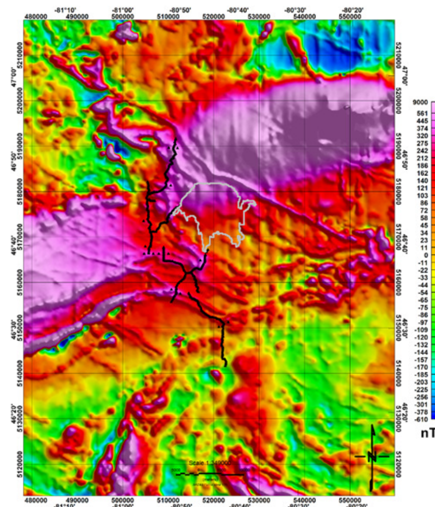
2.5-D Modelling Vs 3-D Inversion cross-section



(Olaniyan et al., 2015)



(Current study)

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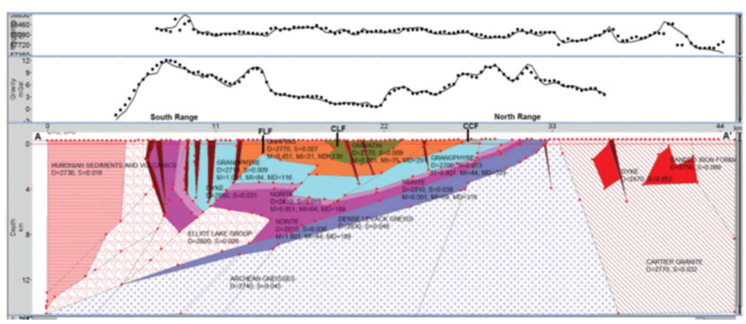
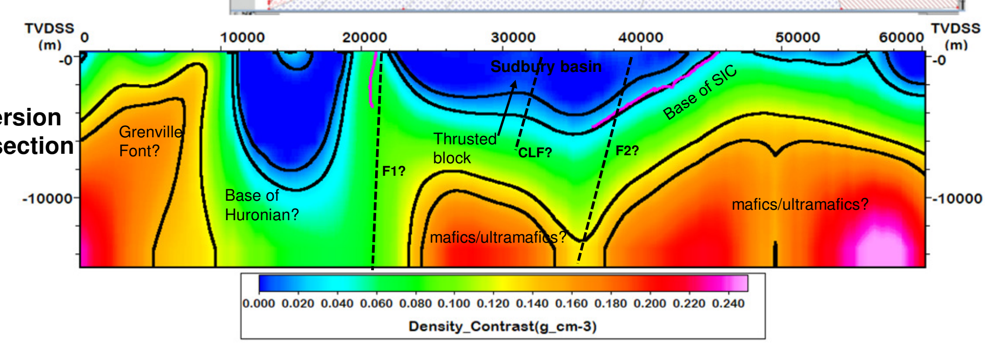
2.5-D Modelling Vs 3-D Inversion cross-section

2.5D Modelling
(Olaniyan et al., 2015)



3D inversion cross-section



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3-D INTEGRATED CROSS-SECTION – SUDBURY TRANSECT

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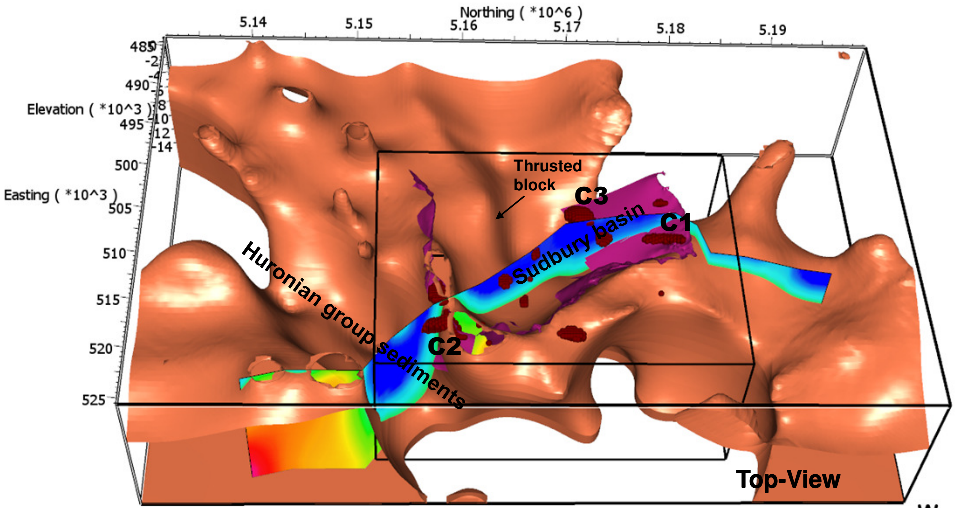

Resistivity (1-100 ohm.m) isovolume
Density Isosurface (>0.06 g/cc)
Shallow Anomalies Investigation

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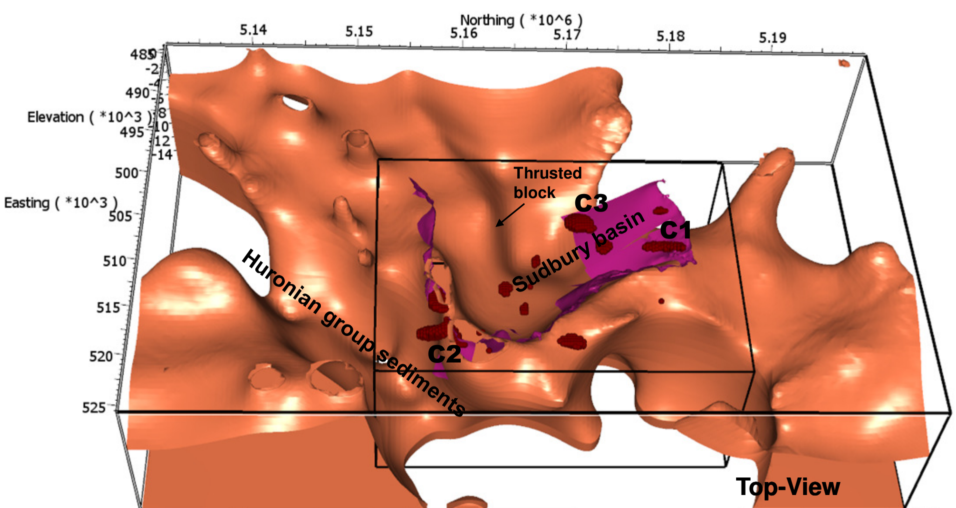

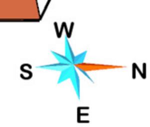

Resistivity (1-100 ohm.m) isovolume
Density Isosurface (>0.06 g/cc)
Shallow Anomalies Investigation

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3-D INTEGRATION OF GEOPHYSICAL MODELS – SUDBURY TRANSECT

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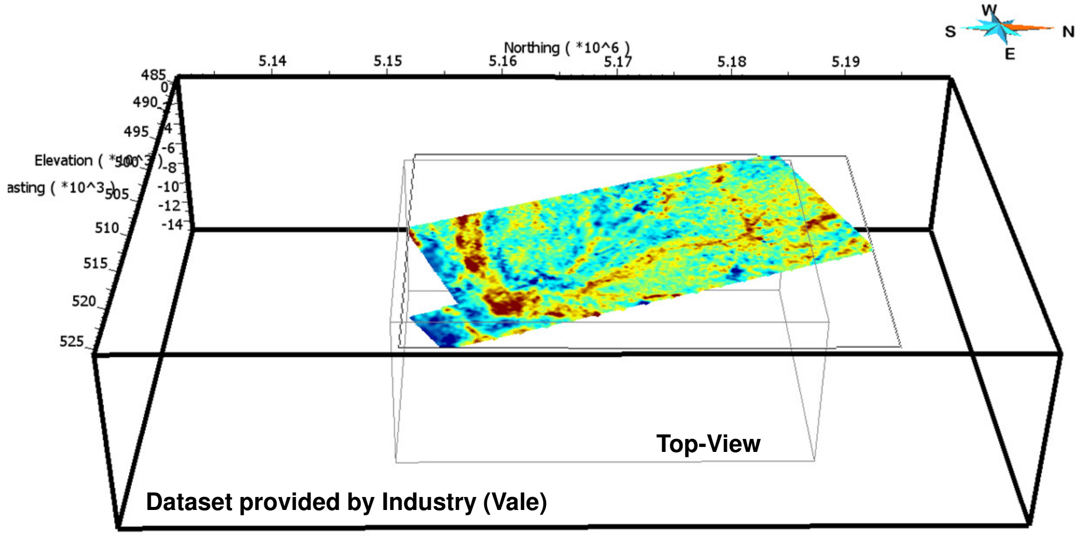
High resolution Gravity Gradiometry dataset (Tzz component)



Shallow Anomalies Investigation

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3-D INTEGRATION OF GEOPHYSICAL MODELS – SUDBURY TRANSECT

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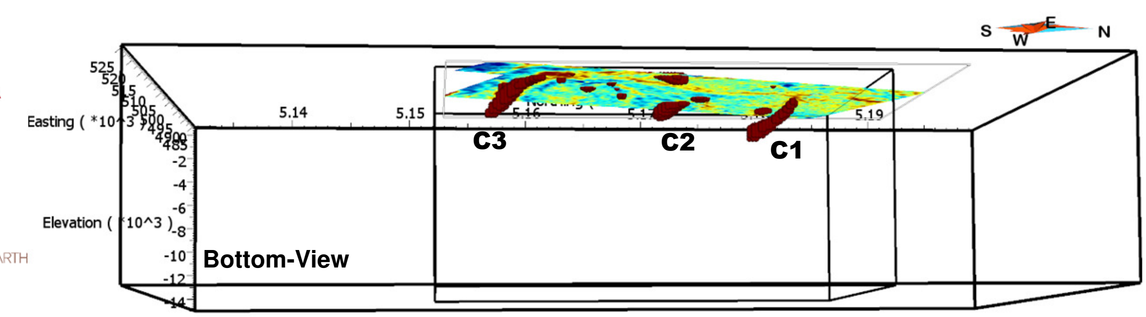
Resistivity (1-100 ohm.m) isovolume



C1, C2 & C3 are conductors

Shallow Anomalies Investigation

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3-D INTEGRATED CROSS-SECTION – SUDBURY TRANSECT

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SUDBURY INTEGRATED NICKEL OPERATIONS

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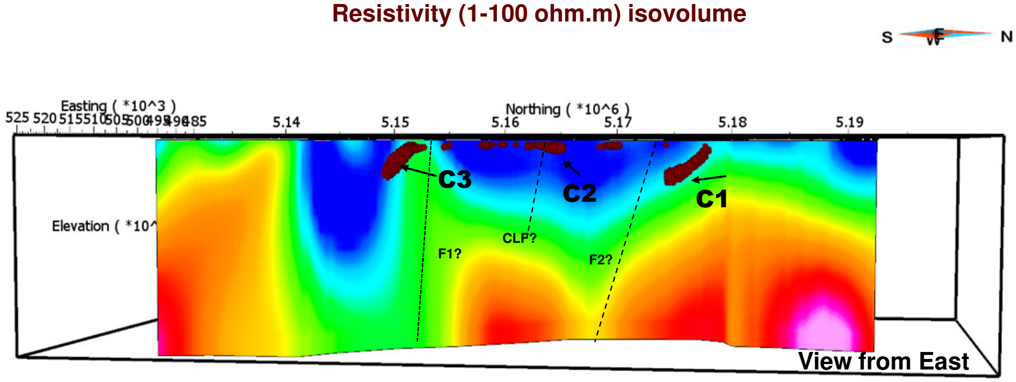
Resistivity (1-100 ohm.m) isovolume



Shallow Anomalies Investigation

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3-D INTEGRATED CROSS-SECTION – SUDBURY TRANSECT

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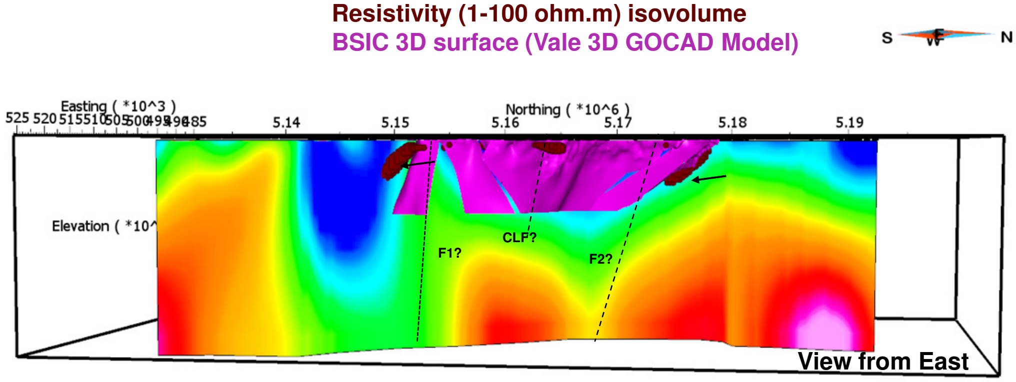
SUDBURY INTEGRATED NICKEL OPERATIONS

MERC

Resistivity (1-100 ohm.m) isovolume
BSIC 3D surface (Vale 3D GOCAD Model)



Contact/footwall type of deposit ?

Shallow Anomalies Investigation

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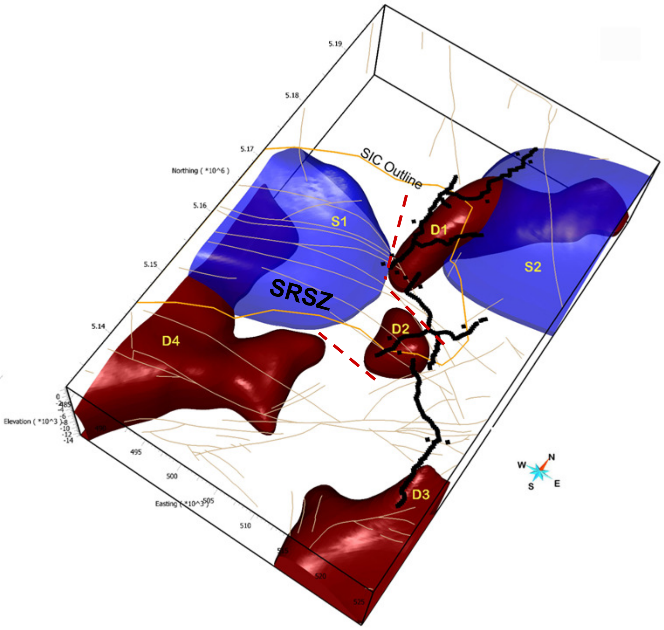
3-D INTEGRATION OF GEOPHYSICAL MODELS – SUDBURY TRANSECT



Red - High density (~0.15 g/cc)
Blue - High susceptibility (>0.035 SI)
Black- Metal Earth Transect
Dashed lines – Interpreted deep seated faults
Regional faults overlaid
SRSZ – South Range Shear Zone

- D1, D2 and D4 are high density bodies that lie exactly below the Sudbury impact structure and might correspond to mafic/ultramafic rocks and are separated by East-West trending faults. D1 appears to be an anticline feature that dips on either side from its central peak that occurs at a depth of ~3 km.
- D3 high density body to the SE might correspond to mafic/ultramafic rocks of Grenville Front Tectonic Zone.
- The blue features, S1 and S2, represent high susceptibility anomalies potentially from deeper magnetic sources that are separated by the NS trending fault

Deeper Anomalies Investigation

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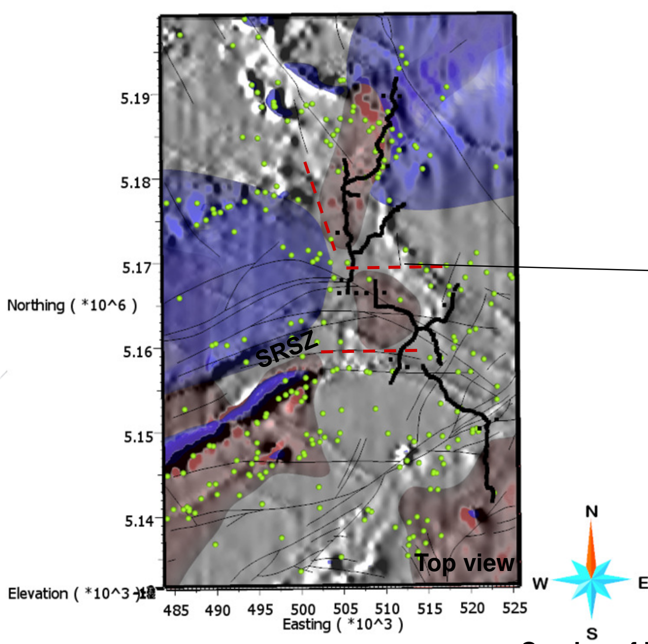
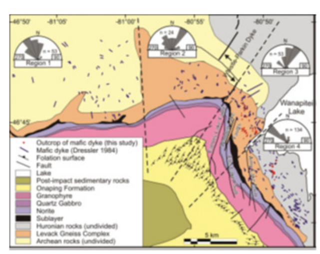
3-D INTEGRATION OF GEOPHYSICAL MODELS – SUDBURY TRANSECT



Red - High density (~0.15 g/cc)
Blue - High susceptibility (>0.035 SI)
Green dots – Mineral occurrences (OGS)
Black Thick Lines - Metal Earth Transect
Black Thin Lines - Regional Faults
SRSZ - South Range Shear Zone
Dashed lines – Interpreted deep seated faults

Folding and/or Faulting below the Sudbury impact structure may have deformed and altered the rocks resulting a change in its magnetic character?

(Clark et al., 2012)



Overlay of Horizontal Derivative magnetic grid

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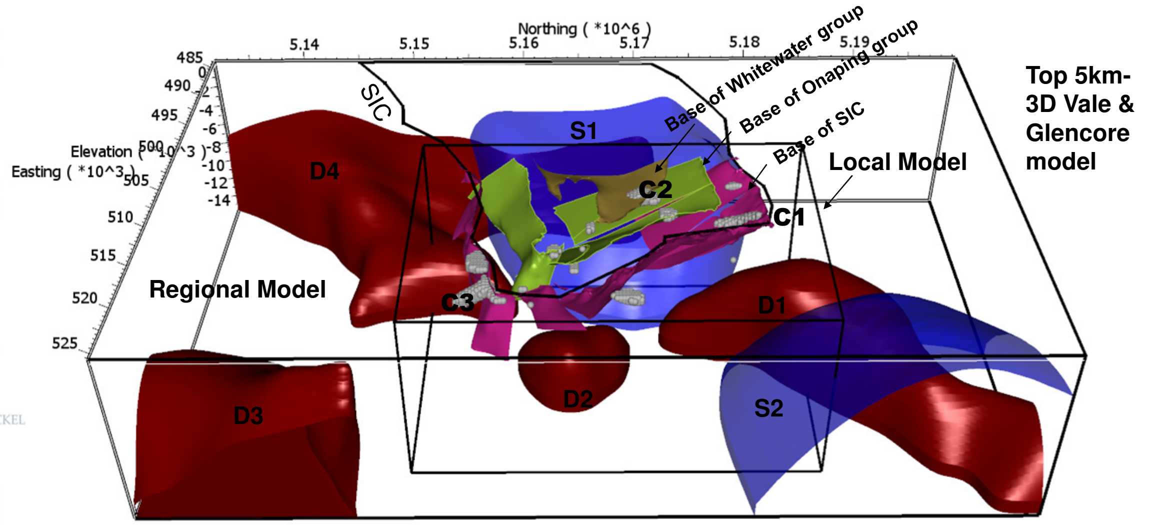
3D INTEGRATED MODEL – SUDBURY TRANSECT

Canad



Red - *High density* (~0.15 g/cc)
Blue - High susceptibility (>0.035 SI)
Borehole constrained Vale 3D surfaces
Grey volumes are conductors

W S N E

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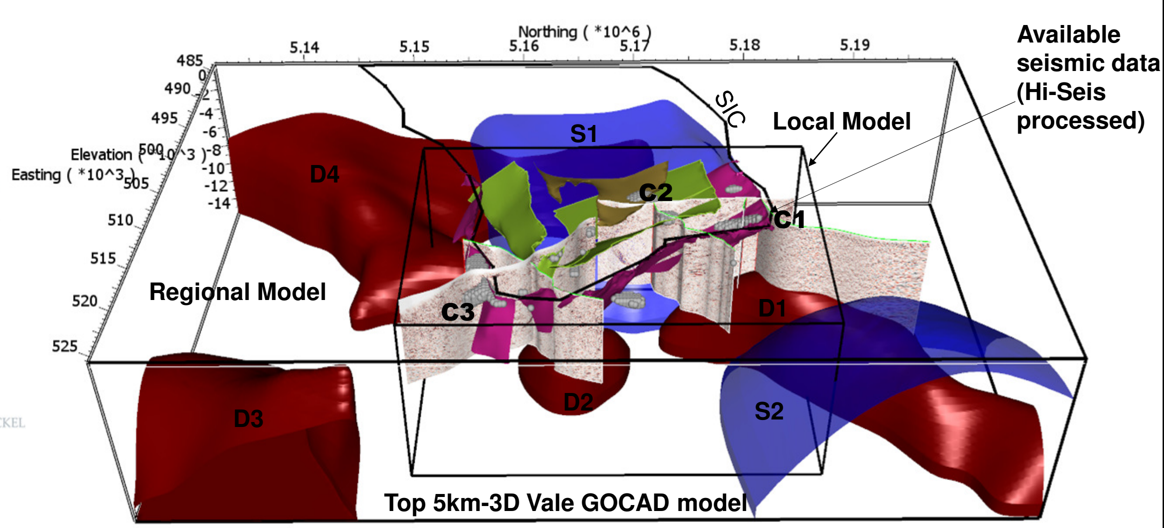
3D INTEGRATED MODEL – SUDBURY TRANSECT

Canad



Red - *High density* (~0.15 g/cc)
Blue - High susceptibility (>0.035 SI)
Colored surfaces are from Vale 3D GOCAD model
White volumes are interpreted conductors C1, C2 & C3

W S N E

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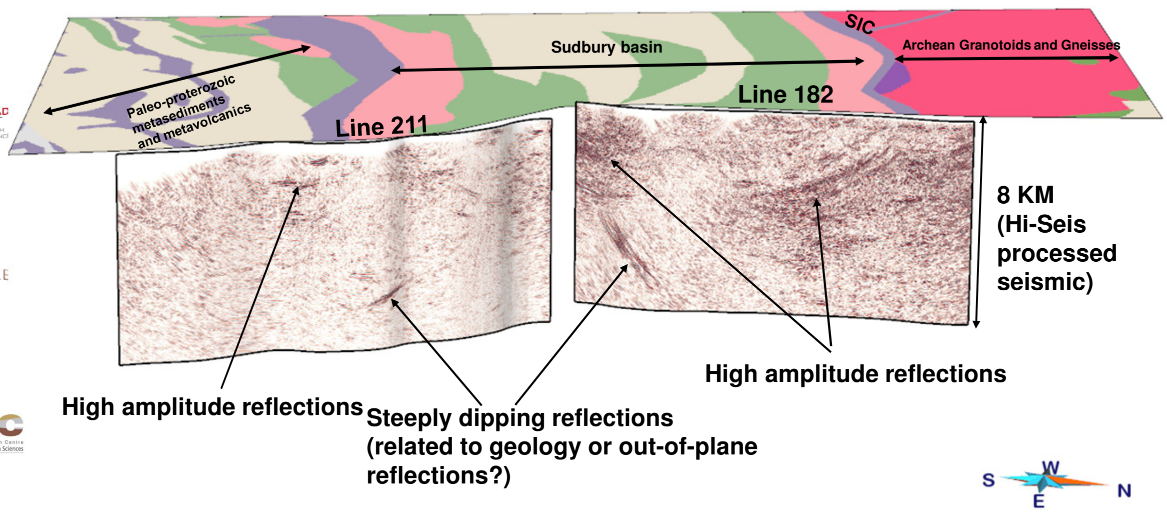
3D INTEGRATED CROSSECTION – SUDBURY TRANSECT



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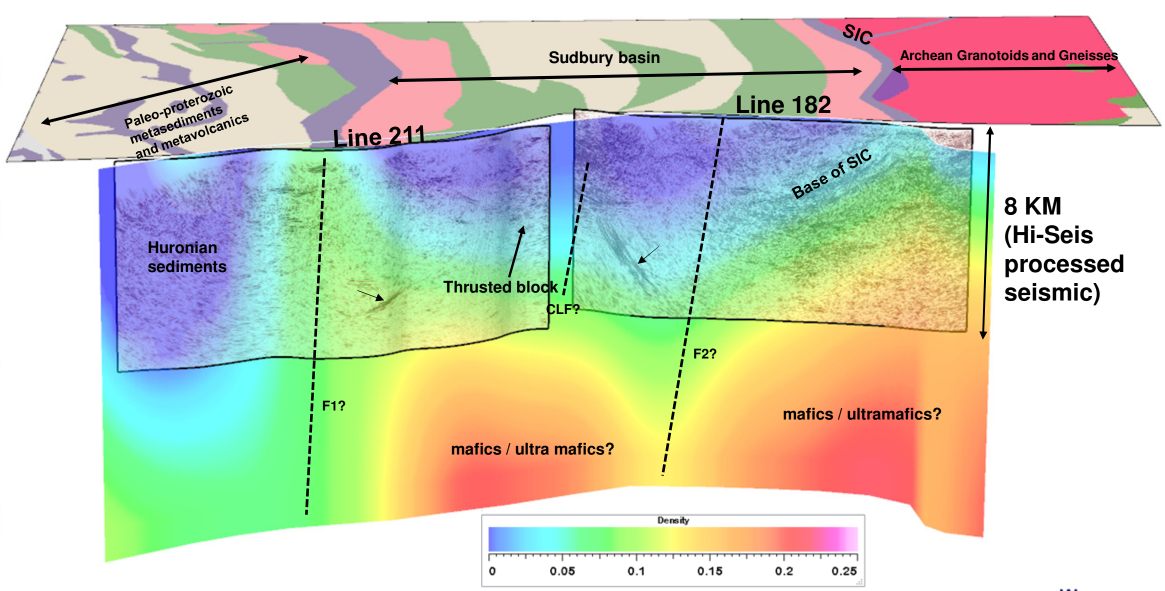
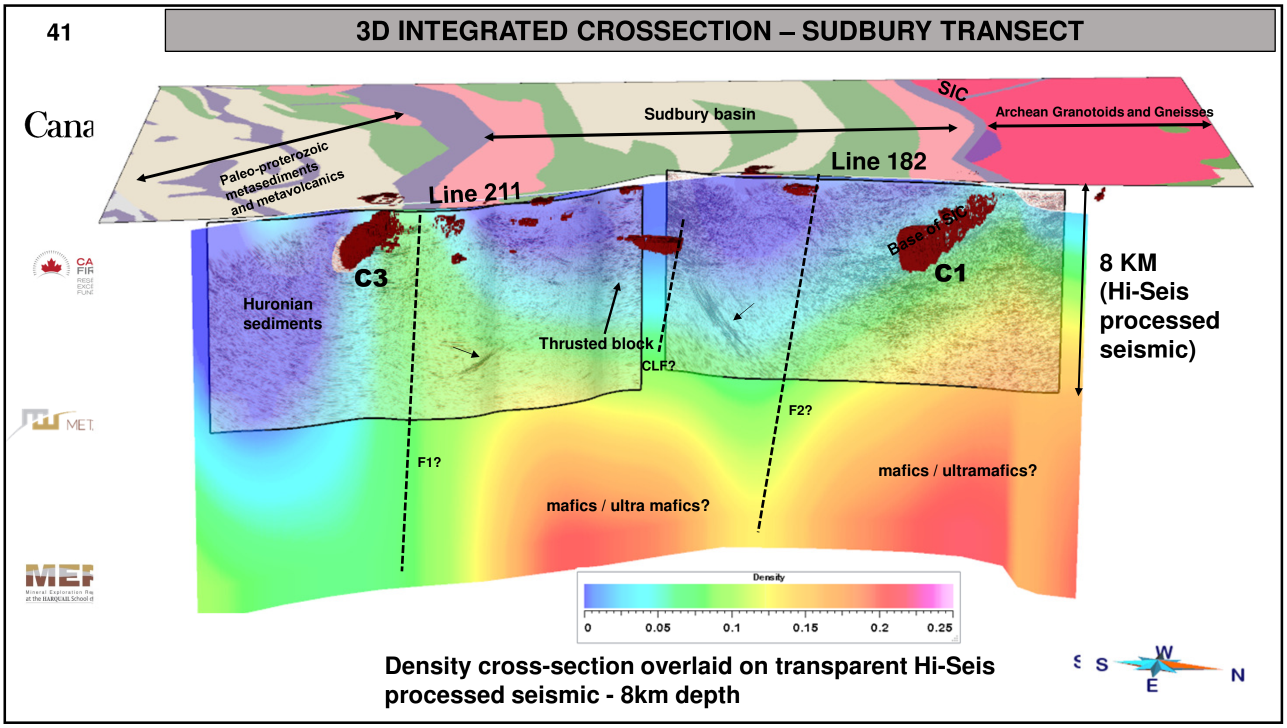
3D INTEGRATED CROSSECTION – SUDBURY TRANSECT



Density cross-section overlaid on transparent Hi-Seis processed seismic - 8km depth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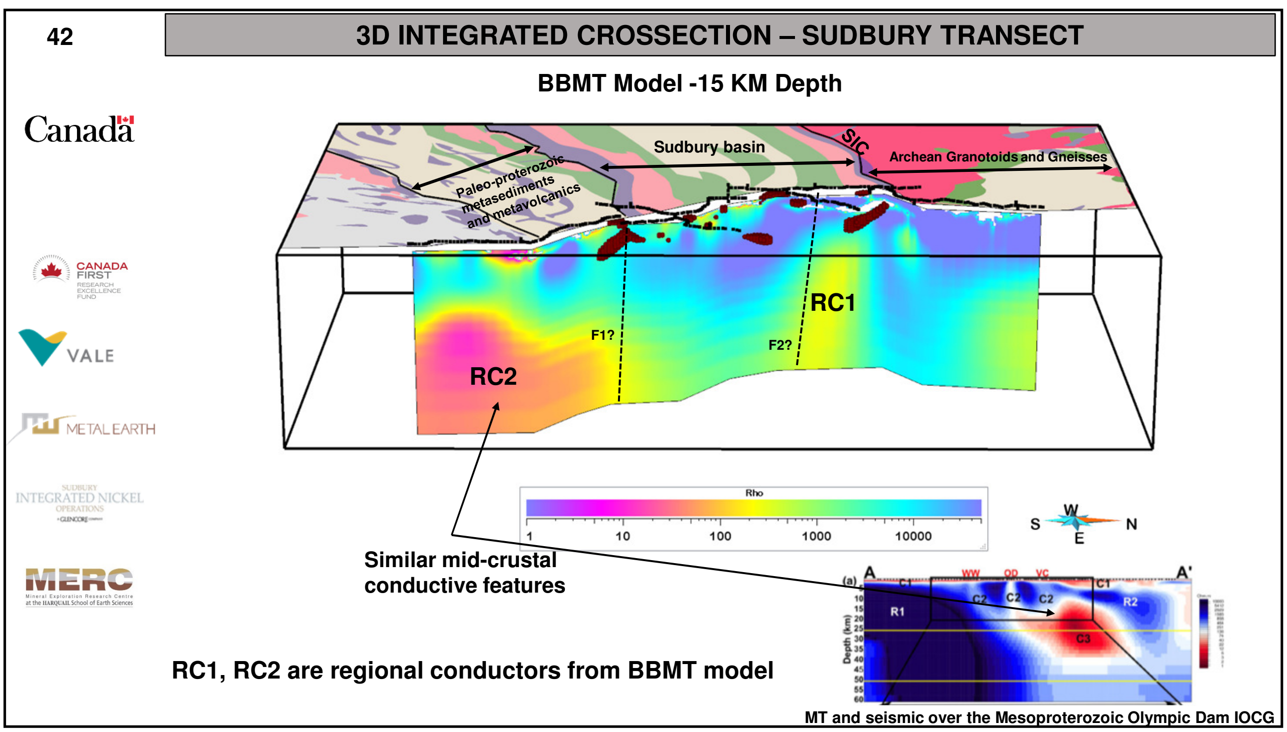
3D INTEGRATED CROSSECTION – SUDBURY TRANSECT
SIC
Sudbury basin
Archean Granotoids and Gneisses
Paleo-proterozoic metasediments and metavolcanics
Line 211
Line 182
Base of SIC
C3
C1
Huronian sediments
Thrusted block
CLF?
F1?
F2?
8 KM (Hi-Seis processed seismic)
mafics / ultra mafics?
mafics / ultramafics?
Density
0 0.05 0.1 0.15 0.2 0.25
Density cross-section overlaid on transparent Hi-Seis processed seismic - 8km depth
S W E N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3D INTEGRATED CROSSECTION – SUDBURY TRANSECT
BBMT Model -15 KM Depth
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Sudbury basin
SIC
Archean Granotoids and Gneisses
Paleo-proterozoic metasediments and metavolcanics
RC1
RC2
F1?
F2?
Rho
1 10 100 1000 10000
S W E N
Similar mid-crustal conductive features
RC1, RC2 are regional conductors from BBMT model
A A'
R1 R2 C1 C2 C3
MT and seismic over the Mesoproterozoic Olympic Dam IOCG

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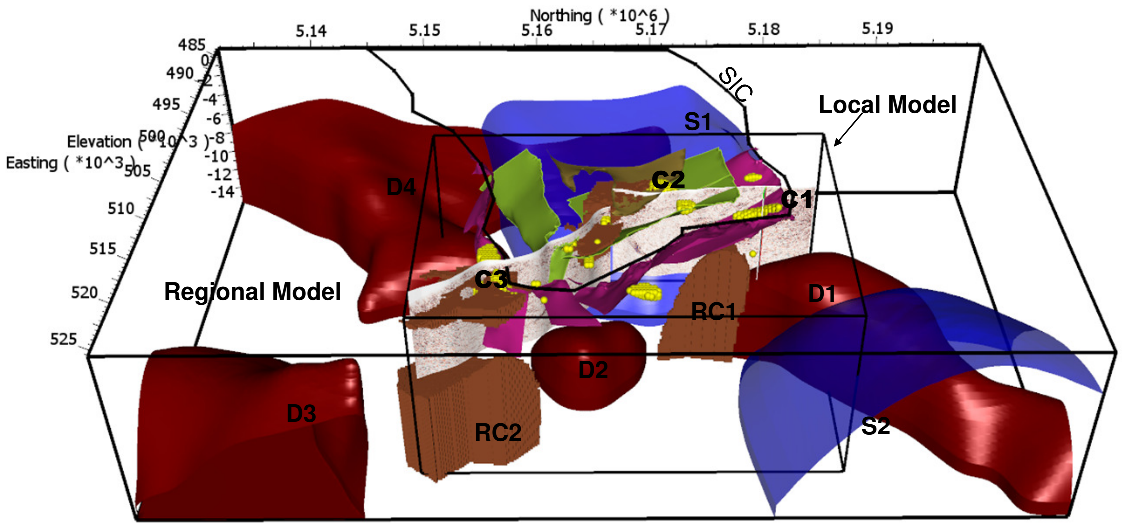
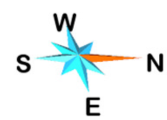
FINAL 3D INTEGRATED MODEL – SUDBURY TRANSECT



Red - High density (>0.15 g/cc)
Blue - High susceptibility (>0.035 SI)
Colored surfaces are from Vale 3D GOCAD model
Yellow volumes (1-100 ohm.m) are interpreted conductors C1, C2 & C3 from AMT model
Light brown volumes(1- 500 ohm.m) are regional conductors RC1, RC2 from MT model



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SUMMARY OF FINDINGS & RECOMMENDATIONS – SUDBURY TRANSECT

Findings:

- We have observed a **good correlation between various geophysical models and geological datasets**
- We identified three probable shallow conductors from AMT model :- **High confidence (based on dense AMT dataset) conductor C1 and C3** near the North-Range and South-Range proximal to the basal contact of SIC and one moderate to low confidence conductor: **C2 within Whitewater group of sediments.**
- We identified two probable mid-crustal level conductors **RC1 and RC2** from **BBMT model** which **might act as additional sources** for shallow conductors **C1 and C3**.
- The potential field inversions provide geophysical evidence of **folding and/or faulting of mafic/ultramafic rocks** in the Archean basement and suggest this deformation may have resulted in **alteration and weaker magnetic and gravity fields** in the East Range.
- High resolution seismic images **also support this deep-seated faulting.**
- We suggest this **deep-seated faulting could have acted as conduits for hydrothermal fluid flow** from deep crustal conductors to shallow conductors thus enhancing the locus of mineralization in the SIC footwall.
- Some of the preliminary findings of this project were **presented at a International conference CSEG Geoconvention (Sept, 2021) and two scientific publications** are in preparation to be submitted to International Journals**.**

Recommendations:

- Constraining the Vale 3D GOCAD surfaces using new available seismic data
- Construct a robust **3D geological model of upper-crust of Eastern Sudbury basin** which will honour all geological and geophysical datasets and help in **constraining geometry of new subsurface structures associated with mineralized (Ni, PGE and Cu) zones**.
- The constrained 3D geological model helps to **identify new sources of mineralization** and **pathways**

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- **Hi-Seis Processed Seismic Dataset**
- **Gravity Gradiometry Dataset**
- **3D GOCAD Model Surfaces**

Provided by Vale

- **Metal Earth Team**
- **Vale & Glencore Team**

Helpful discussions

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- **Seequent (Geosoft Oasis Montaj)**
- **Pouran Behnia (GIS Support)**

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