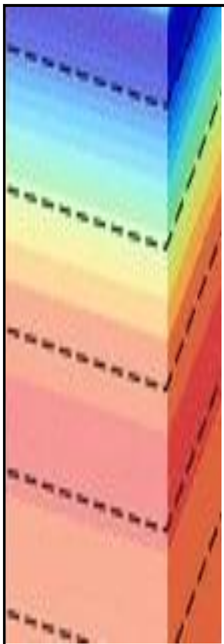

Conductivity footprints of the world class gold districts in the Red Lake and Timmins, Canada

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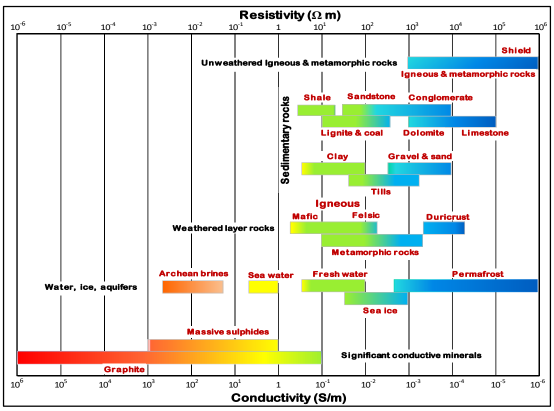
Introduction to the MT method

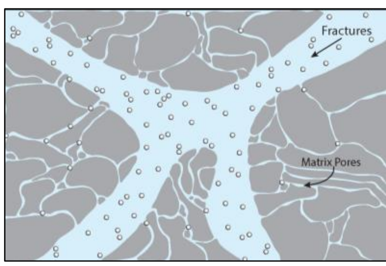
Property: electrical conductivity



modified from Palacky, 1988

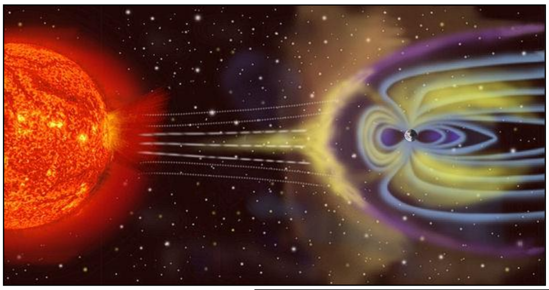
High conductivity (low resistivity) can be caused by large scale interconnected networks of:

- **Fluids**
- **Ores**
- **Melts**
- **Graphite**
- **Sulphide**



Source of Natural Electromagnetic Fields

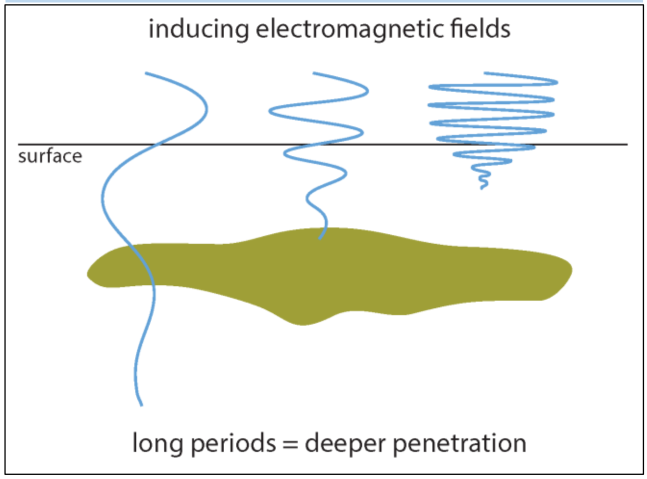
- Complex interaction between solar plasma (wind) and Earth's magnetosphere
- Long period (< 1 Hz or > 1 s)



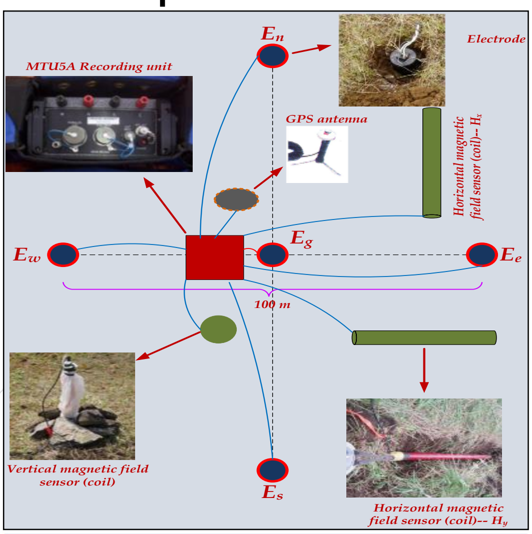
- Lightning
- Short Period (> 1 Hz or < 1 s)

Electromagnetic Induction into the Earth

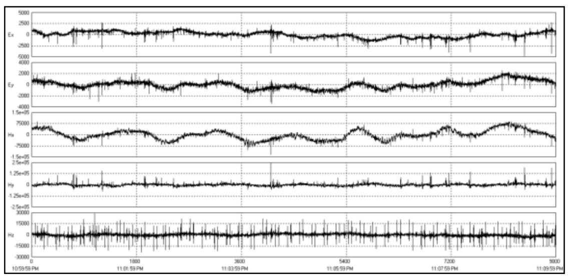
- The sounding depth depends on the subsurface conductivity and the frequency contents of the induced fields (skin effect).



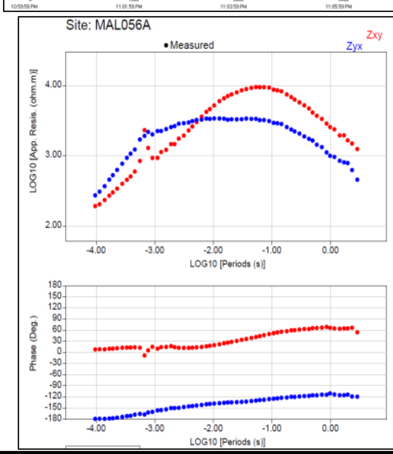
Field setup and Measurements



- Time variations of Electric (E) and magnetic (H) fields are recorded by electrodes and coils
- [E_x(t) , E_y(t), H_x (t) , H_y (t), H_z (t)]



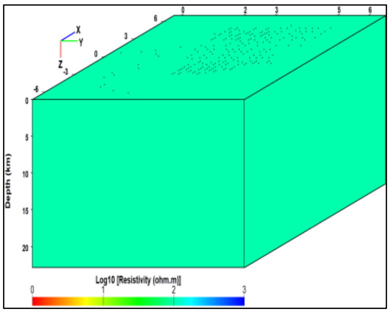
Time series for E and H



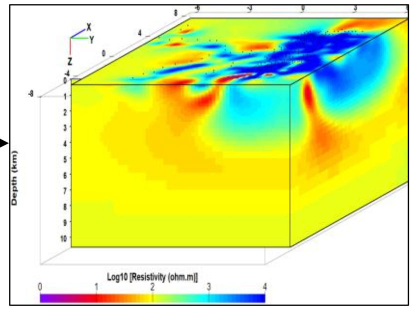
The "true" conductivity distribution of the subsurface is found by modelling and inversion

General concept of Inversion

Data space



Model space



Inversion

minimization of the objective functions

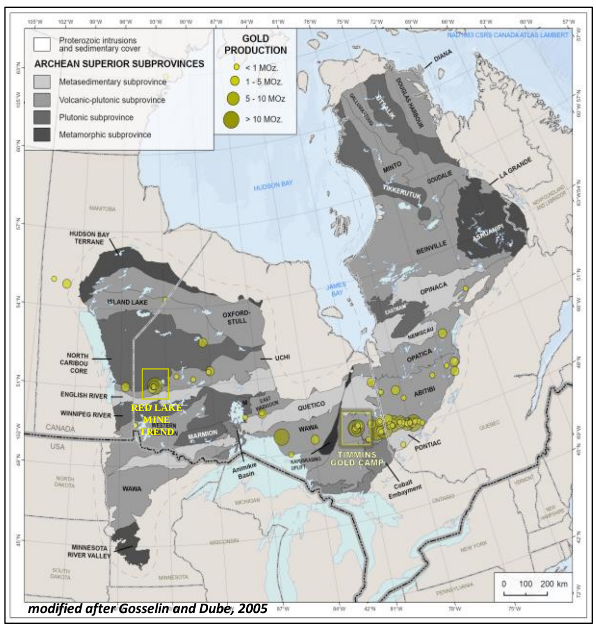
$$\varphi = \varphi_d + \lambda_{\varphi m}$$

Data misfit term   Constraint term

- **3D Inversion - Modular EM (ModEM) code by Egbert and Kelbert, 2012 and Kelbert et al., 2014**
- **Data preparation and visualization - 3D_Grid (Meqbel, 2017)**

General Objectives

- **The Metal Earth objective is to understand factors responsible for the differential metal endowment in the Archean greenstone belts**
  - *Geological and geophysical signatures*
  - *Fault geometry*
  - *Crustal architecture*
  - *Tectonic/geodynamic history*
- **MT will contribute by delineating crustal conductivity structures**
  - Constrain source and pathways of mineralized fluids
- **Provide tectonic/geodynamic explanation for the structures with constraint from other methods**
  - Improve the understanding of the mineral systems in the greenstone belts
- **MT study across world-class Au districts**
  - **Red Lake- produced >29.6 Moz Au**
  - **Timmins - produced >76.8 Moz Au**



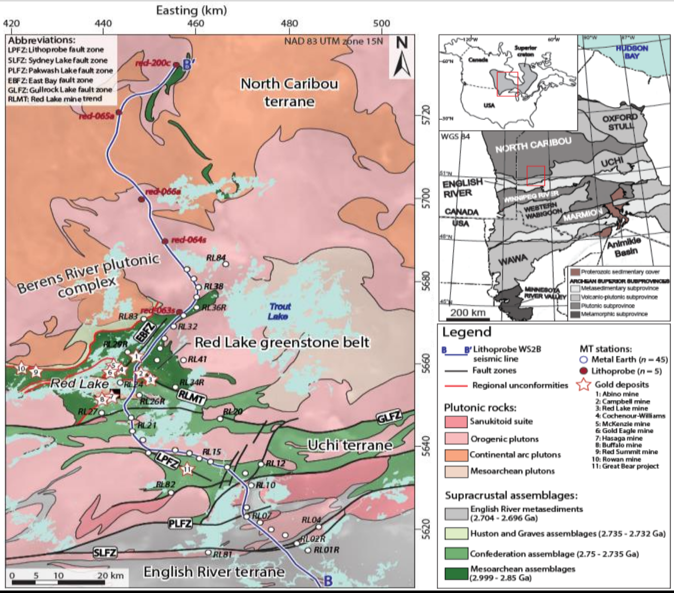
modified after Gosselin and Dube, 2005

Geology: (2023) https/doi/10.1130/G50660.1

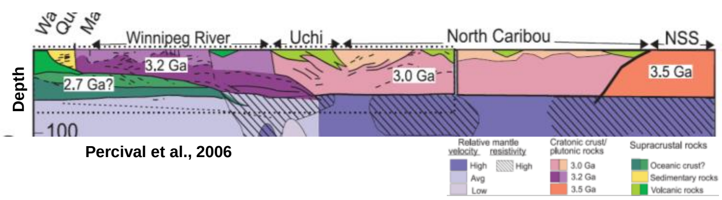
Crustal conductivity footprint of the orogenic gold district in the Red Lake greenstone belt, western Superior craton, Canada

Ademola Q. Adetunji, Gaëtan Launay, Ian Ferguson, Jack M. Simmons, Chong Ma, John Ayer, and Bruno Lafrance

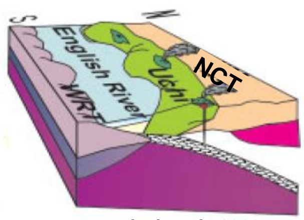
- **Uchi terrane is a Meso-Neoarchean fault-bound greenstone belt of metavolcanics, metasedimentary and plutonic rocks**
- **It hosts multiple orogenic Au deposits - the largest deposits are within the Red Lake greenstone belt which has produced >29.6 Moz**
- **The Cochenour and Campbell-Red Lake deposits are among the largest and richest Archean gold deposits in Canada**
- **Investigated with 50 magnetotelluric (MT) stations - roughly along Lithoprobe WS2B Seismic line**



Geologic and Tectonic setting



Percival et al., 2006



Percival et al., 2006

ca. 2.698 - Amalgamation of WRT with Uchi-NCT and Crustal extension

Post-collisional D_3 strain occurred after 2.70 Ga, overprinting and reactivating earlier structures

Late-stage Au mineralization associated with D_3 strain and metamorphism

Main-stage Au mineralization associated with D_2, occurred before 2.712 Ga
- **includes the largest deposits in the Red Lake mine trend**

D_2 deformation produced the main penetrative structures

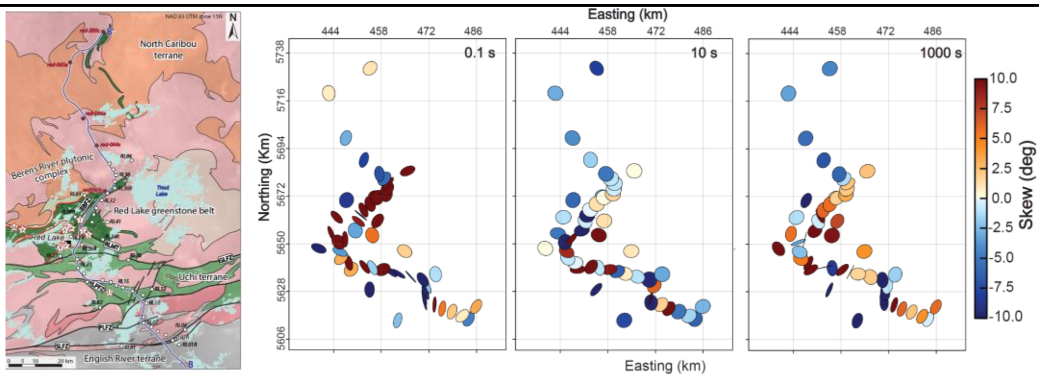
Reactivation of D_1 fabrics and metamorphism
Emplacement of post-tectonic plutons

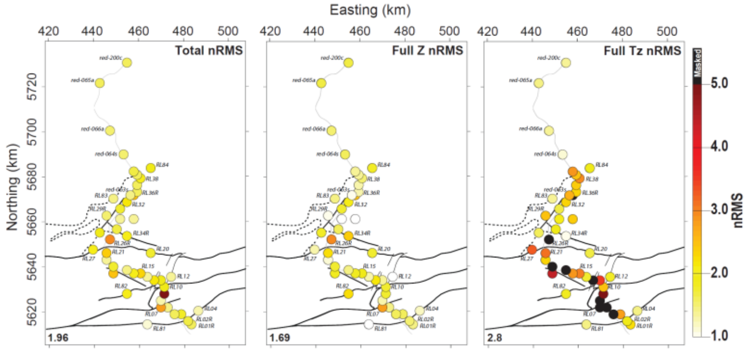
Shear zones formed during D_2 and D_3

ca. 2.72 - 2.70 Ga Kenoran orogeny
- Convergence between NCT and southern terranes
- Thrusting of WRT under the NCT

2.99 - 2.695 Ga - Tectonic events recorded by Uchi terrane, NCT and Berens River plutonic complex

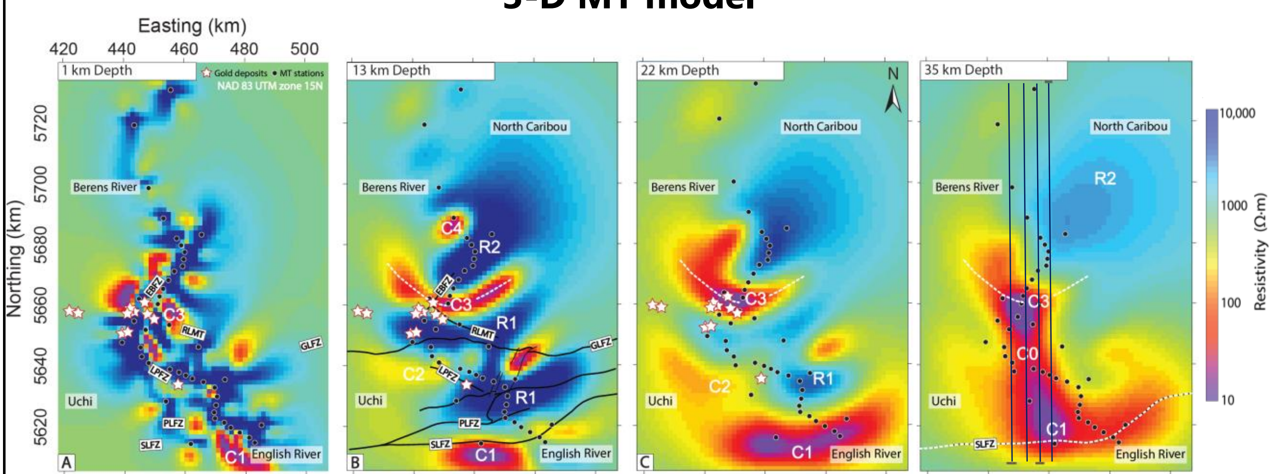
MT data



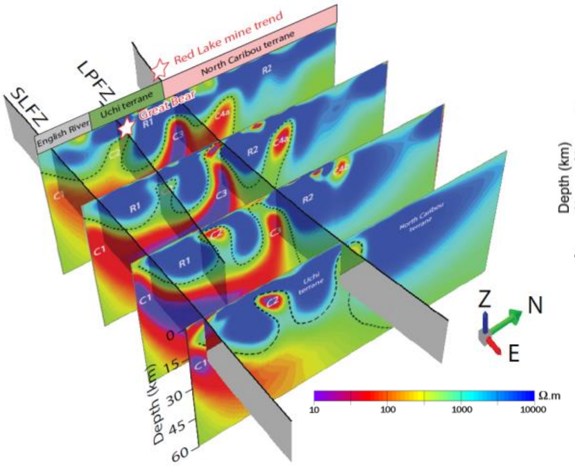


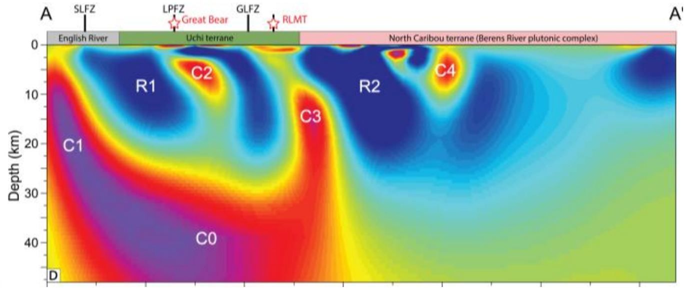
- ModEM
- 5% error on impedances components and 0.03 on the tipper.
- nRMS of 1.96 after 118 iterations
- Many additional inversions, sensitivity, and resolution tests

3-D MT model



- Resistivity model defines a generally resistive 2,000–10,000 Ω.m upper crust - R1 and R2
- Upper crust beneath Red Lake mine trend is resistive with some parts having >20,000 Ω.m
- Shallow crust in the Berens River plutonic complex contains several localized conductors (C4)
- C1, C2, and C3 are large-scale subvertical conductivity anomalies.
- The lower crust of the NCT is less resistive (with <1000 Ω.m) than the upper crust

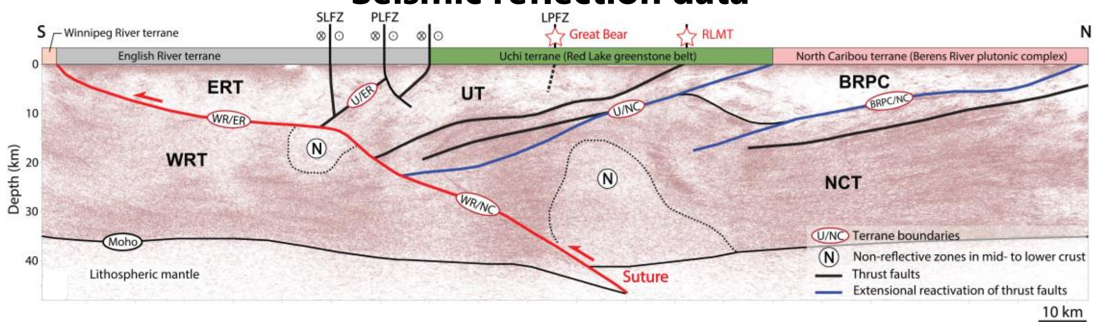


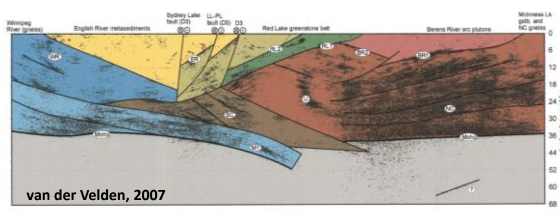


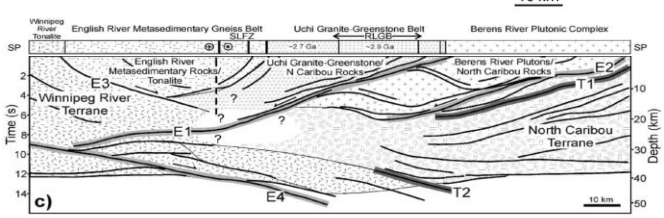
- **C0 - laterally extensive north-dipping conductor (<20 Ω.m), with its top at 20-25 km depth**
- **C1, C2, and C3 are large-scale subvertical conductivity anomalies.**

- **C0 is a large-scale middle- to lower- crustal depths conductor**
- **C1 aligns with the boundary between WRT and ERT and connects with C0**
- **C2 is well resolved and coincides with the Great Bear deposit and might be connected to C0**
- **C3 lies directly below the Red Lake mine trend with its top at 10 km and extending to depths >15 km, is consistently imaged as a subvertical feature, and most likely connects with C0.**

Seismic reflection data



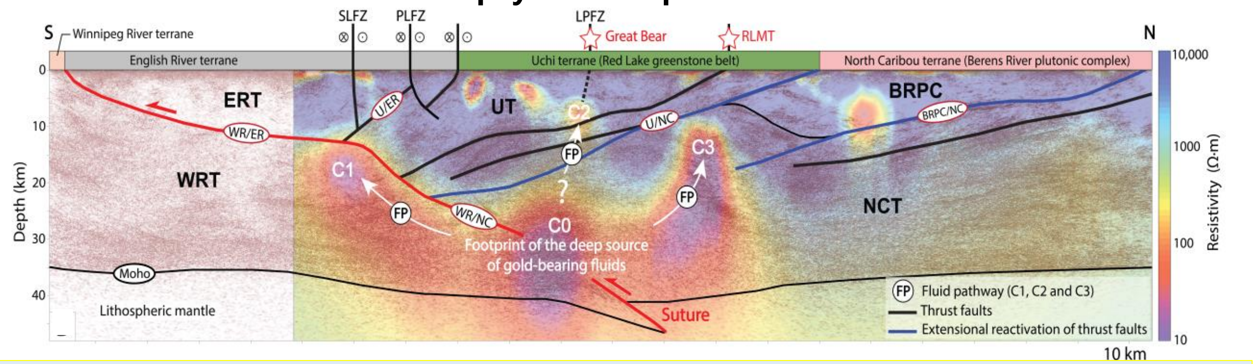




- **Shear zones beneath the Red Lake mine trend have moderate dips to the south with varying interpretations**

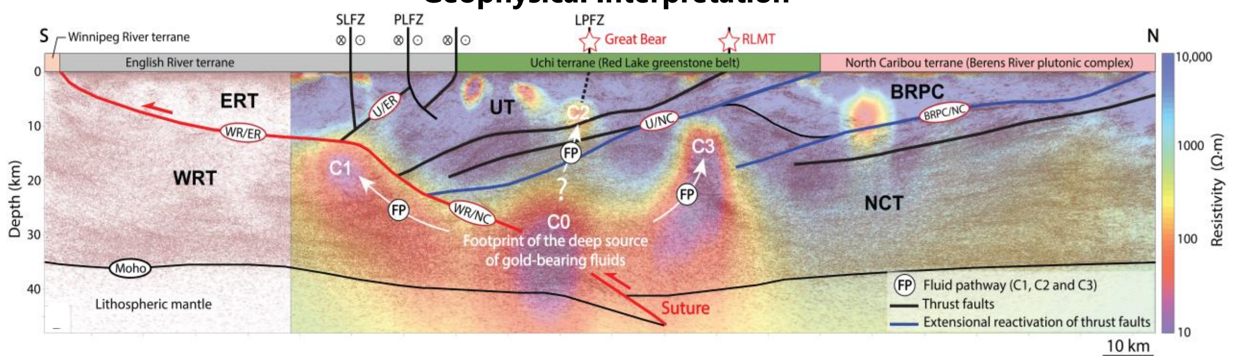
- **Overall interpretation provides evidence for northward subduction of WRT under NCT**

Geophysical Interpretation

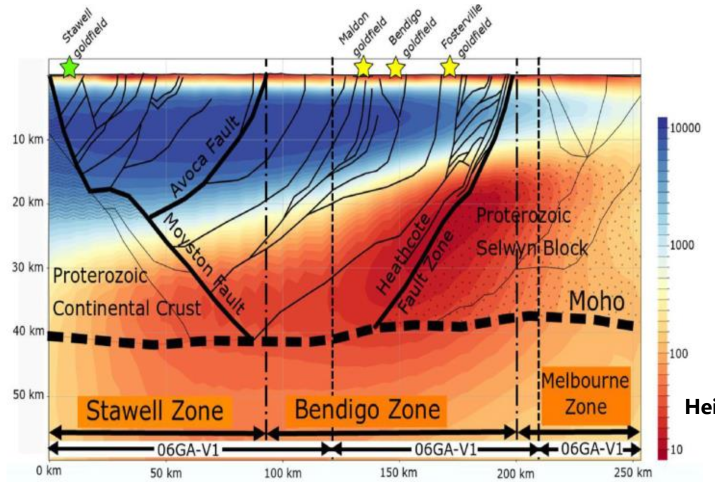


- **Crustal-scale conductor C1 coincides with significant north-dipping seismic reflections, which extend into the mantle interpreted to represent the suture associated with attempted subduction of the WRT under the NCT**
- **The geometry of C1 is consistent with subduction-related devolatilization and transport of fluids along the subducting plate**
- **Conductors C2 and C3 represent possible fluid pathways beneath major Au deposits in the RLGB**
- **Both resistivity and seismic results at depths >10–15 km are thus consistent with fluid transport along a steep fault system**

Geophysical Interpretation



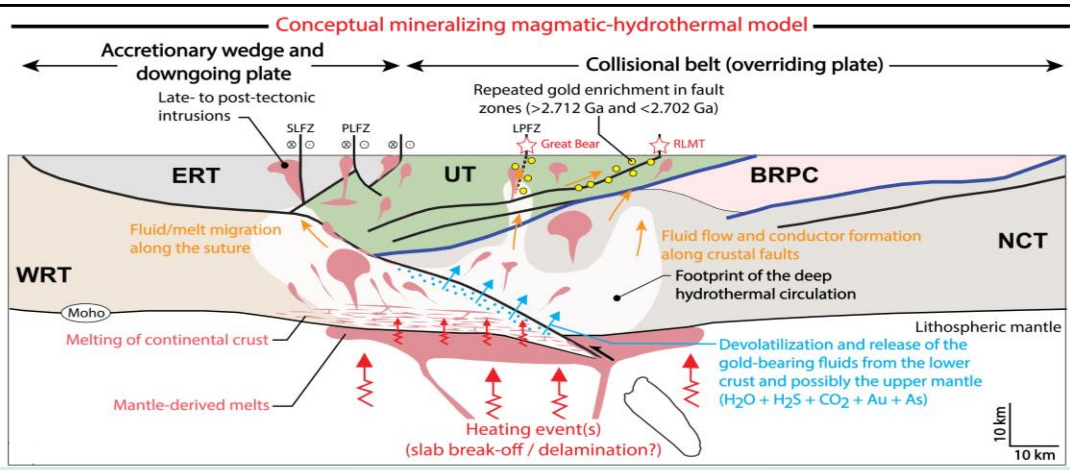
- **Conductors C0 and C1 are coeval with the formation of the suture between the NCT and WRT**
- **Their interpretation as the source region for CO_2- and Au-rich fluids and as fluid pathways for the main-phase RLGB mineralization requires them to have formed prior to 2.712 Ga**
- **Incomplete connection of C2 and C3 to the deposits and the resistive crust beneath the Red Lake mine trend suggests:**
  - **Localized late overprinting of the fluid pathways affected by intrusion of late- to post-orogenic granites**
  - **Thermal processes during the peak metamorphism associated with the intrusions,**
  - **Development of extensional tectonic structures.**



Deep crustal origin of the orogenic gold deposit in south-eastern Australia constrained by MT

Heinson et al., 2021

- **Heinson et al. (2021) interpreted a <20 Ω·m resistivity zone at >20 km depth beneath the Lachlan orogenic gold field in southeastern Australia as the source region for gold-rich fluids**
- **Fluids attributed to reactions in carbon- and pyrite-rich sedimentary rocks under amphibolite conditions at ~550ºC**
  - **Production of Au-rich fluids**
  - **Formation of flake graphite at grain boundaries**



- **Fluid-pathway conductors are interpreted to be iron sulfides and/or graphite produced by hydrothermal interaction of mineralizing fluids with surrounding rocks**
- **Enhanced conductivity of the fluid source region is attributed to interconnected graphite and/or sulfides**
- **Source region was formed as a result of metamorphic devolatilization of subducted supracrustal rocks**
- **Later large-scale tectonic deformation involved reactivation of existing structures**
- **Interconnected sulfide and/or graphite may have remained in shear zones during reactivation or even become more efficiently connected, preserving the signature of earlier fluid transport**

Conclusions

- **Tectonomagmatic processes during the RLGB Au mineralization were related to convergence between the WRT and the Uchi–North Caribou terranes, cessation of subduction, and delamination/slab break-off events**
- **The conductors beneath the study area are interpreted to represent the conductivity signature of altered rocks and structures associated with the orogenic gold system in the RLGB formed during the last major tectonic events**
- **Formation of a the large-scale lower crustal conductor beneath the RLGB and ERT would have required relatively widespread heat in order to have produced the temperatures required for**
  - **development of graphite flakes**
  - **granulite facies metamorphism needed to produce the CO_2- and Au-rich fluids.**
- **The required heat may have resulted from slab break-off or delamination of the subducted WRT**
- **Crustal heating could have also resulted from southward migration of subduction and the interaction of subduction zone–derived melts with the overlying crust**

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- **Extensional tectonics associated with orogenic collapse at ca. 2.7 Ga may have been responsible for both crustal heating and the late-stage Au mineralization**
- **The MT results do not preclude a moderately conductive zone in the mantle, so the data cannot exclude a mantle contribution. However, the large mid- to lower-crustal conductor is a more likely source for the majority of the fluids**
- **It is also possible that the middle to lower crust beneath the RLGB was previously enriched in Au-rich sulfides by mantle-derived fluids creating the source for the mineralization**
- **Observation of a large subduction-related conductor (C1) and the capability of the devolatilization process of supracrustal rocks to provide the necessary Au, S, and fluids for the mineral system provide strong support for the role of subducted supracrustal rocks**

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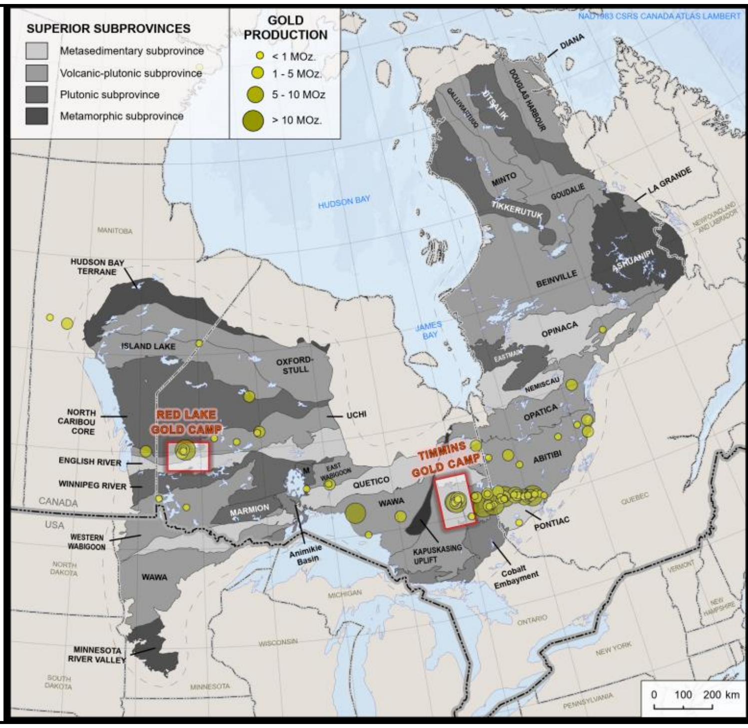
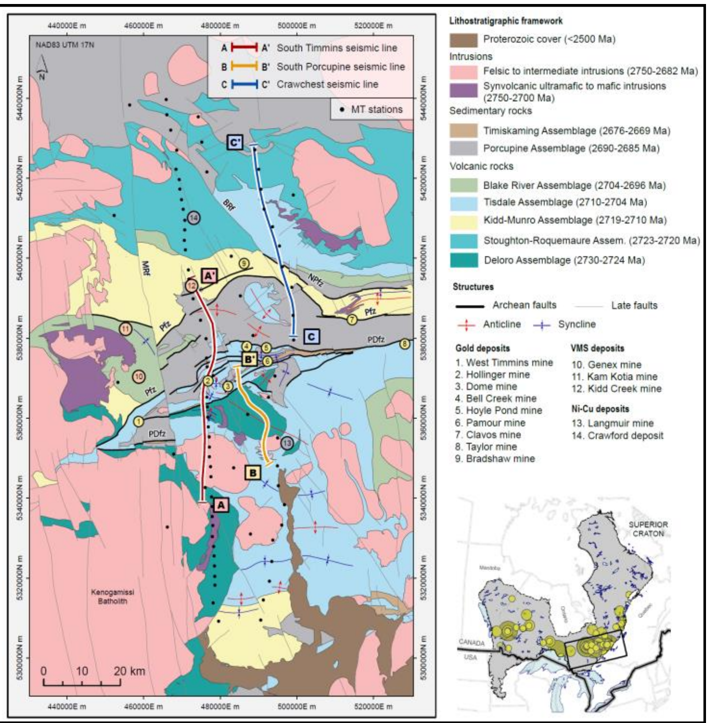


Timmins

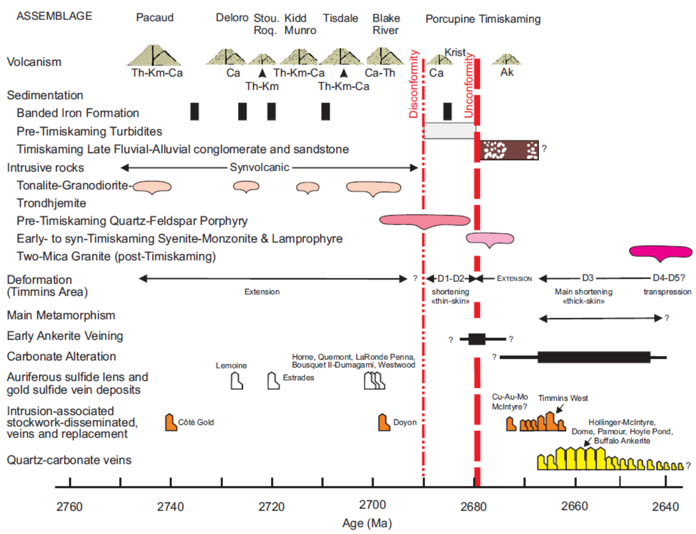
- **Abitibi greenstone belt hosts the world's largest Archean orogenic gold camp (Timmins-Porcupine gold camp)**
  - **>2,190 metric tons gold**
- **Well endowed with base metals**
  - **world-class Kidd Creek VMS deposit**
  - **multiple Ni-Cu-PGE deposits associated with komatiite and mafic-ultramafic intrusion**
- **80 MT stations - along Discover Abitibi Seismic lines**
  - **Crustal architecture**
  - **Conductive corridors/faults/shear zones**
  - **Alterations footprints**



Modified from Ayer et al,2005; Montsion et al., 2018

Geology

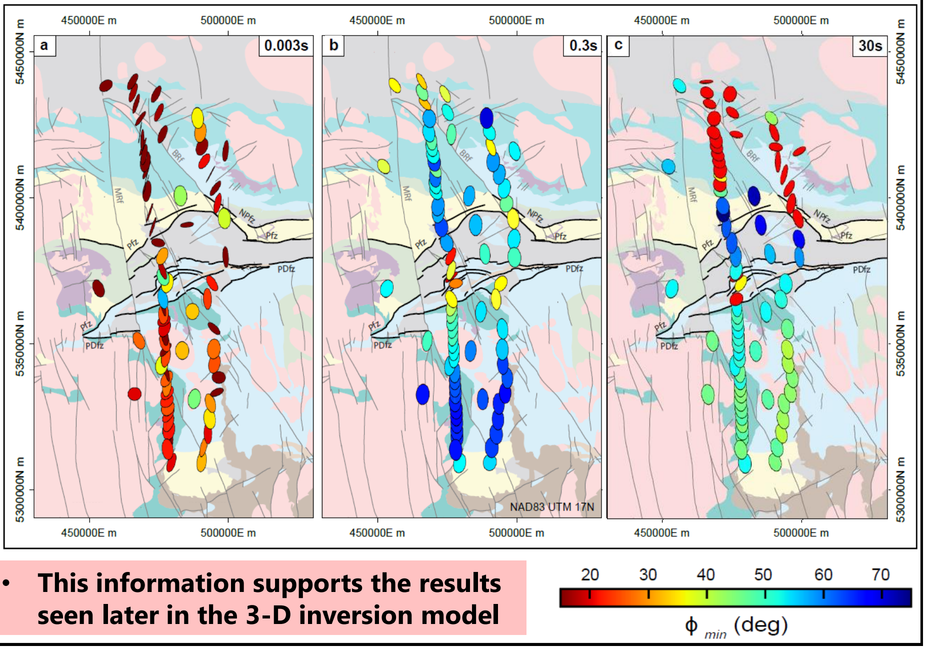
- **D_1 - D_2 --- 2685 - 2679 Ma**
  - **Thin skinned folding and thrusting**
  - **Pipestone deformation zone**
  - **Uplift of pre-Timmiskamin assemblages**
- **Syn-orogenic extension**
- **D_3 --- ca 2660-2640 Ma**
  - **Main regional shortening**
  - **Main phase of Au mineralization**
- **D_4 ---- constrained to Porcupine-Destor**
- **The world-class deposits occur along the Porcupine-Destor and Pipestone deformation zones**



Geologic and metallogenic timeline diagram for southern Abitibi greenstone belt (Dubé et al., 2020)

Phase Tensor responses

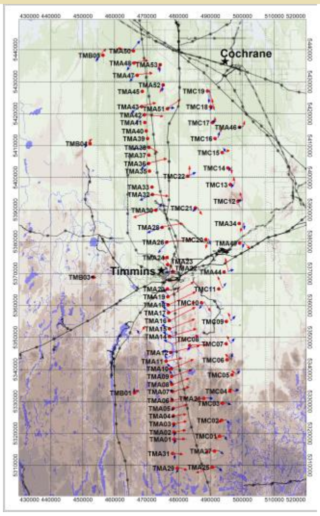
- **0.003 s - strong NW-SE fabric that appear parallel to the BRF-crustal rocks**
- **0.3 s - increased conductivity at intermediate depth in the deformation zones and Porcupine metasedimentary rocks**
- **30 s - increased conductivity at depth associated with the PDdz. It also highlights the deep conductors in the north of the NPdz**

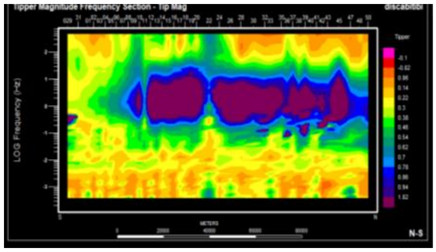


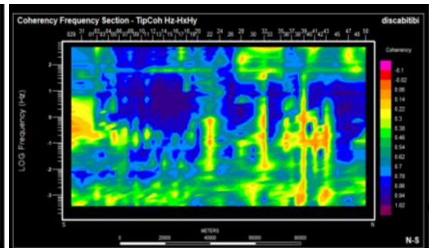
- **This information supports the results seen later in the 3-D inversion model**

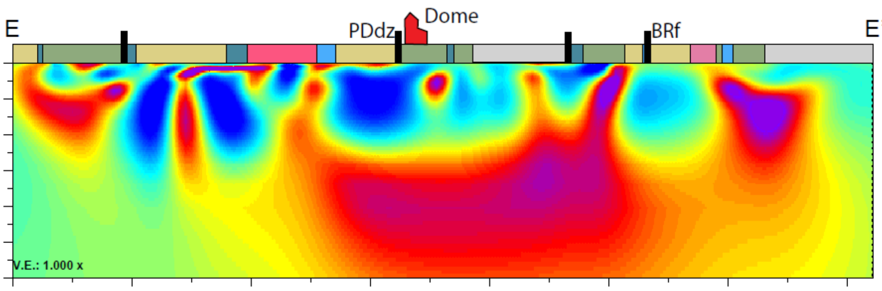
Data and Modelling

- High Tipper magnitude and artificially high coherences at locations where noise > signal magnitude

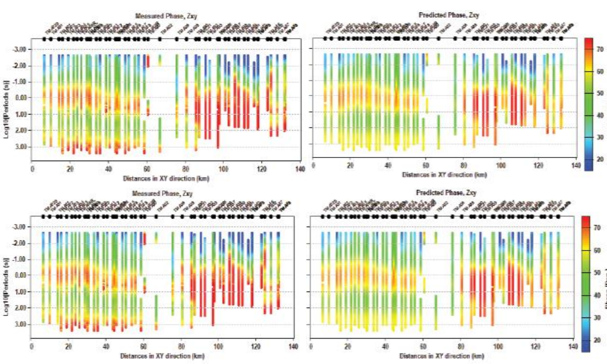


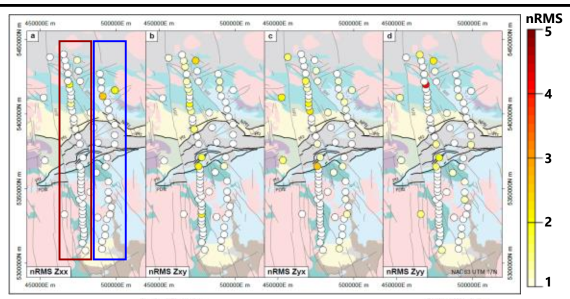


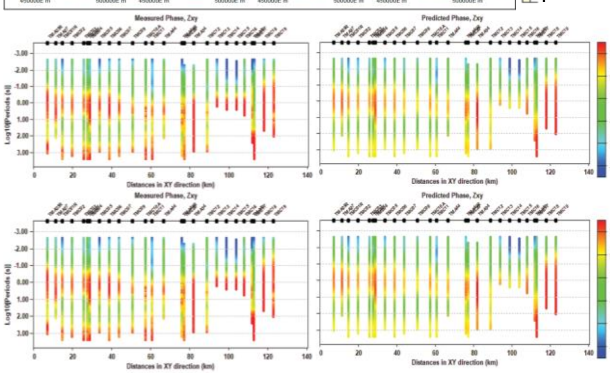


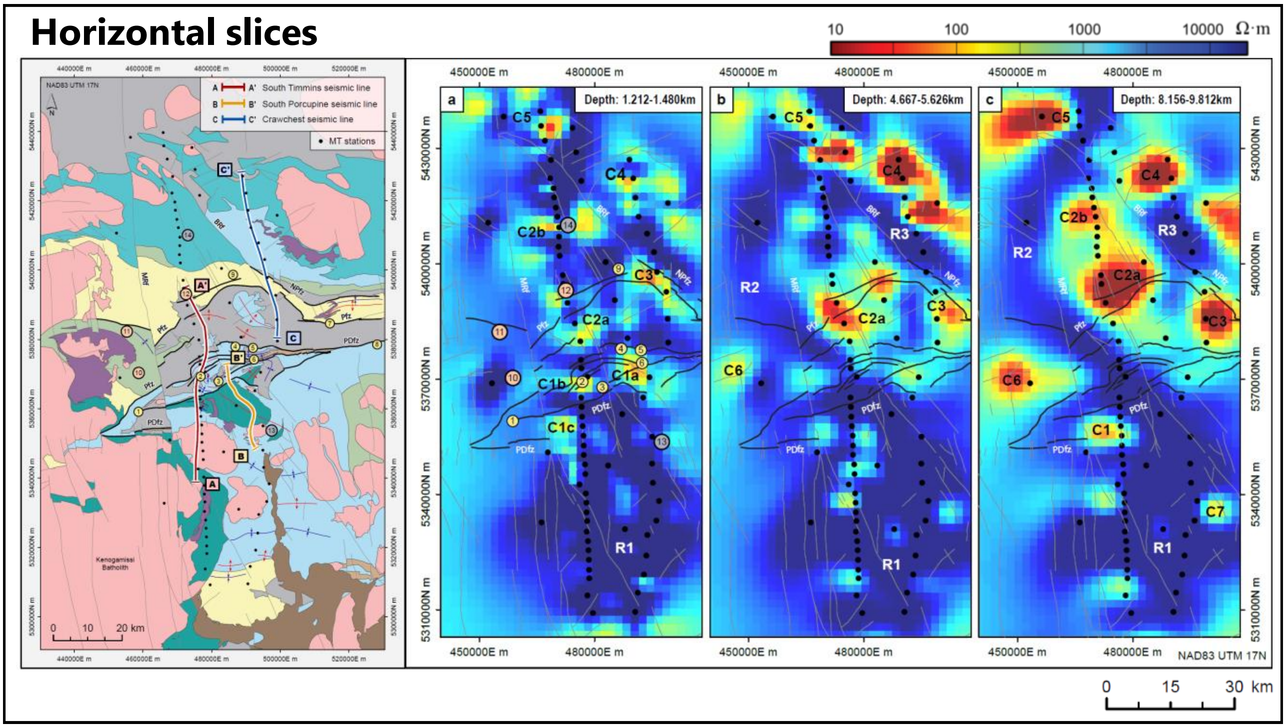


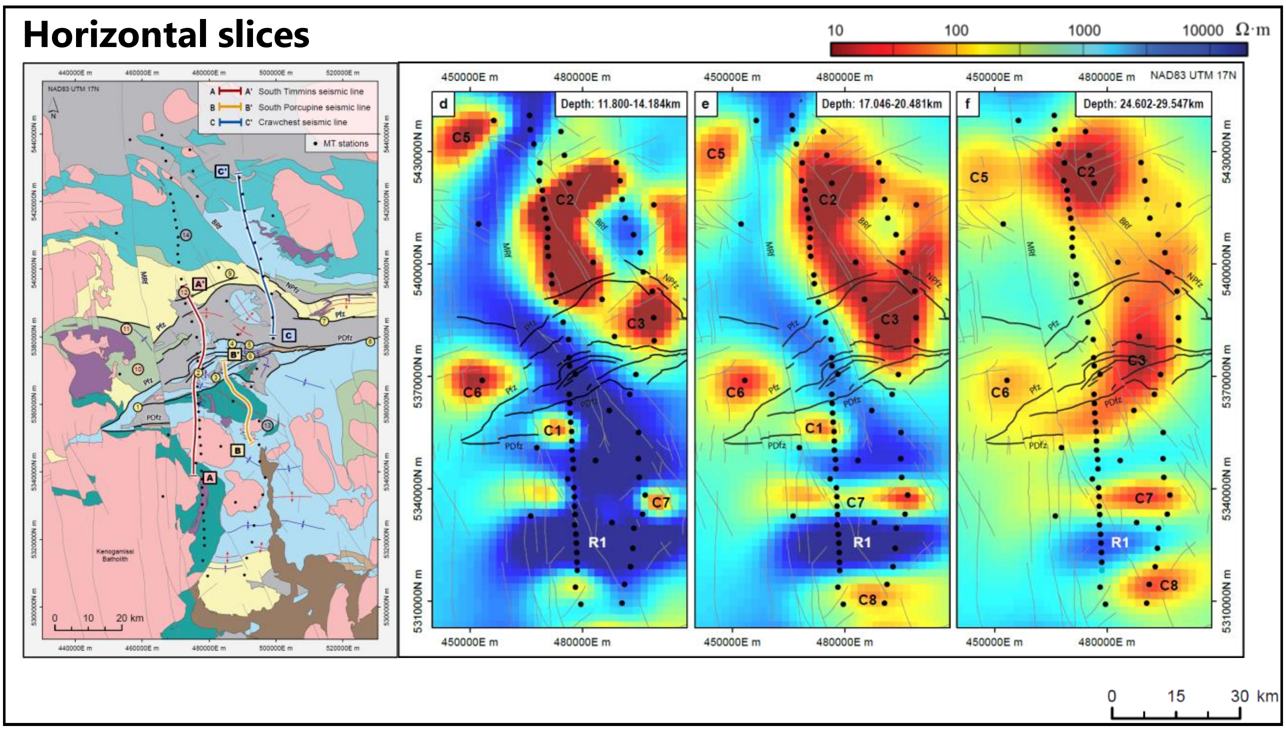
- ModEM
- 5% error on impedance components
- 111 iterations with nRMS misfit of 1.05
- Tests for sensitivity and resolution



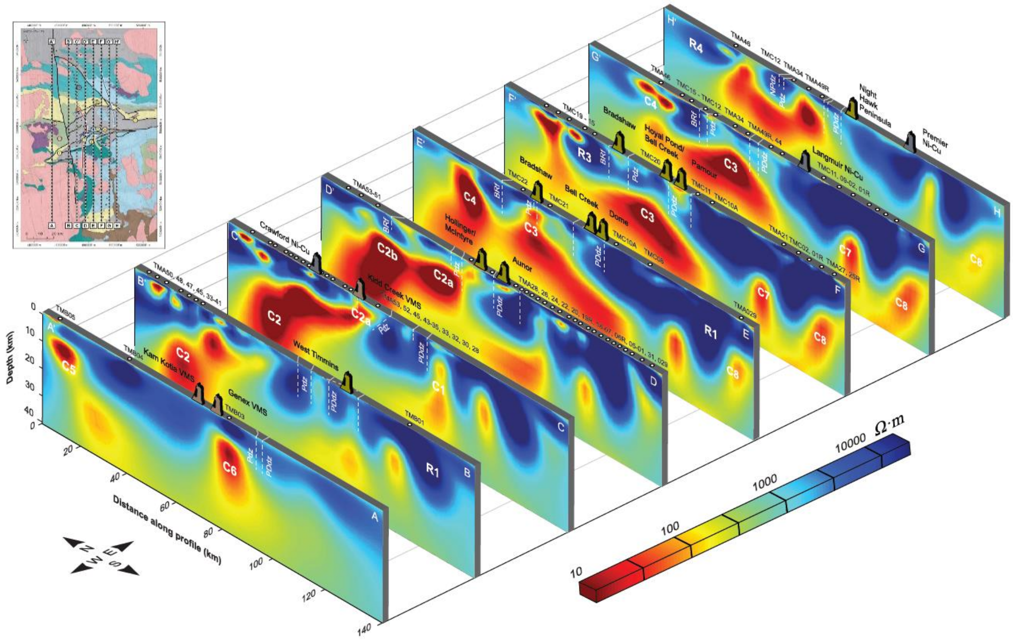




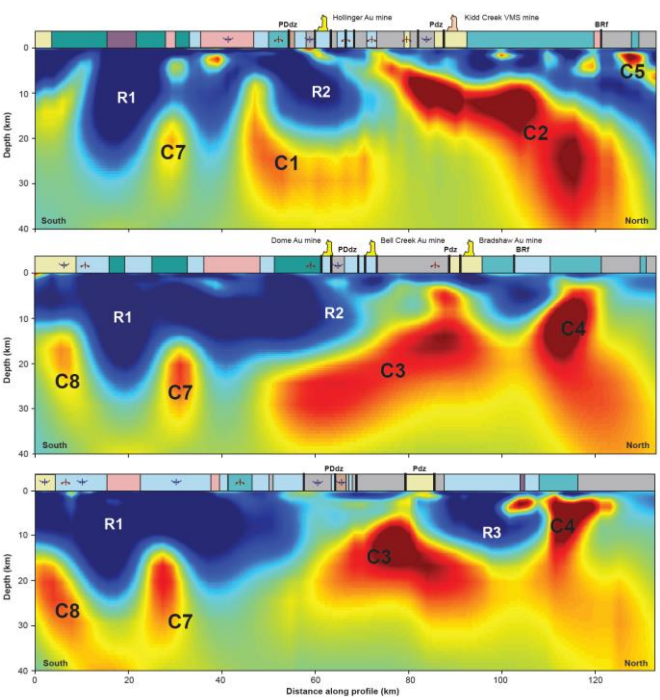

Horizontal slices
10
100
1000
10000 Ω·m
a
Depth: 1.212-1.480km
b
Depth: 4.667-5.626km
c
Depth: 8.156-9.812km
450000E m
480000E m
5430000N m
5400000N m
5370000N m
5340000N m
5310000N m
C5
C4
C2b
C3
C2a
C1b
C1a
C1c
C6
C2a
C1
C7
R1
R2
R3
NAD83 UTM 17N
0
15
30 km
South Timmins seismic line
South Porcupine seismic line
Crawchest seismic line
MT stations
Kenogamissi Batholith
0
10
20 km

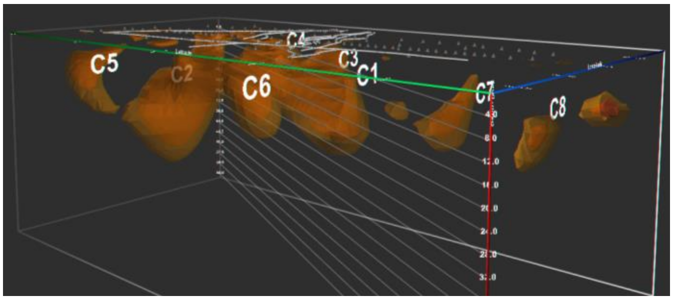

Horizontal slices
10
100
1000
10000 Ω·m
d
Depth: 11.800-14.184km
e
Depth: 17.046-20.481km
f
Depth: 24.602-29.547km
450000E m
480000E m
5430000N m
5400000N m
5370000N m
5340000N m
5310000N m
NAD83 UTM 17N
C5
C2
C3
C6
C1
C7
C8
R1
0
15
30 km
South Timmins seismic line
South Porcupine seismic line
Crawchest seismic line
MT stations
Kenogamissi Batholith
0
10
20 km

Vertical slices

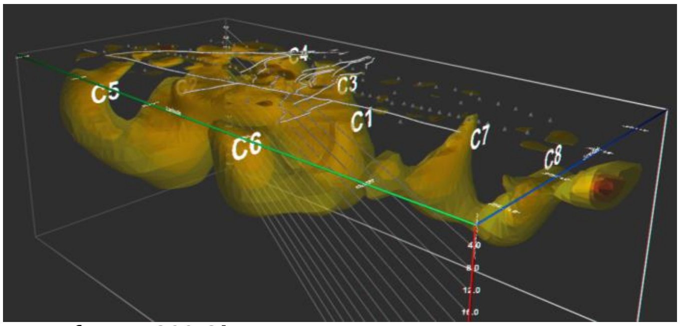


- **Generally resistive upper crust and conductive mid-to-lower crust**
- **Resistor R1 extends to mid-crust while R2 & R3 are mostly confined to the upper crust**
- **Resistivity decreases from south to north with R1 having values >50,000 Ω·m**
- **E-W trending conductive anomaly C1 and N-S anomaly C2 are associated to the PDdz and Pdz**
- **Linear NW-SE trending conductors C4 aligns with BRf**
- **Conductors C3 underlies the Porcupine assemblages and dips both north and south**
- **Conductors C1-C4 are connected at depth to the conductive lower crust that could be source of mineralized fluids**

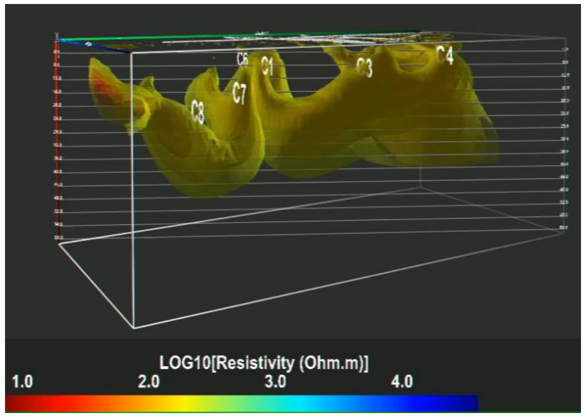




Isosurface at 100 Ohm.m



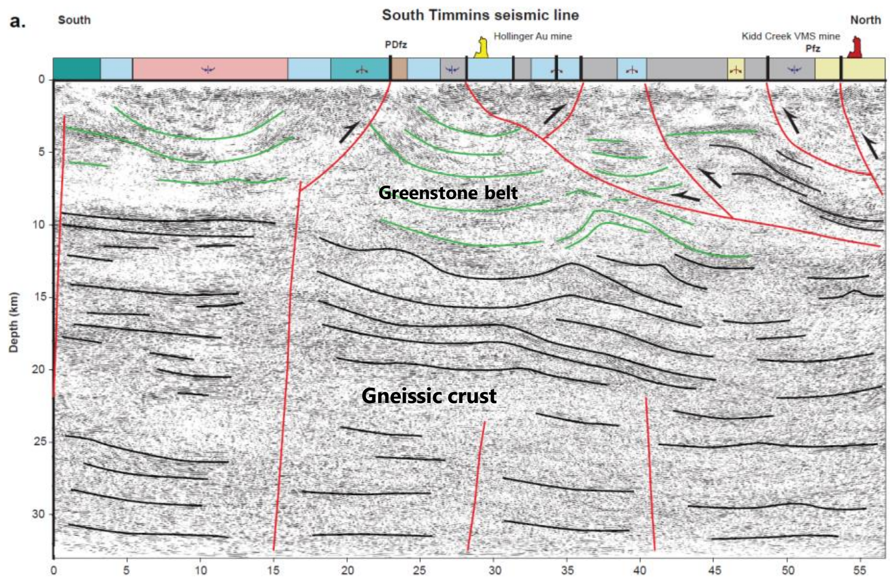
Isosurface at 200 Ohm.m



Seismic reflection

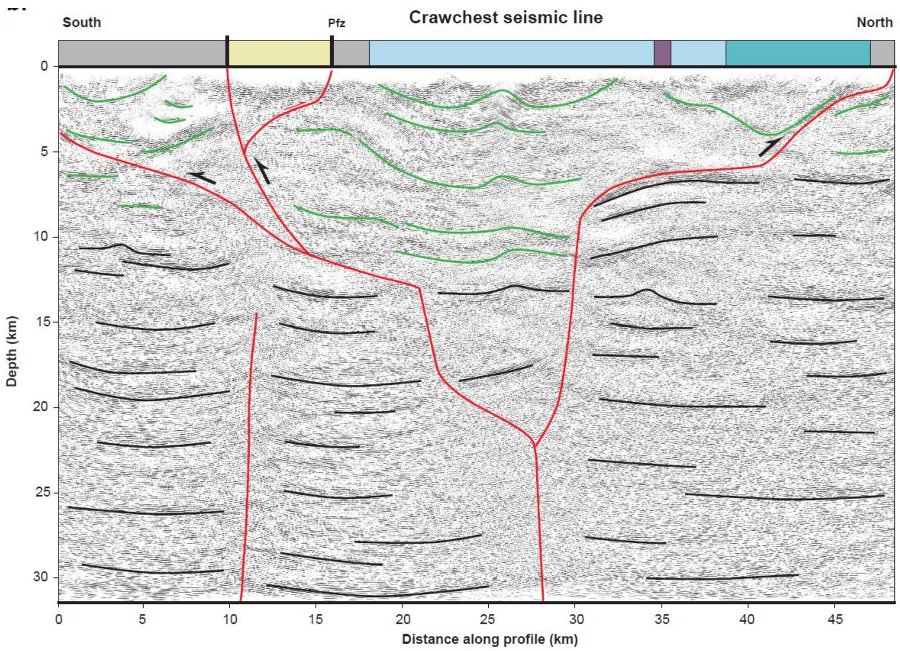
- Reflectors in greenstone belt- highlight folded structures and thrust faults
- Truncation of reflectors in the upper crust suggests a south dipping PDdz and north dipping Pdz
- Diffusive reflection zones in mid-lower crust suggest multiple subvertical fault zones in the basement
- PDdz and Pdz are crustal scale faults

a.

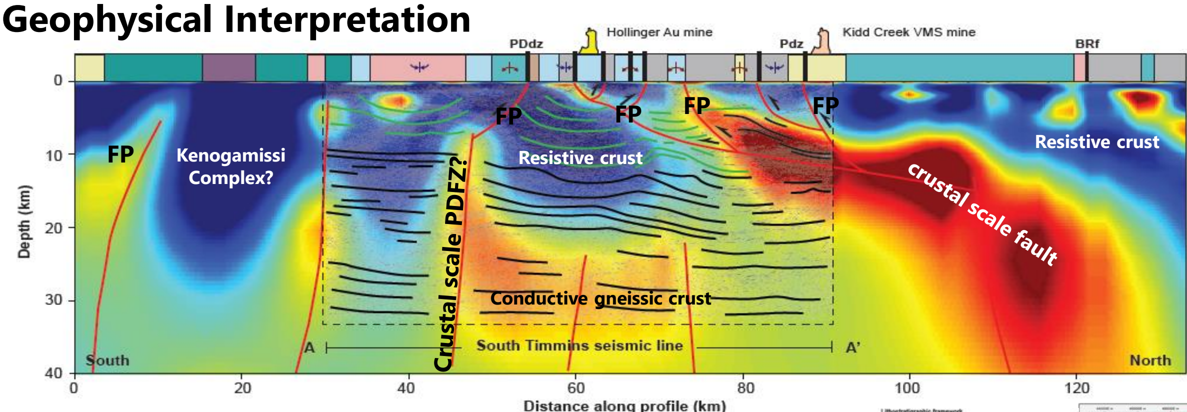


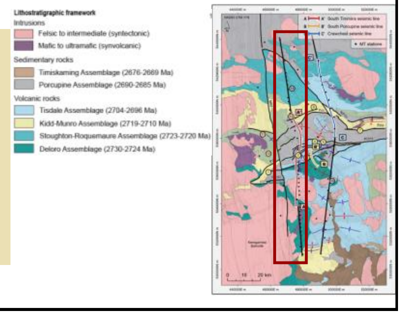
- **Thick-skinned deformation strain was accommodated across the whole crust**
  - **Subvertical faulting in the basement and folding & thrusting in the upper crust, which may facilitate transport of Au bearing fluids from depths to shallow levels and trap Au in folded structures**

- **Reflectors in the upper crust highlight folded structures within the greenstone**
- **Kidd Munro assemblage in a pop-up structure bounded by the NPdz and Pdz**
- **Truncation of reflectors and diffusive reflection zones highlight several steep , interconnected, and deep-rooted faults**
- **Sub-horizontal reflectors in the mid-lower gneissic basement**
- **Thick-skinned deformation (i.e., basement-involved thrusting and folding**

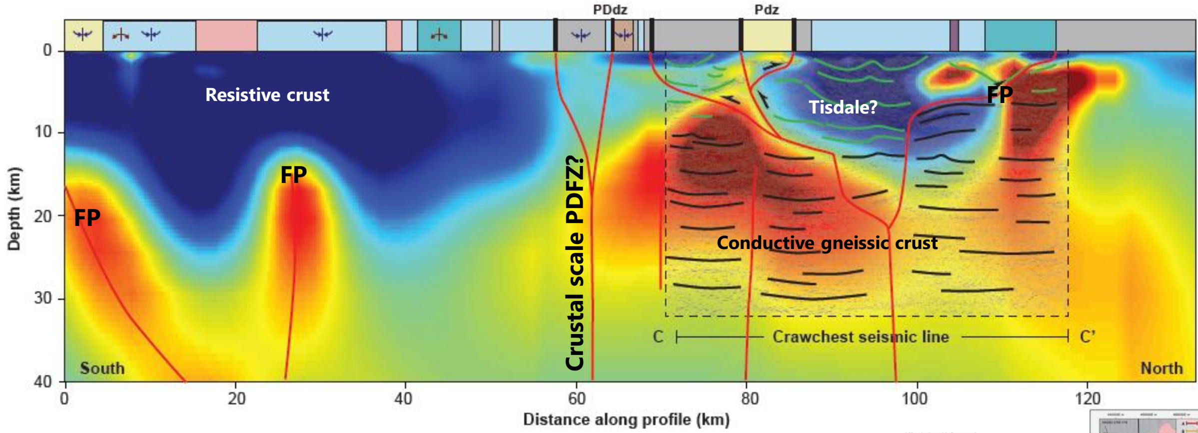


Geophysical Interpretation

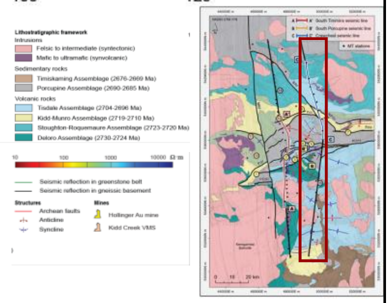


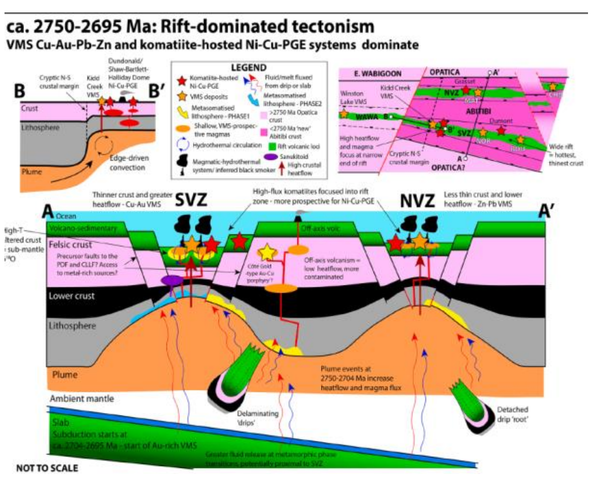


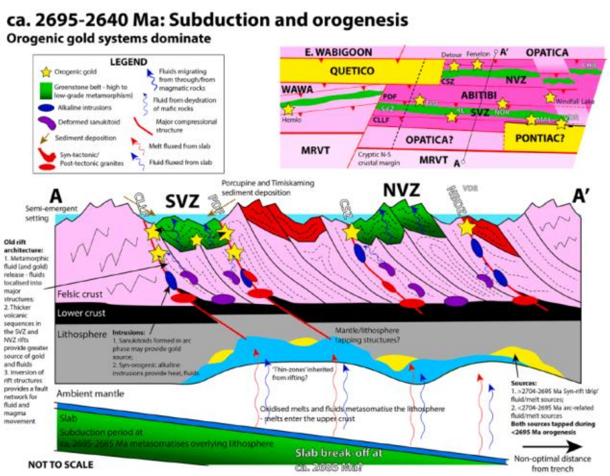
- **Resistive greenstone belt and Kenogamissi complex underlain by the conductive mid-to-lower gneissic crust**
- **Several conductive corridors spatially associated with PDdz, Pdz and NPdz and major deposits**
- **PDdz and Pdz are crustal scale faults**
  - **Footprint of the fluid migration pathways through the crust**



- **Conductors are connected at depth to the conductive mid-lower crust**
  - **Source of gold bearing fluids?**
  - **Deep seated mineralizing system associated to the Pipestone deformation zone?**







Mole et al., 2022

Conclusions

- **Orogenic gold deposits are closely associated with crustal-scale major fault zones**
- **The faults are pathways that channel hydrothermal fluids responsible for gold deposition**
- **Hydrothermal circulation could be active over several deformation events**
- **Deformation events typically control gold mineralization**

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