Magnetotellurics

an Introduction for Geologists

Presented at the TGDG, June 2020

QUANTEC Geoscience

Rob Gordon P.Eng

What is MT

Discussion for Today

- Theory and source fields
- Deployment and data collection
- Data presentation
- Applications & examples

What is MT

MT stands for Magnetotellurics

- Magnetotellurics (MT for short) is an electromagnetic geophysical technique that uses natural electric fields from lightning sources, solar flares and ionospheric resonances that induce current flow in the ground which allows us to image the earth's electrical resistivity structure from surface to great depths.

- Data are processed and presented as resistivities and can be correlated with geology, structure and can highlight both conductive features for targeting and or resistive features for targeting.

- Deep penetrating method. MT routinely measures from surface to 2, 5, 10 or many 10s of km depending on the application.

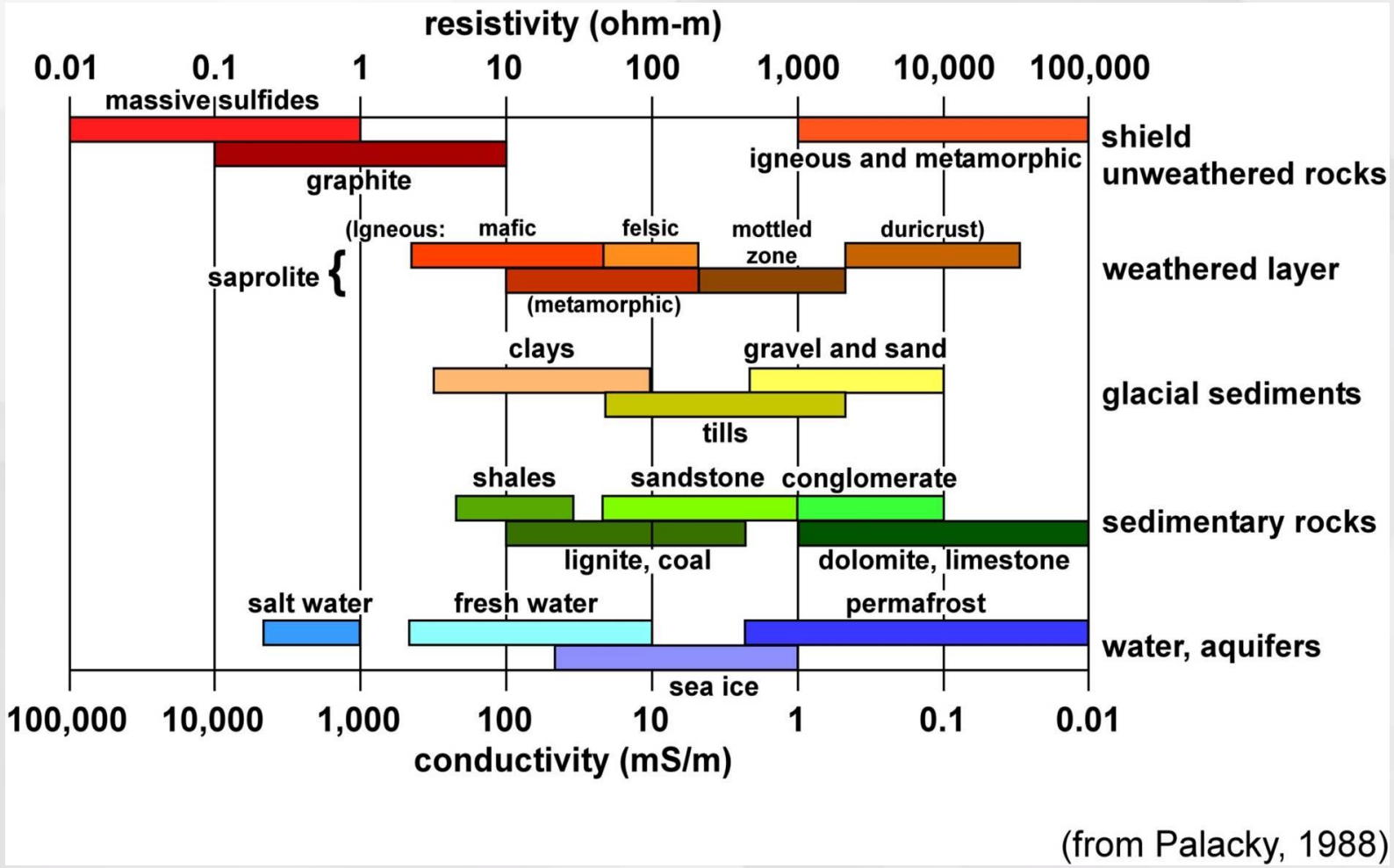
How do we get Resistivity and depth information

- Passive surface measurement of the earth's natural electrical (E) and magnetic (H) fields
- The ratio of the electric field to magnetic field provides simple information about subsurface conductivity.

$$\rho_a = (1/5f) * |E/H|^2 \text{ (ohm-metres)}.$$

  - The ratio is usually represented as both **apparent resistivity** as a function of frequency and phase as a function of frequency.
  - The depth of investigation is inversely proportional to frequency, that is the ratio at higher frequency ranges gives information on the shallow earth, whereas deeper information is provided by the low-frequency range, according to skin depth relationship
  - Measure changes in E and H w/time and across frequency ranges (10kHz to 0.001 Hz)

Resistivity - a relationship to Geology



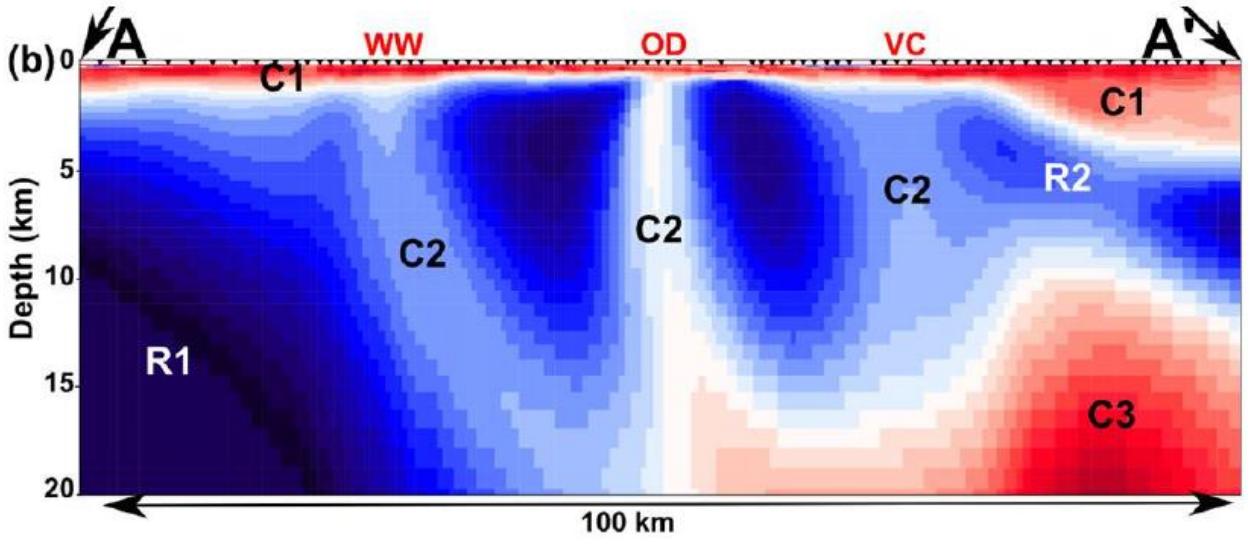
(from Palacky, 1988)

Common rocks	
Topsoil	50–100
Loose sand	500–5000
Gravel	100–600
Clay	1–100
Weathered bedrock	100–1000
Sandstone	200–8000
Limestone	500–10 000
Greenstone	500–200 000
Gabbro	100–500 000
Granite	200–100 000
Basalt	200–100 000
Graphitic schist	10–500
Slates	500–500 000
Quartzite	500–800 000
Ore minerals	
Pyrite (ores)	0.01–100
Pyrrhotite	0.001–0.01
Chalcopyrite	0.005–0.1
Galena	0.001–100
Sphalerite	1000–1 000 000
Magnetite	0.01–1000
Cassiterite	0.001–10 000
Hematite	0.01–1 000 000

‘Proof’ of Concept- the Olympic Dam Model

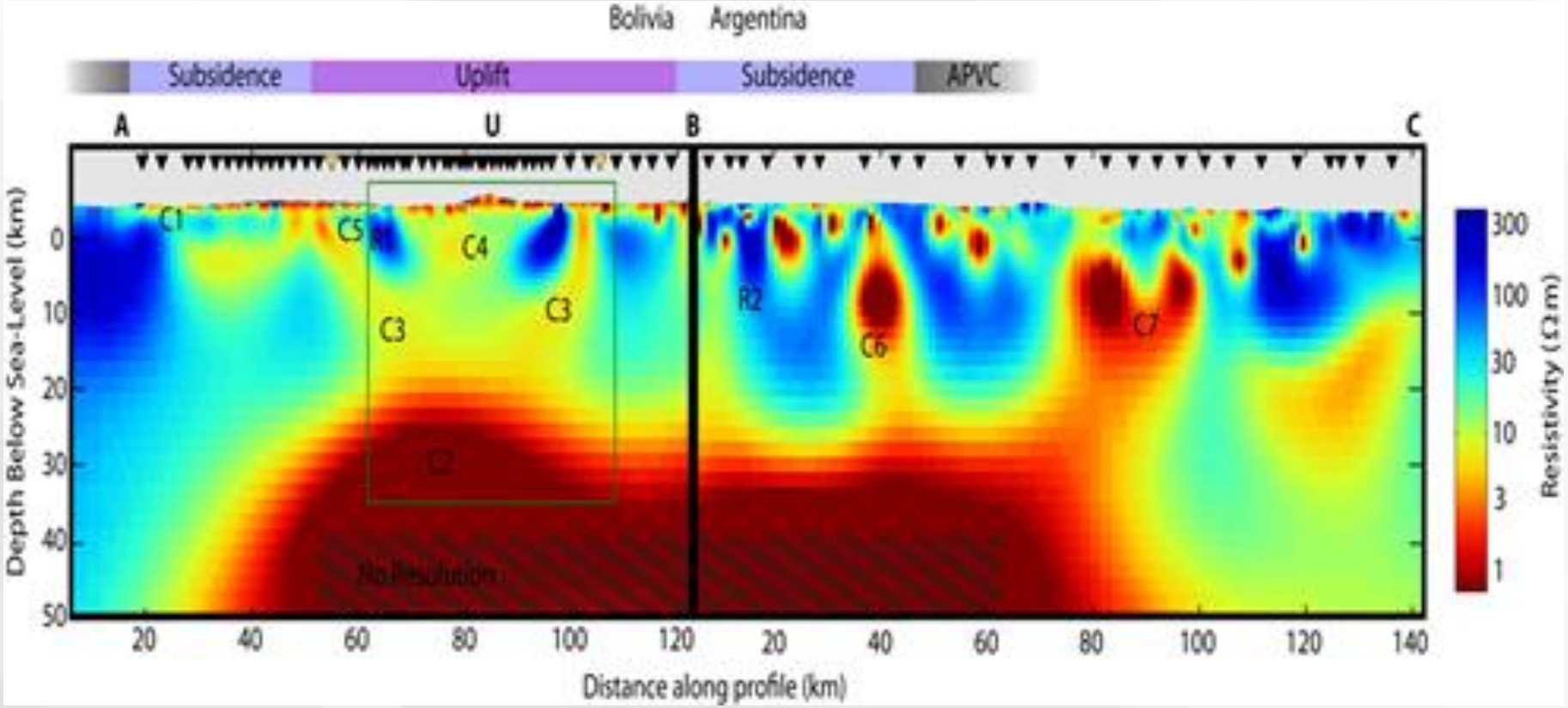
“Fingers of God” – the Scottish Astrologer, 2016

Australian Research Study



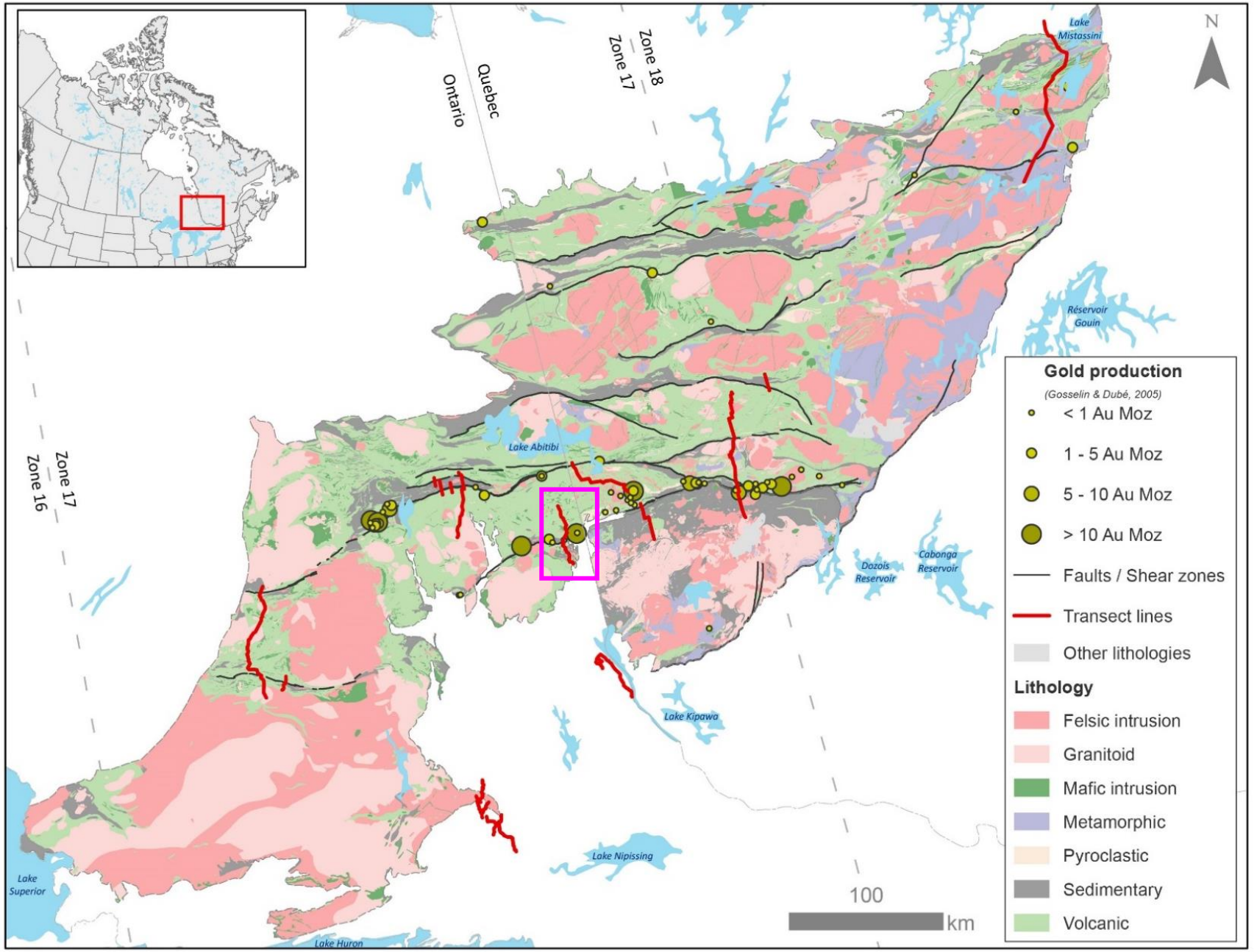
Fingers of God, new edition. Heinson et al., 2018, SciReports

Regional Survey - Bolivia



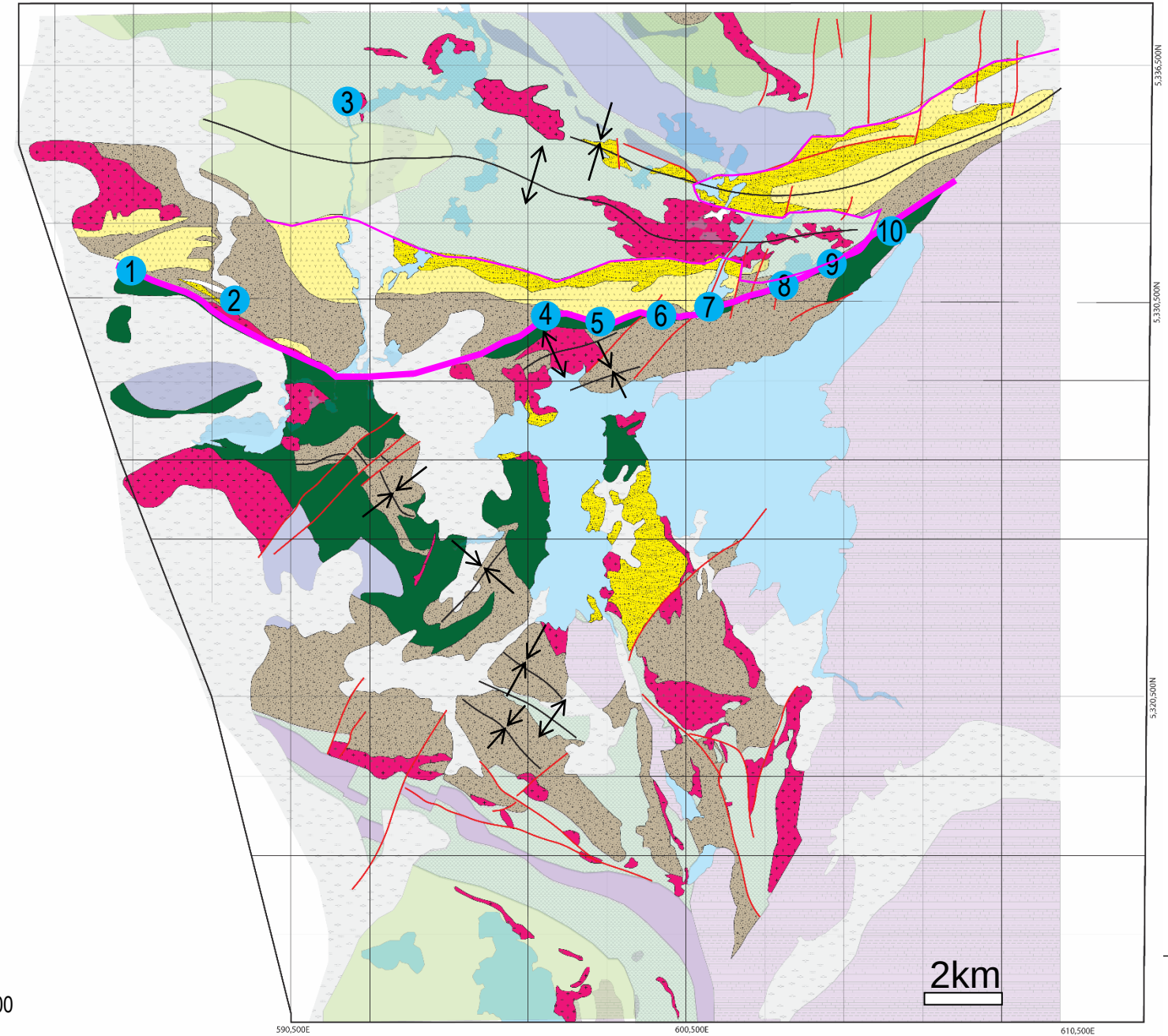
Andes Centrales (22°S): Volcan Uturuncu,Bolivia. Comeau, Unsworth et al., Geology (2015).

Abitibi Transects



Larder Lake area, Cadillac - Larder Lake Break and Gold Deposits

1. Anoki
2. McBean
3. Upper Beaver
4. Omega
5. Fernland
6. Cheminis
7. Bear Lake
8. Barber Larder
9. McGarry
10. Kerr Addison



From: Jackson, 1995, OGS Map 2628, 1:50,000

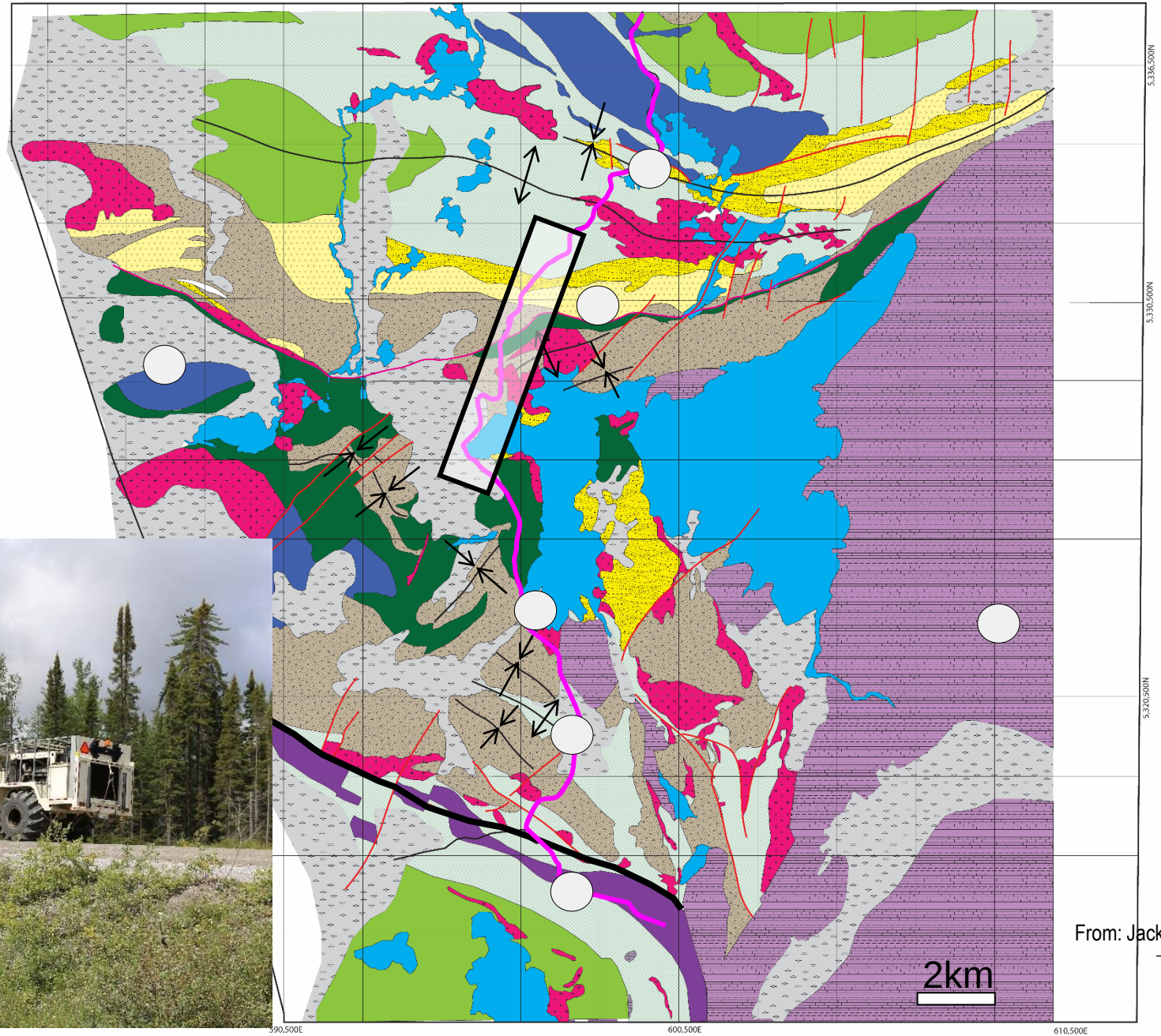
Metal Earth

how are these faults expressed geophysically

Transect Scale Research

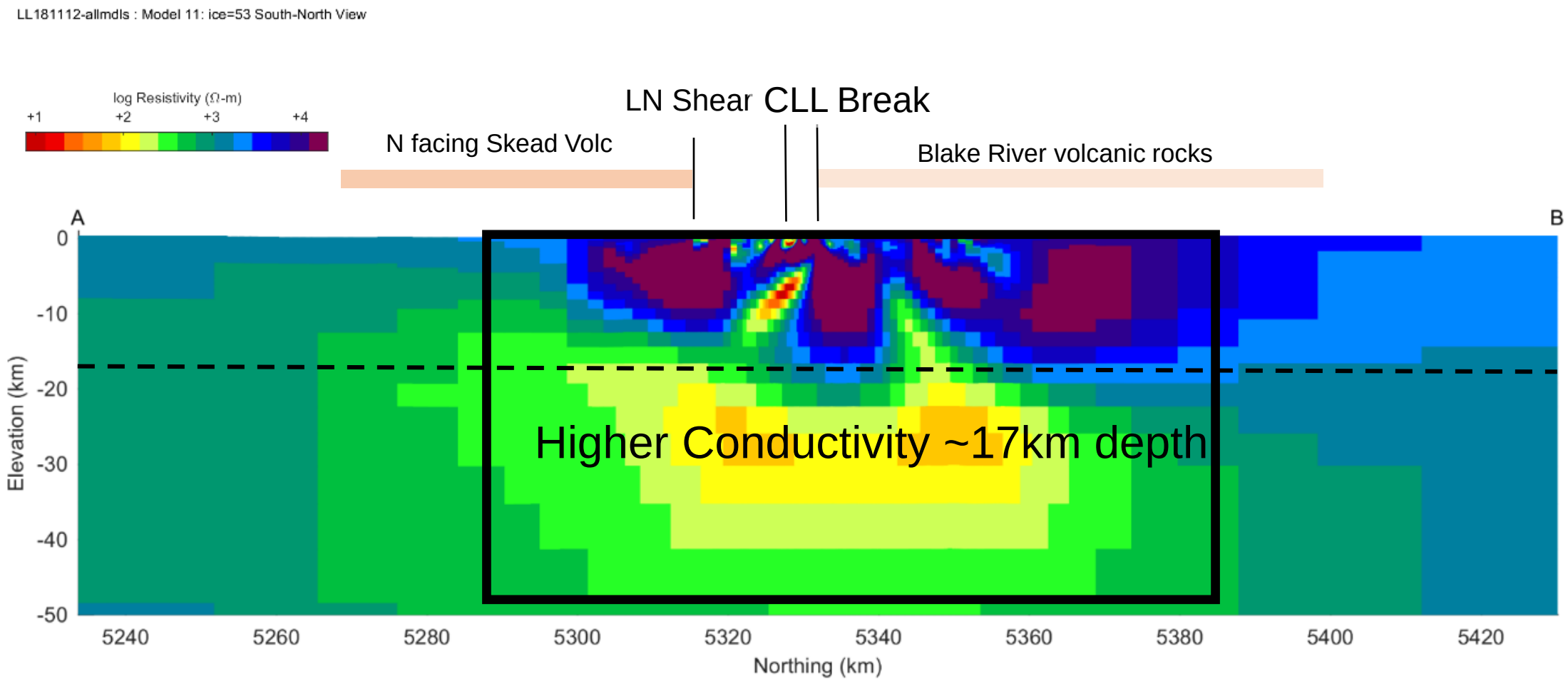
Larder Lake Transect

Seismic & MT



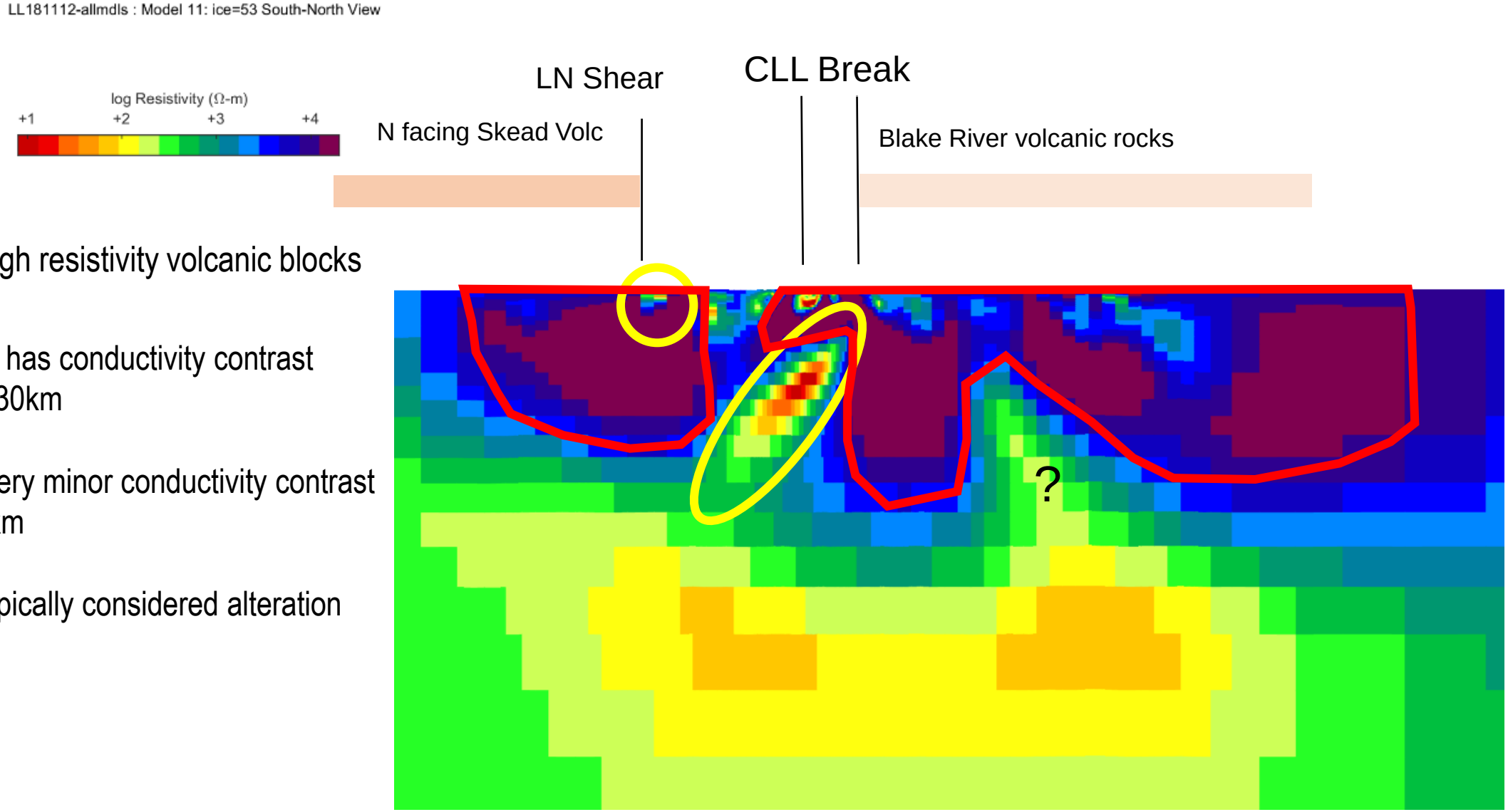
From: Jackson, 1995, OGS Map 2628, 1:50,000

Larder Lake MT – AMT section, 3D inversion



Graham Hill, Personal Com..

Larder Lake MT – AMT section, 3D inversion



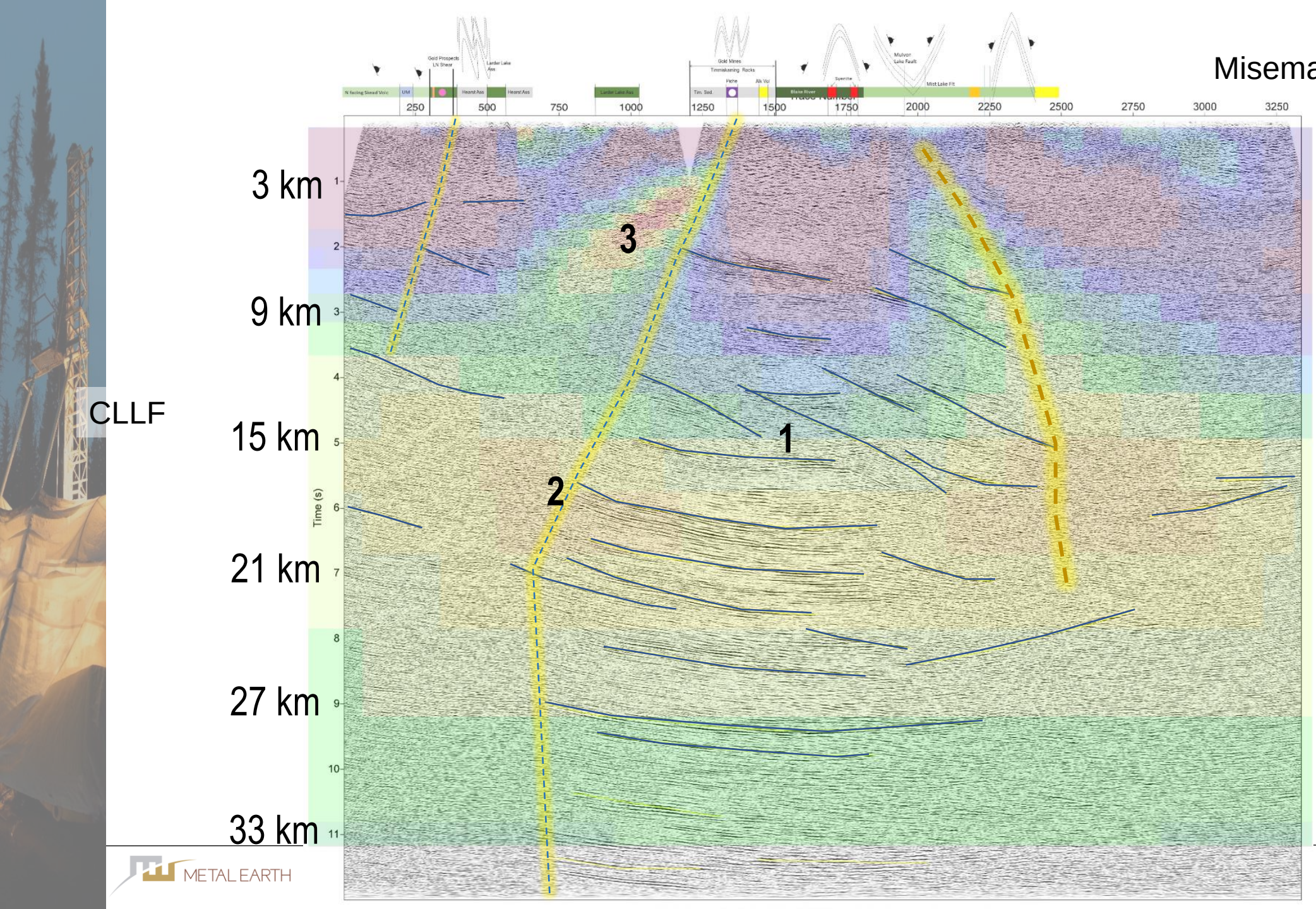
Mapping high resistivity volcanic blocks

C-LL break has conductivity contrast traced to +30km

LN shear very minor conductivity contrast to under 3km

Contrast typically considered alteration effect

Graham Hill, Personal Com..



The fertile, highly endowed faults manifest themselves geophysically as large through going features that separates domains that have distinct physical properties.

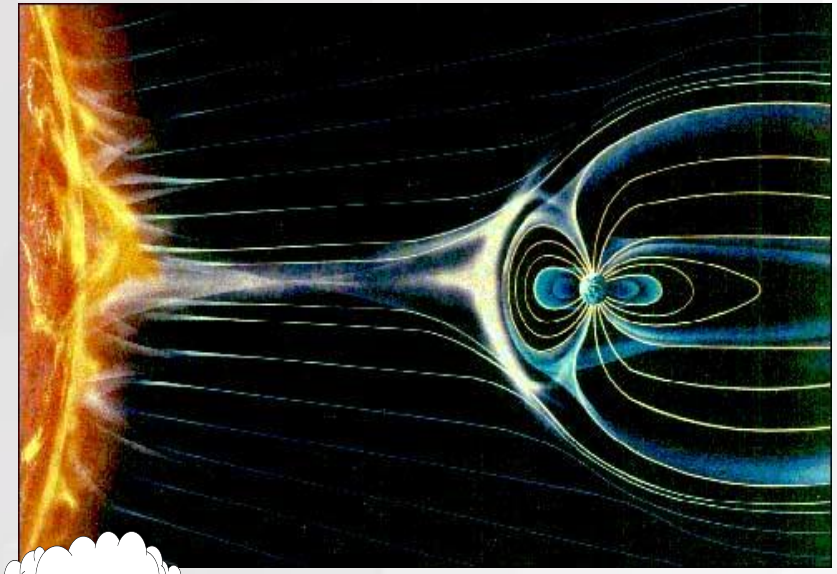
MT surveys shows a distinct contrast in the structural hanging wall of the fertile systems.

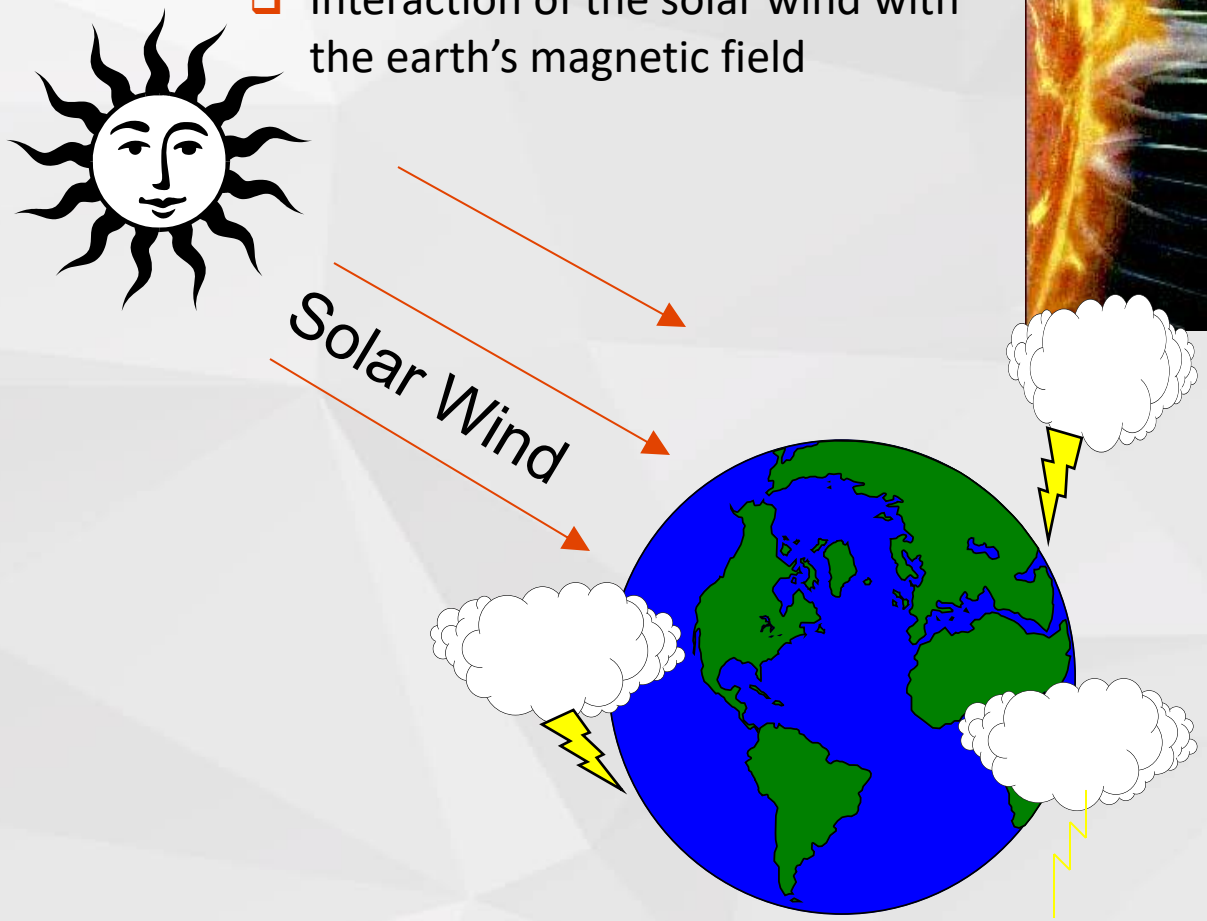
History of MT

- 1847: existance of large scale earth currents (Barlow)
- 1950's: Theory proposed (French and Russians)(1953-Cagniard)
- 1960's: Academic/gov't systems developed - first uses for academic and geothermal projects (Map plate boundaries, alteration, etc.)
- ~1980: Commercial systems for hydrocarbon exploration
- ~1981/1982 – Data quality/systems improve: useable data
- 1980's: Many in-house oil company groups / mostly deeper applications
  - Shell, Amoco, Sohio, Arco, CGG
- 1990's: Most work and research outsourced to contractors and consultants
  - More use of higher frequencies - More usage in mining
  - Major advancements in acquisition, processing and interpretation (24bit etc)
- 2000's: Distributed data collection for detailed MT / 2D inversion improving
- 2010's: 3D inversion; continued improvements; computing speed

MT natural source fields

- Lower frequencies:
  - f < 1 Hz
  - Interaction of the solar wind with the earth's magnetic field





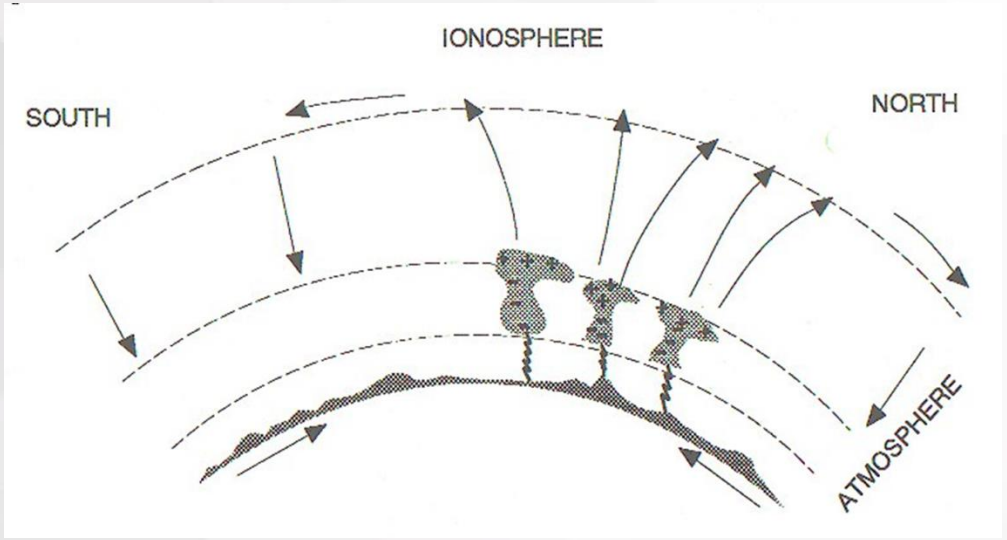
- Higher frequencies:
  - f > 1 Hz
  - Global lightning activity

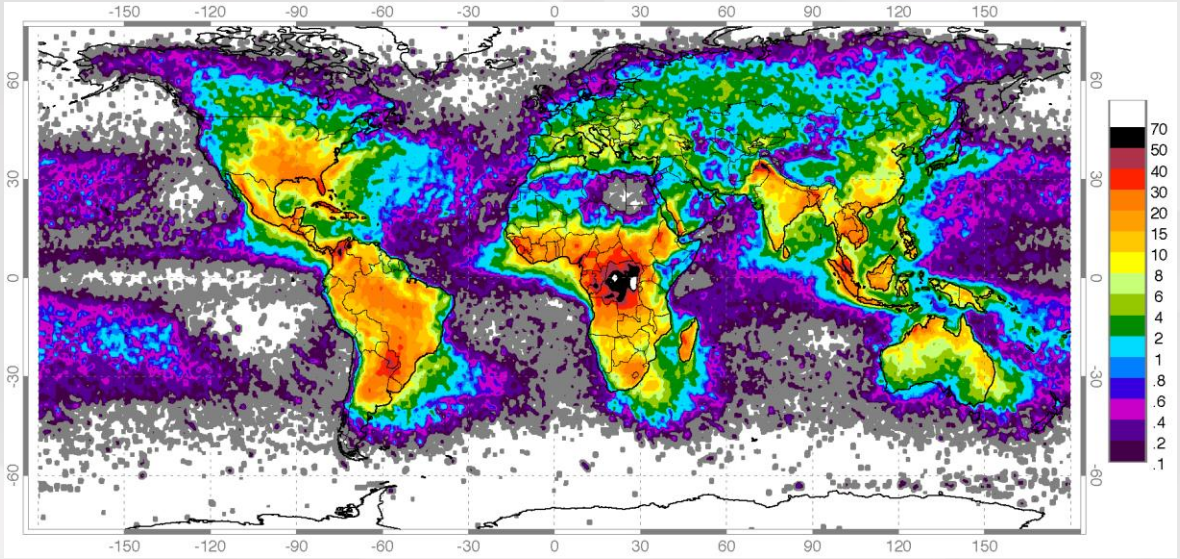
Thunderstorms

SPARTAN MT

Lightning - high frequency

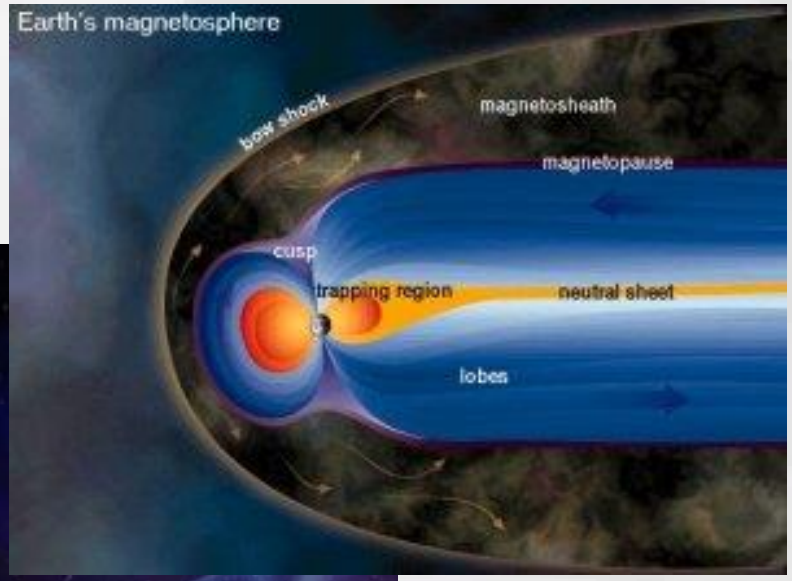
- Source field almost always present, subject to seasonal variation regionally

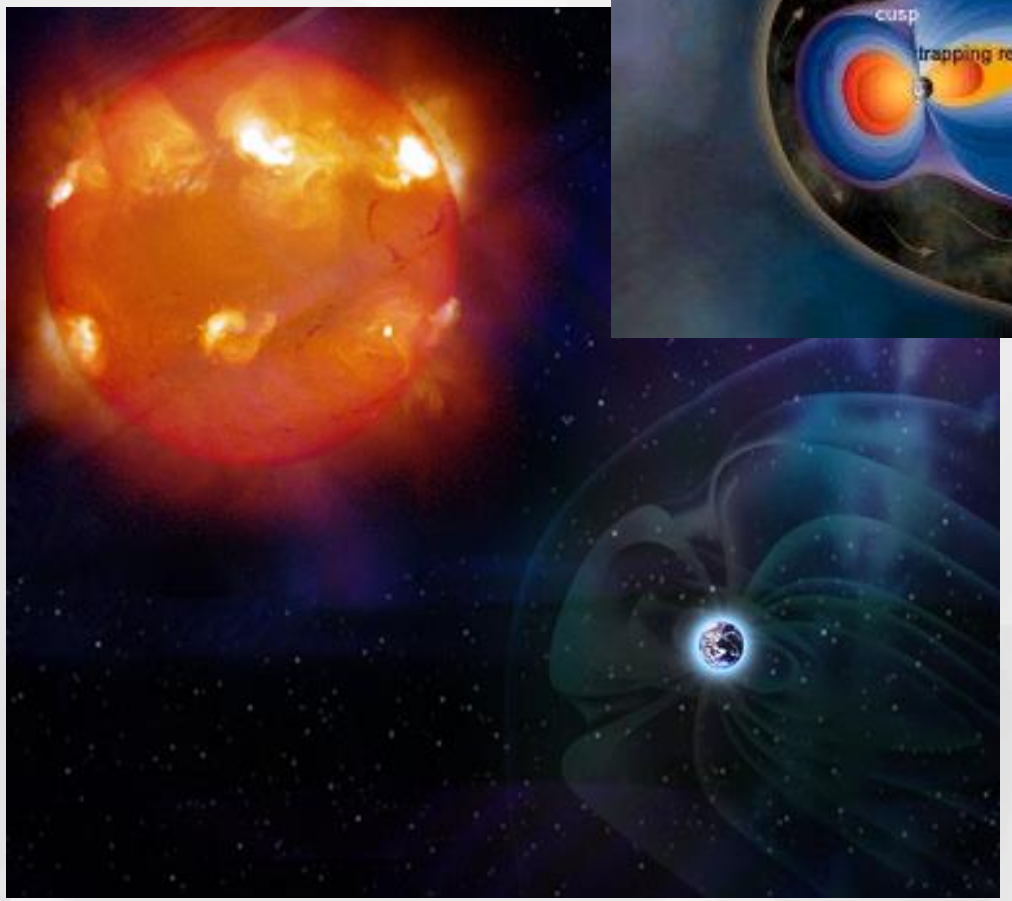




- High Frequencies: World-wide thunderstorm activity
  - Energy travels around Earth in waveguide
  - Bounded by Earth surface and Ionosphere
  - Frequencies generally > 1Hz

Distortion of magnetosphere – low frequency



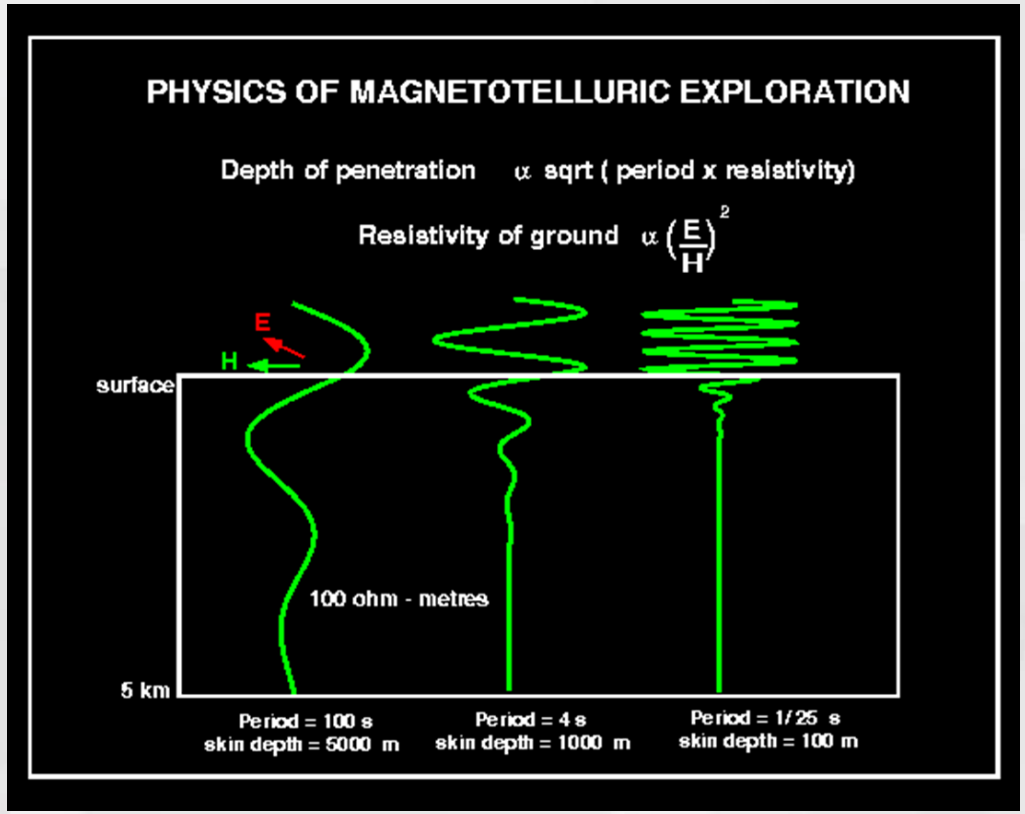


Intensity of solar flares increases and decreases over an 11-year cycle period

Aurora is caused by the same energy

What are we measuring?

Natural electromagnetic waves that are generated in the earths atmosphere by a range of physical mechanisms. As these travel into the Earth's interior they decay at a rate dependent upon their wavelengths.



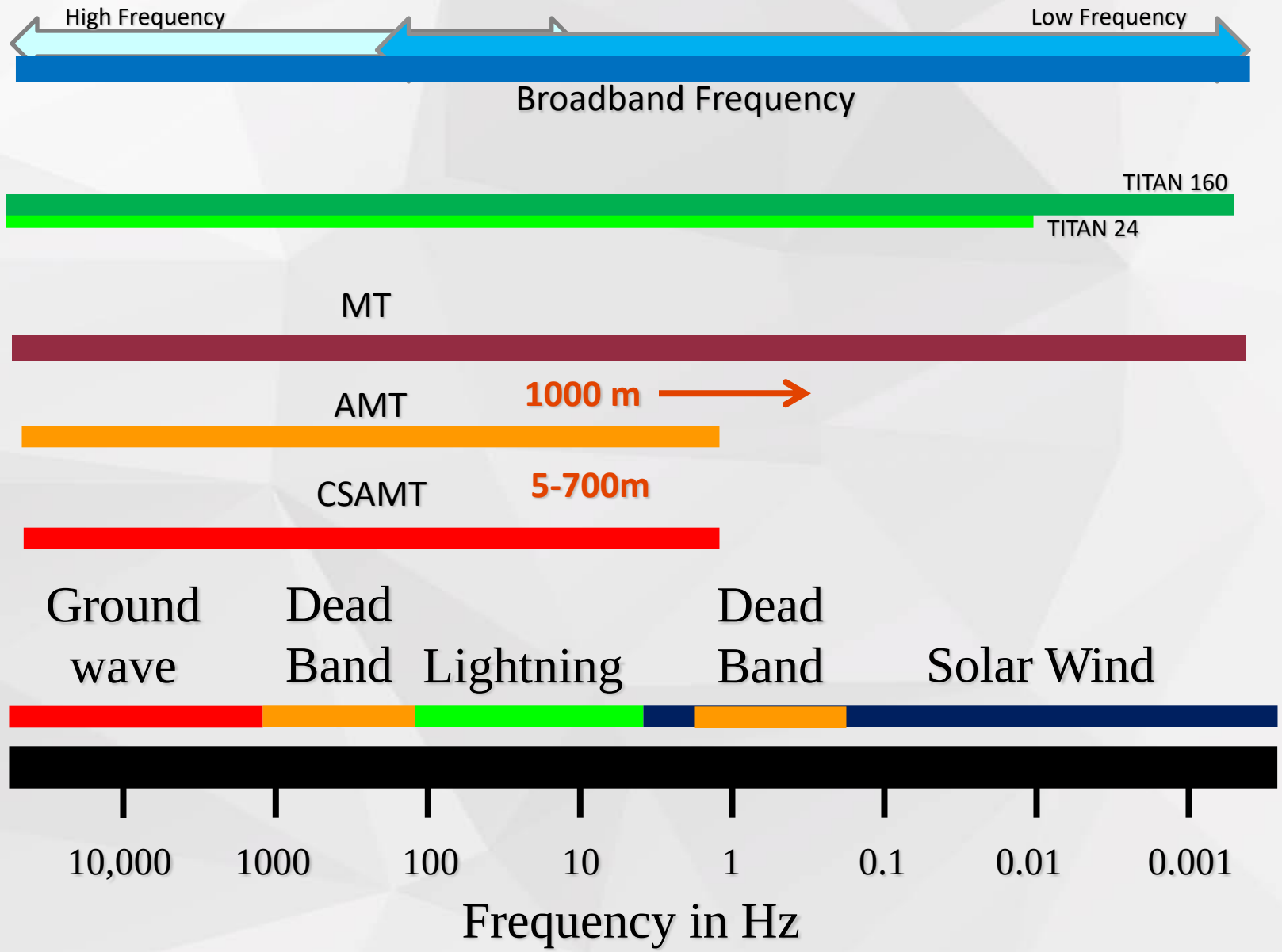
- High frequency signals which originate from lightning activity
- Intermediate frequency signals come from ionospheric resonances
- Low frequency signals are generated by sunspots (<1 Hz)

From Magnetotelluric Research Overview / 6 April 2001 / unsworth@phys.UAlberta.ca

MT/AMT/CSAMT

- **MT**
  - Generally refers to Broad Band recording from >10,000 Hz to .001Hz (also referred to as 1000 seconds) or as low as 10K S (.0001Hz) from surface to great depths – (up to 100km and more)
- **AMT**
  - Refers to “Audio” frequencies
  - Generally recording > 1 Hz to 10KHz+
  - The bandwidth works well where high resolution inversion modeled resistivity results are needed to depths of 1 km, (more or less).
- **CS AMT**
  - Refers to “Controlled Source” AMT (depth range of up to 1000m but typically useful for 500m (more or less)
  - Advantageous for measurements with smaller dipoles less than 50m

MT – frequency bandwidth & survey types



SPARTAN MT
(Broad band or LF & HF)

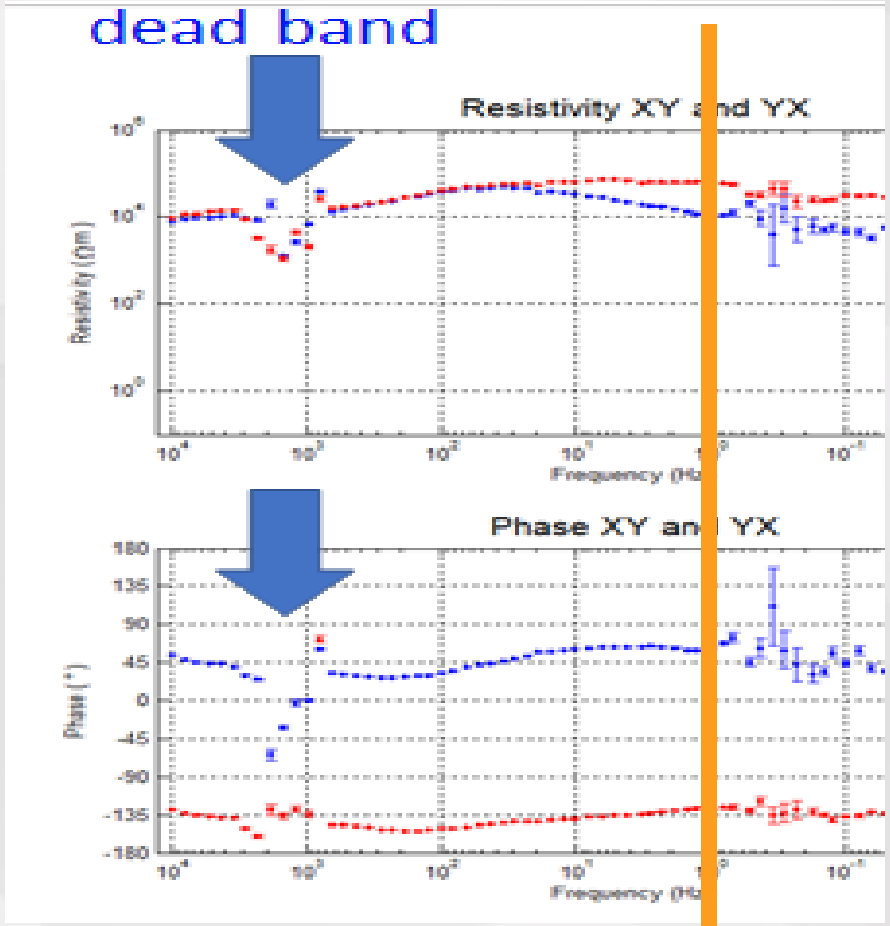
TITAN MT
(distributed array /close spacing)

Shallow

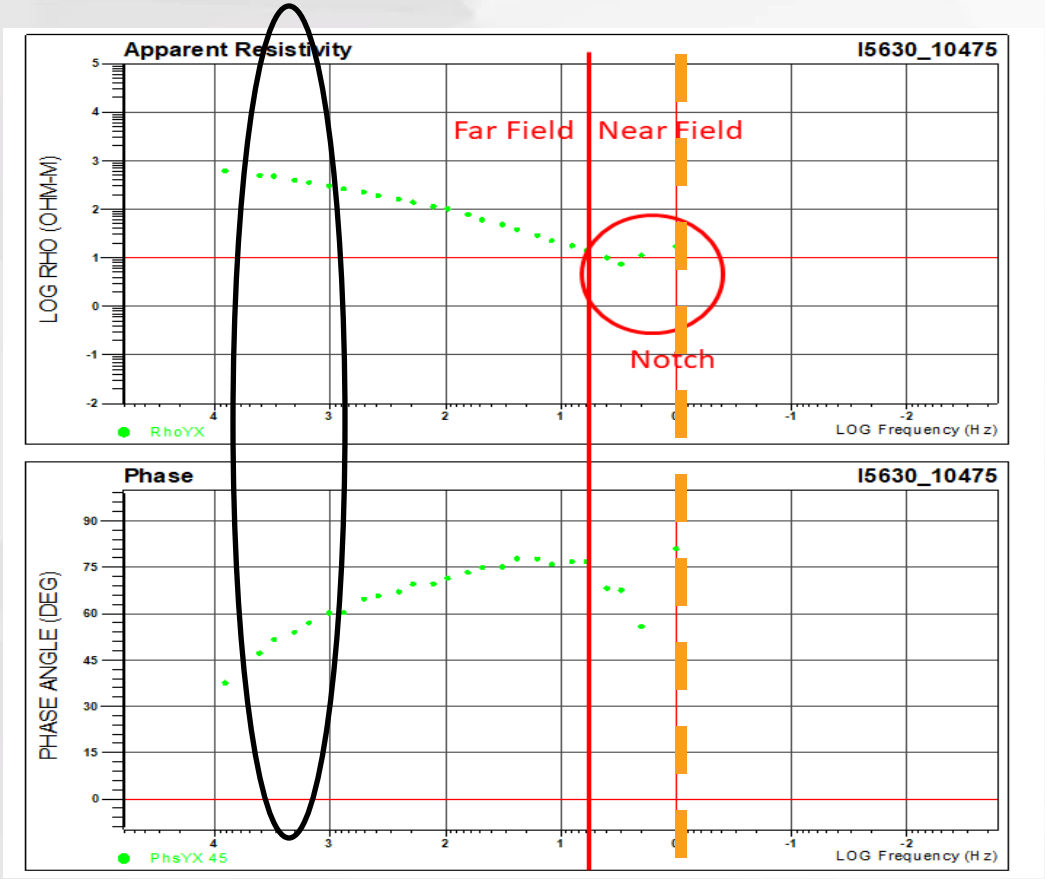
Deeper

Example of dead band on AMT

- **AMT – 2 hr read**



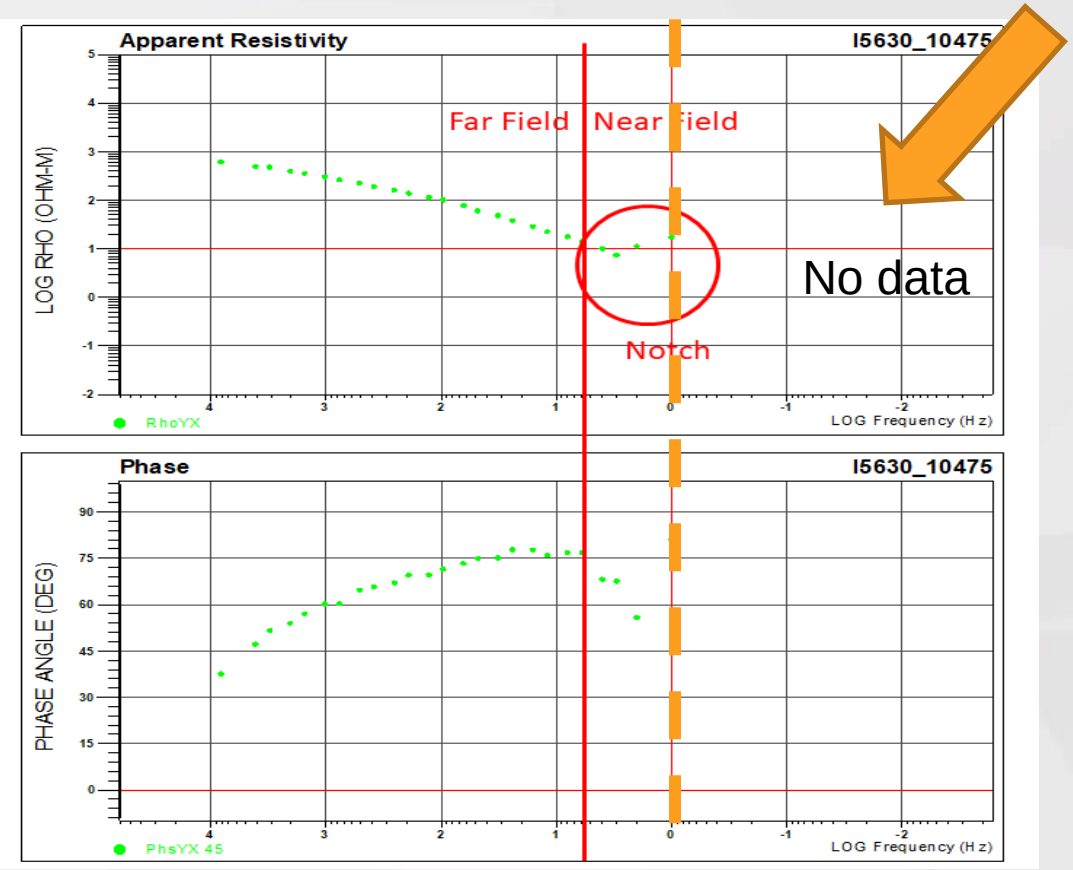
- **CS-AMT**
  - Captures good signal in deadband
  - No lower frequencies



Summary

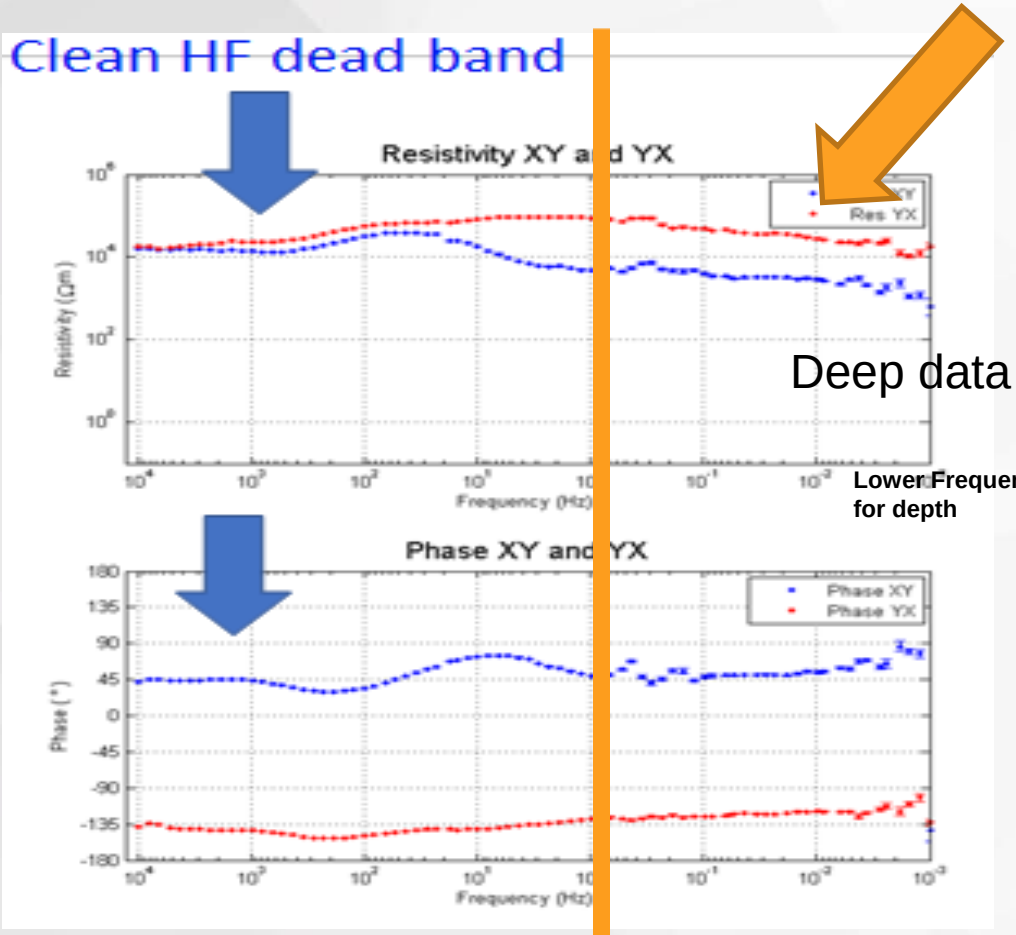
❑ CS-AMT

- ❑ Depth limited



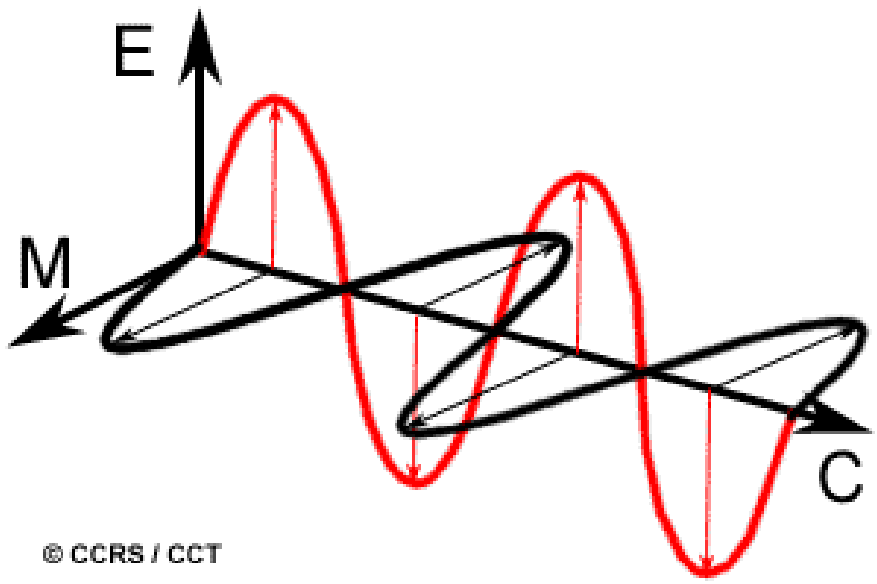
❑ MT– overnight read

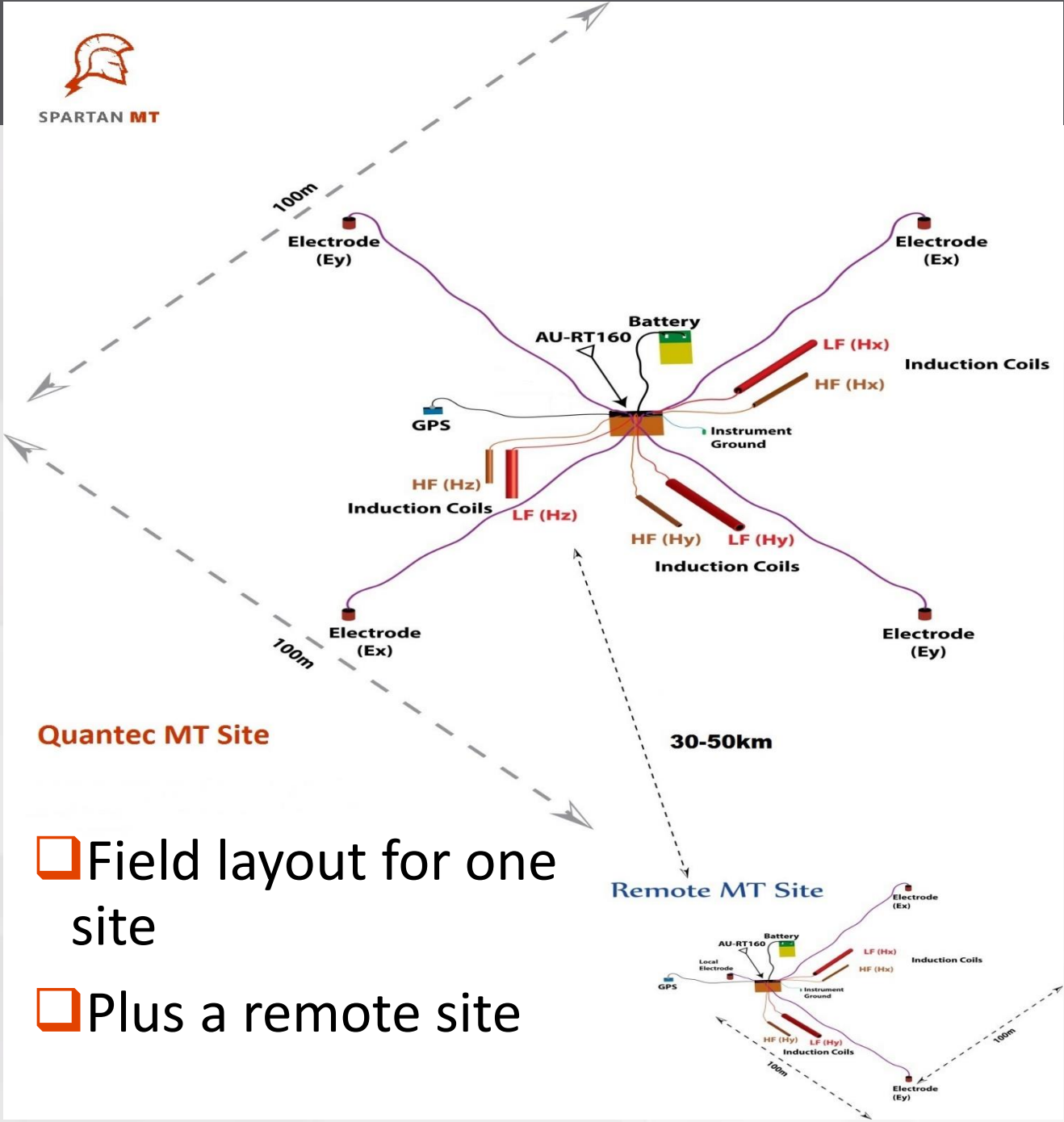
- ❑ Captures good signal in dead band and lower frequencies for depth



MT data acquisition

Measure the natural **electric field** and the natural **magnetic field** over a range of frequencies

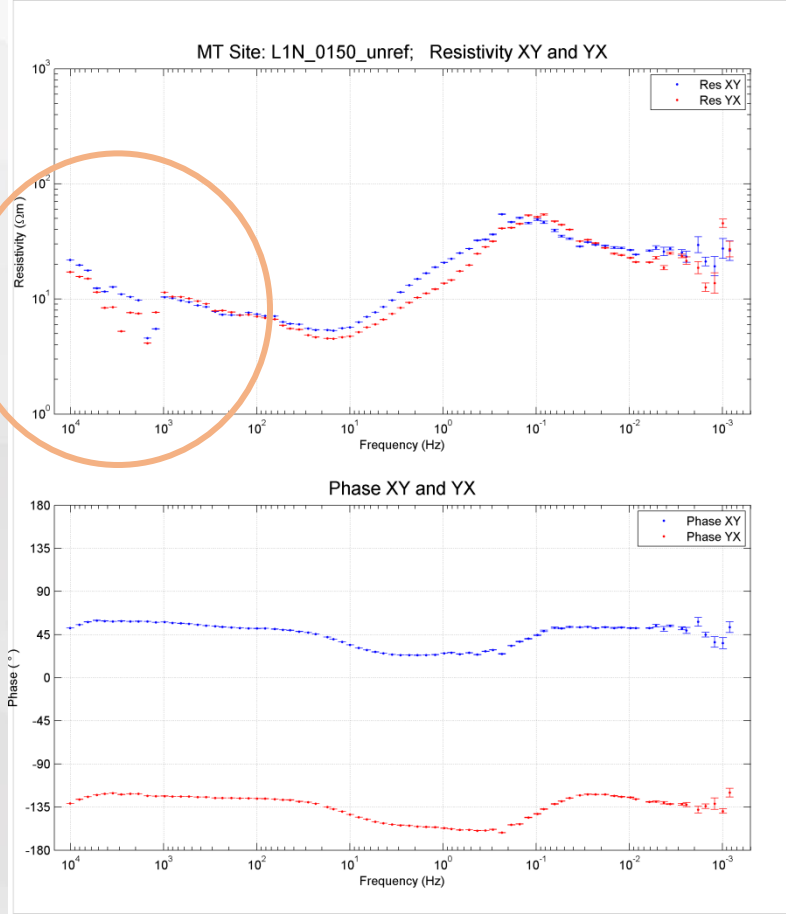




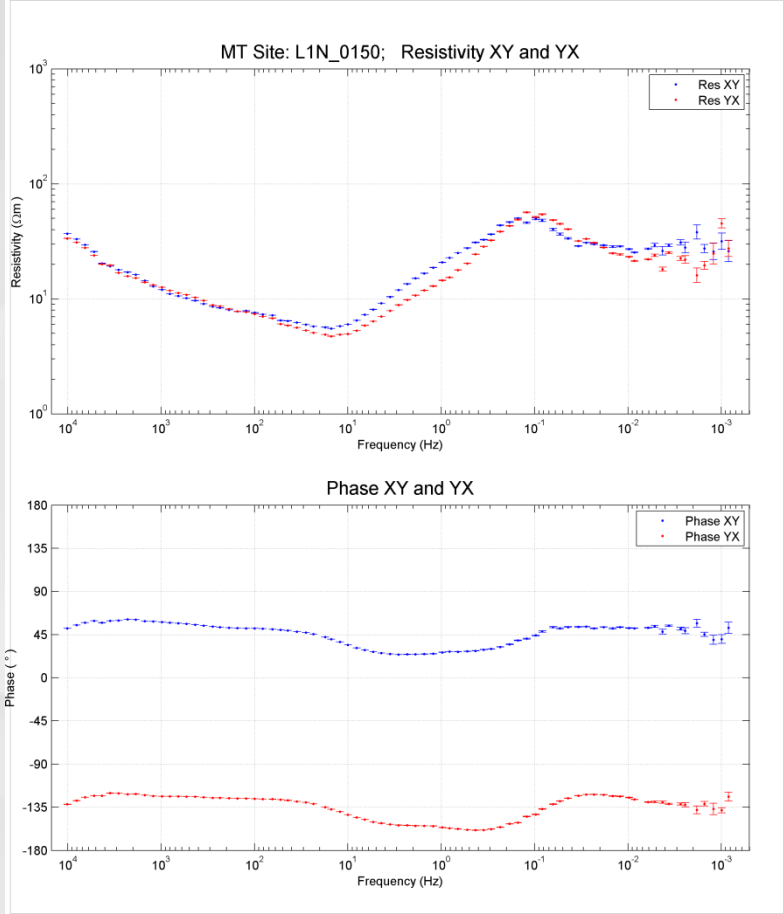
- Field layout for one site
- Plus a remote site

Need for the remote site

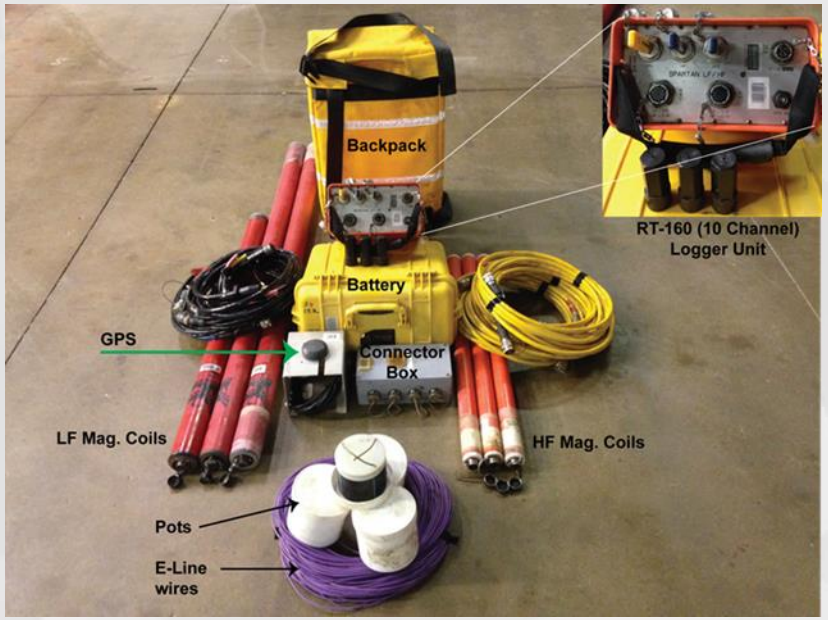
- Un-referenced site



- Referenced site



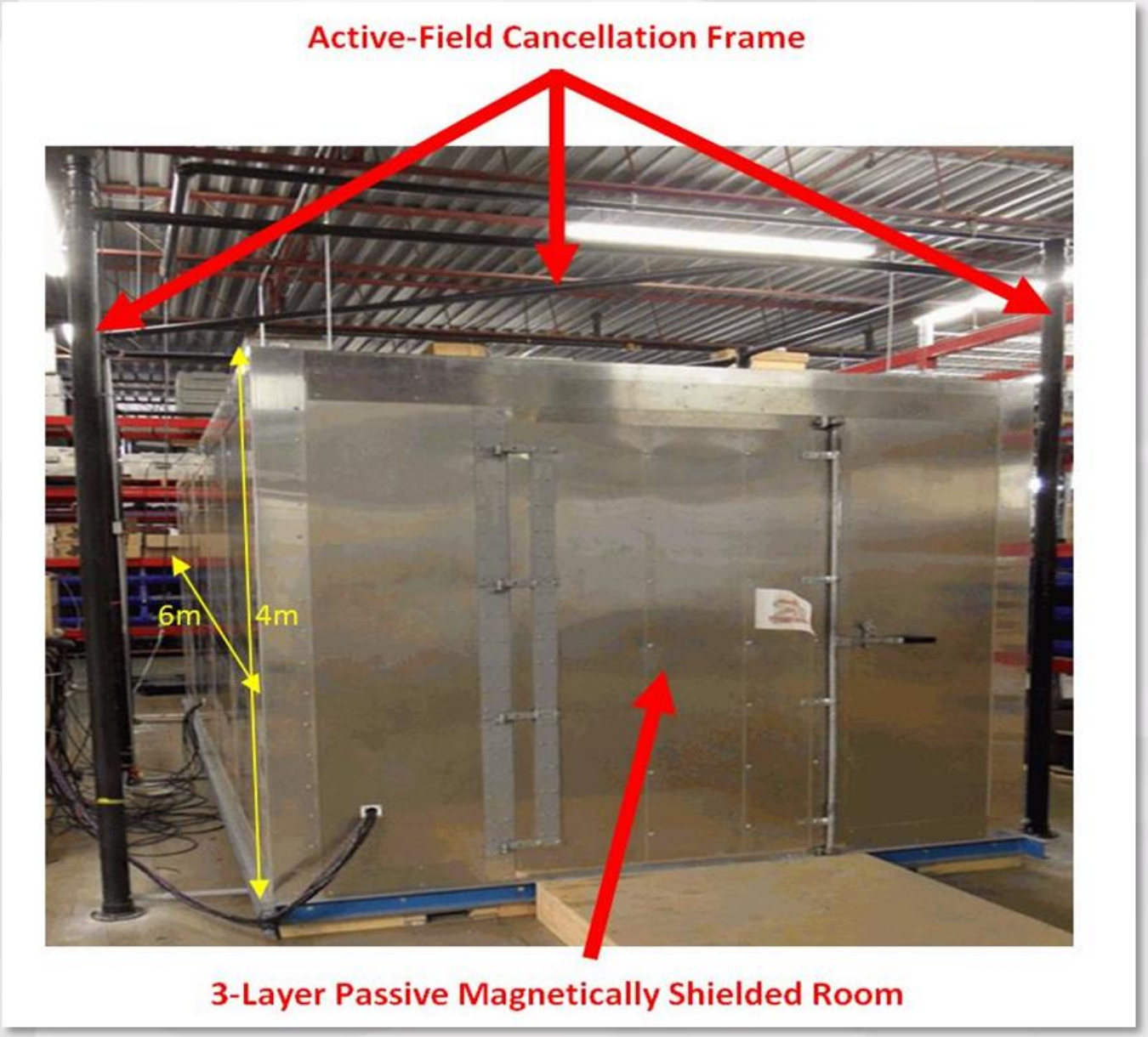
Typical equipment required for one site

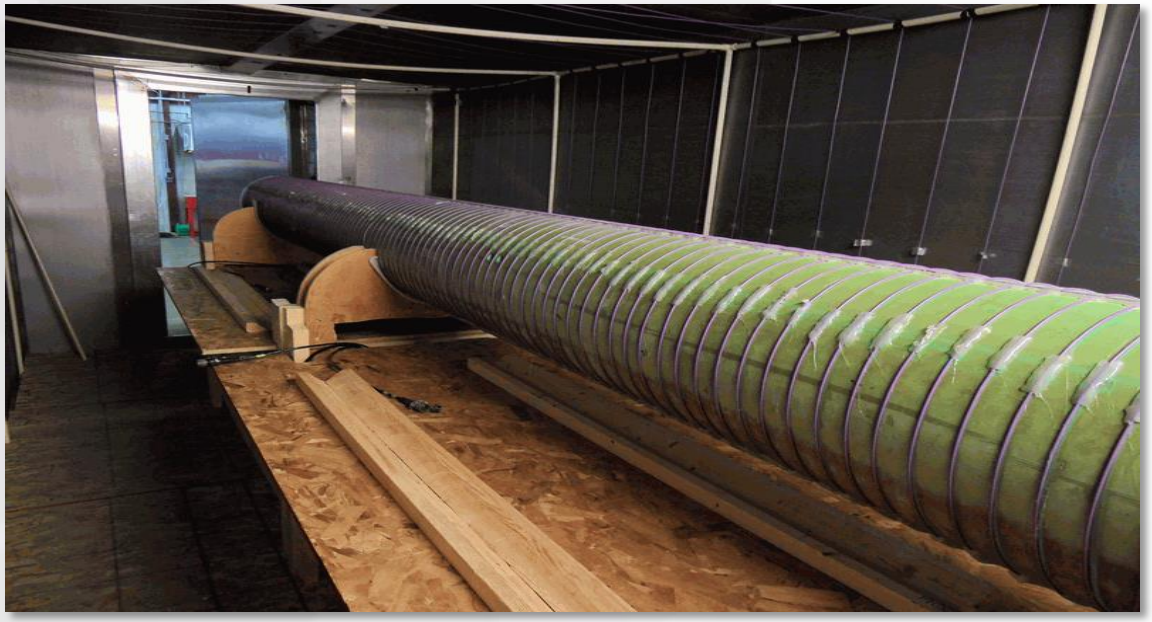


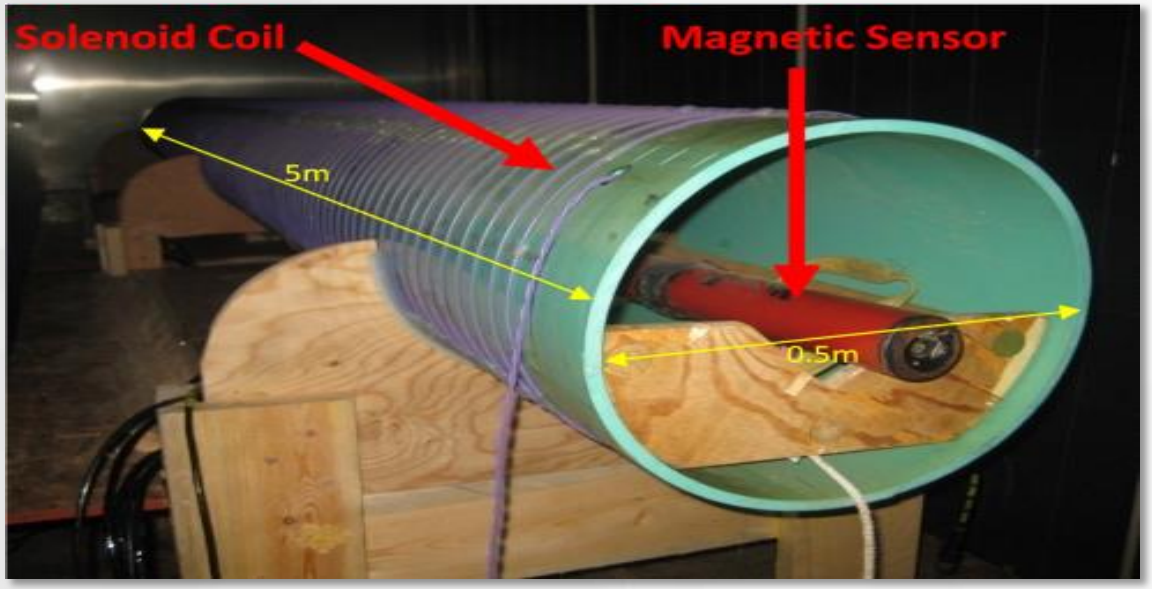
Portable , can go almost anywhere

Testing the coils prior to starting a survey

Calibrated coils



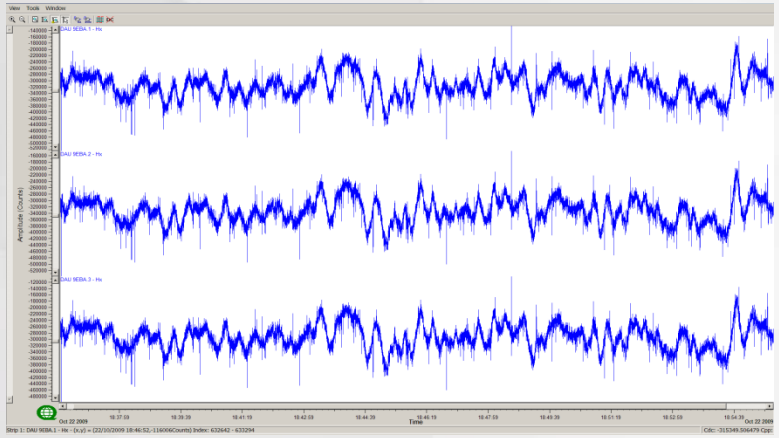




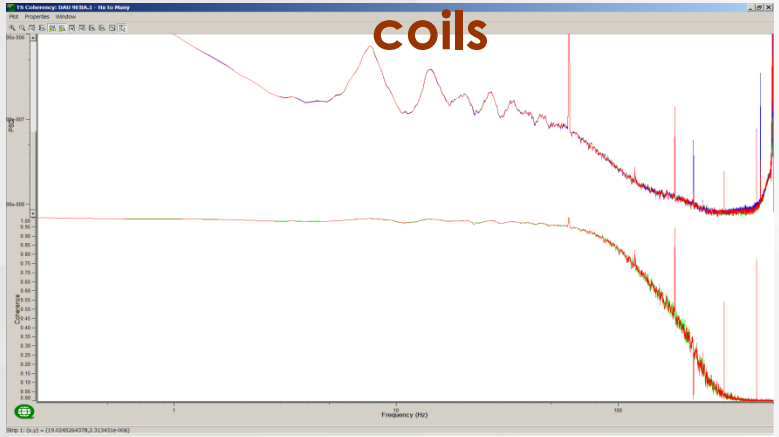
Testing the coils prior to starting a survey

Parallel sensor test

Example of coil layout during a PST



Time series of 3 parallel low frequency coils



Power Spectrum (top) and coherency (bottom) of the coils from the TS shown above


Parallel Sensor Test (PST)


Accessing Site


Preparation


Installation


Levelling


E- Line


Electrode


Contact Made


Quality Control


Overnight Acquisition


Pickup

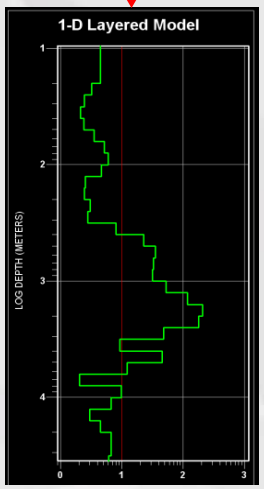
From data collection to product

- **DATA**
- **INVERSION**
- **RESISTIVITY MODEL**

$$\begin{pmatrix} 0 & Z \\ -Z & 0 \end{pmatrix}$$

ρ

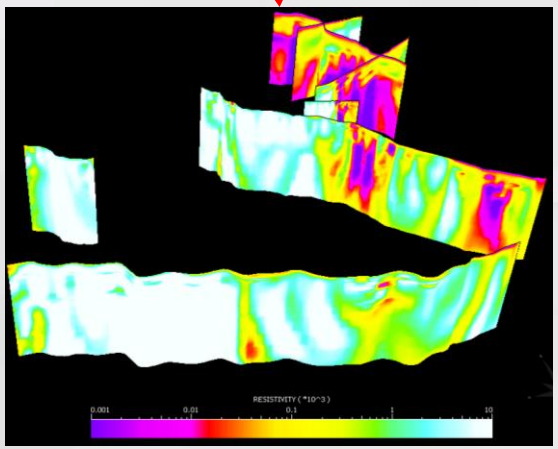
1-D



$$\begin{pmatrix} 0 & Z_{xy} \\ Z_{yx} & 0 \end{pmatrix}$$

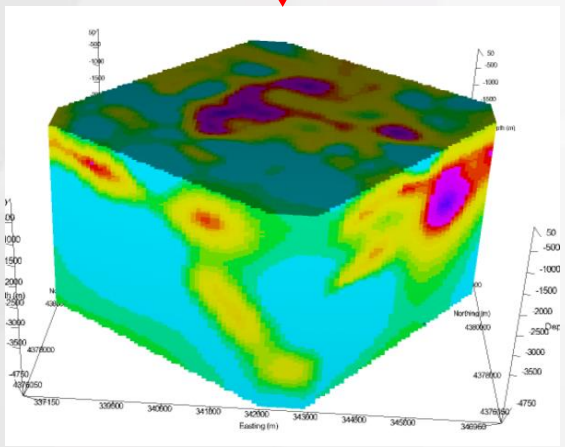
ρ_{xy}, ρ_{yx}

2-D



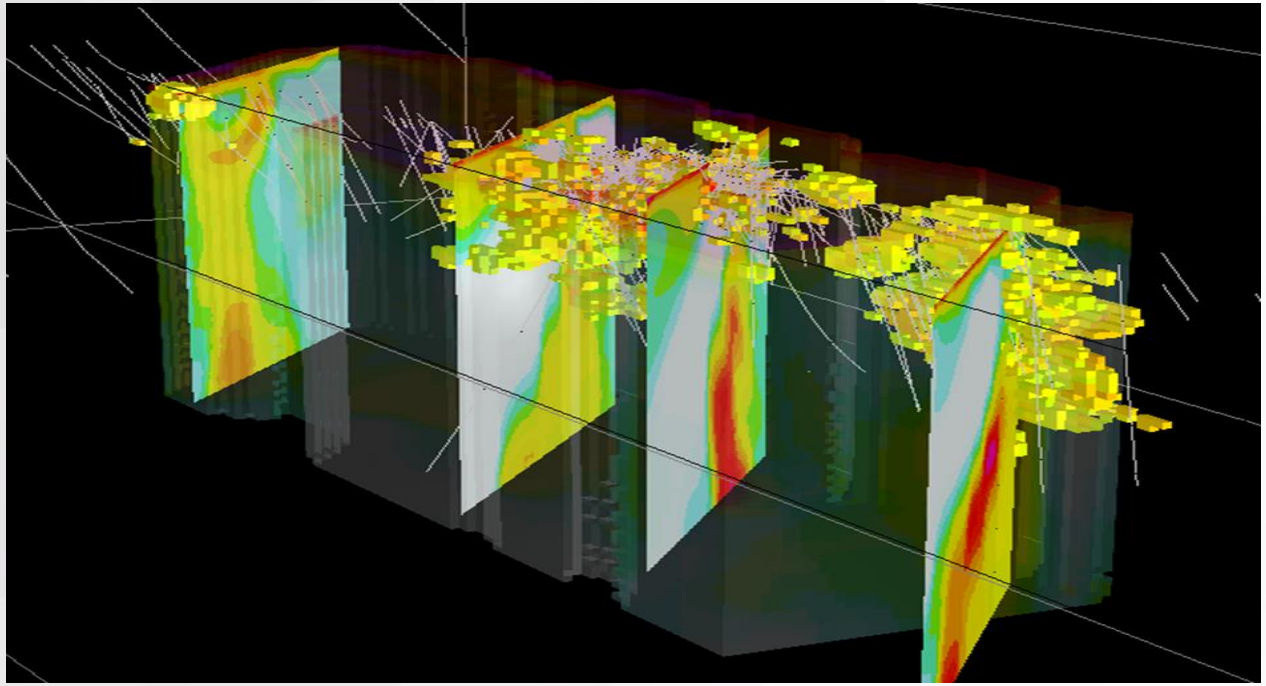
$$\begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}$$

3-D

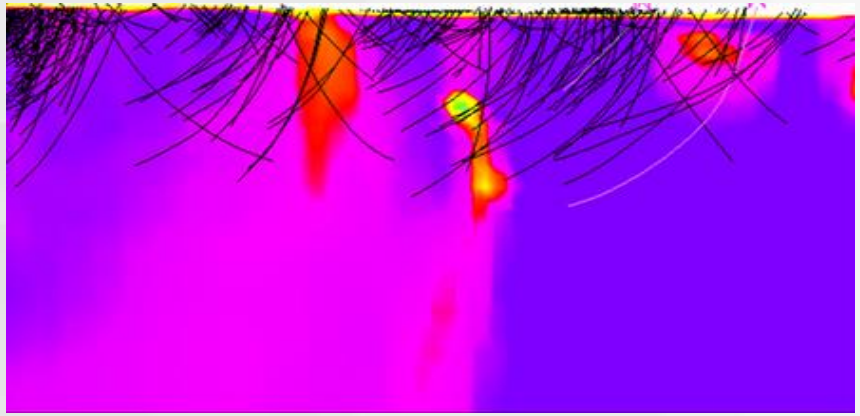


MT applications - flexible resistivity mapping

- **Mining & Exploration**
  - Porphyry exploration
  - Gold exploration
  - Structural mapping - Faults/ shears
  - Near-mine exploration
  - Pre-Mine Risk evaluation
  - Regional potential target evaluation
  - Basin mapping (depth of cover)
  - Crustal studies
- **Oil & Gas**
- **Geothermal**

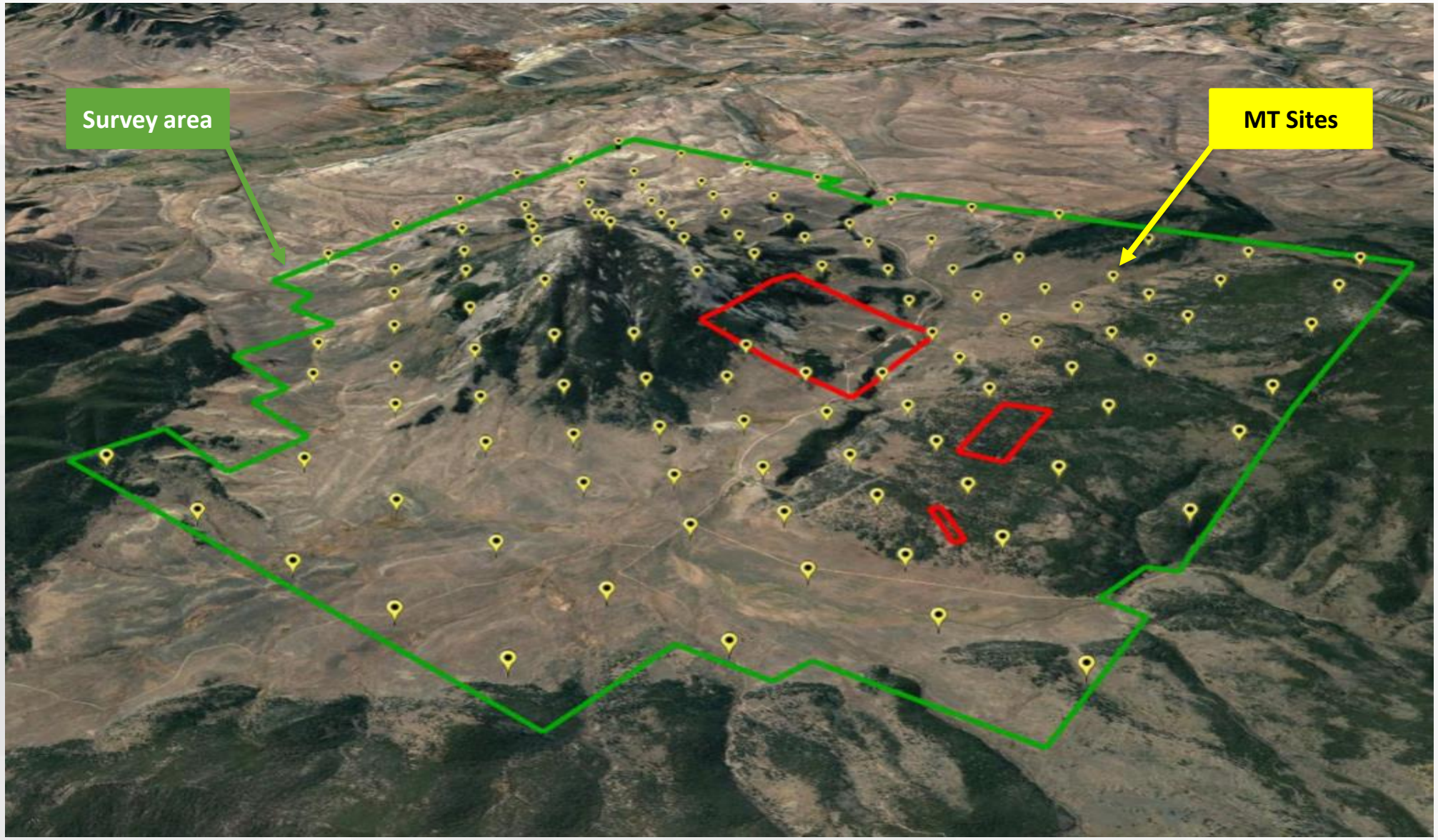


Timmins Camp, Dester Porcupine fault

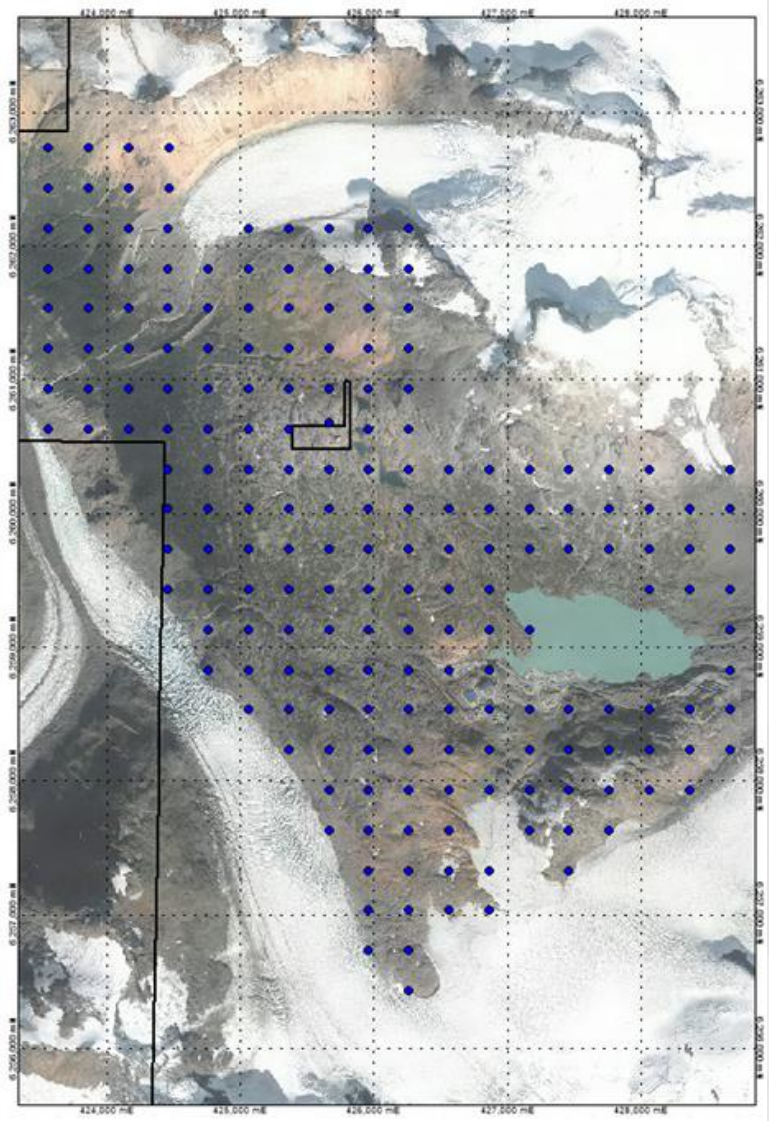


Louvicourt (constrained MT inversion)

Survey design



Planning and costing

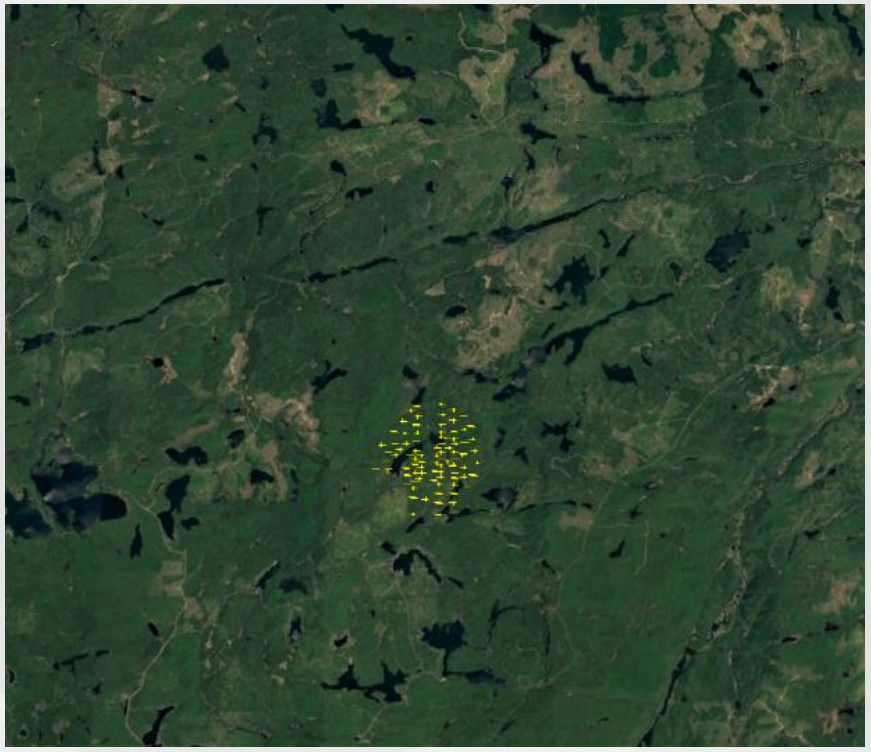


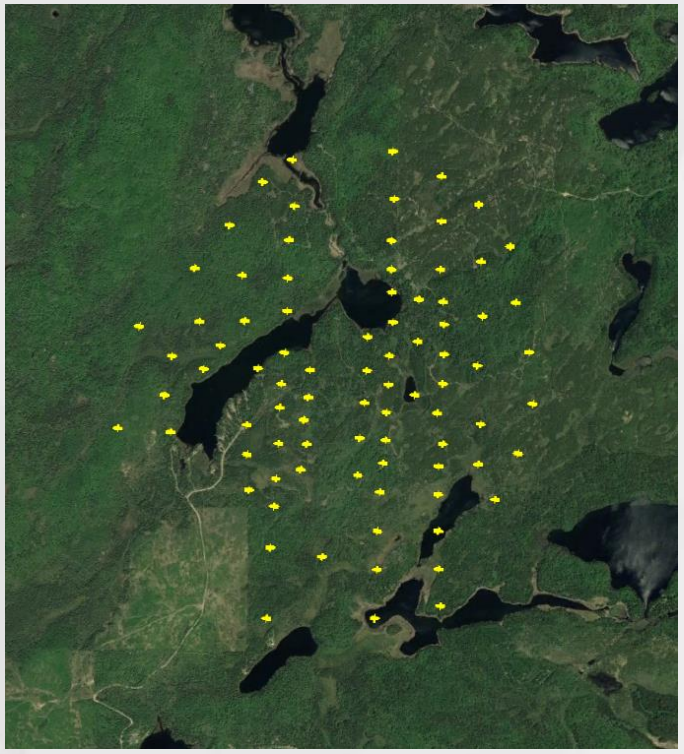
	Services for Project Supplied by Quantec or Client	Quantec	Client
1	Supply of all necessary people, equipment and vehicles as outlined in **A.2** to complete the survey.	y	
2	Data processing and reporting as specified in Schedule D.	y	
3	Accommodation and meals for the Quantec crew for the duration of the survey.	y	
4	Disposables, i.e. gasoline/fuel, water, etc.	y	
5	Communications facilities for data transfer / upload for processing and charging equipment. Suitable internet and 7/24 power.	y	
6	Maps and survey files of idealized GPS defined coordinates and location details in digital format must be delivered to Quantec prior to field data collection.		y
7	Vehicular access to project site as well as within grid survey area. This includes roads cleared to allow for the required access by a 4x4 pickup truck to the project site and open roads to the active portions of the survey area.		y
8	Permits, site access, fees and landowner consents needed to access the survey area. Should there be any delays due to these items, standby charges may apply.		y
9	Site-specific training as required by Client including: safety and emergency procedures, environmental procedures, and social procedures for handling local residents, landowners or labour.		y

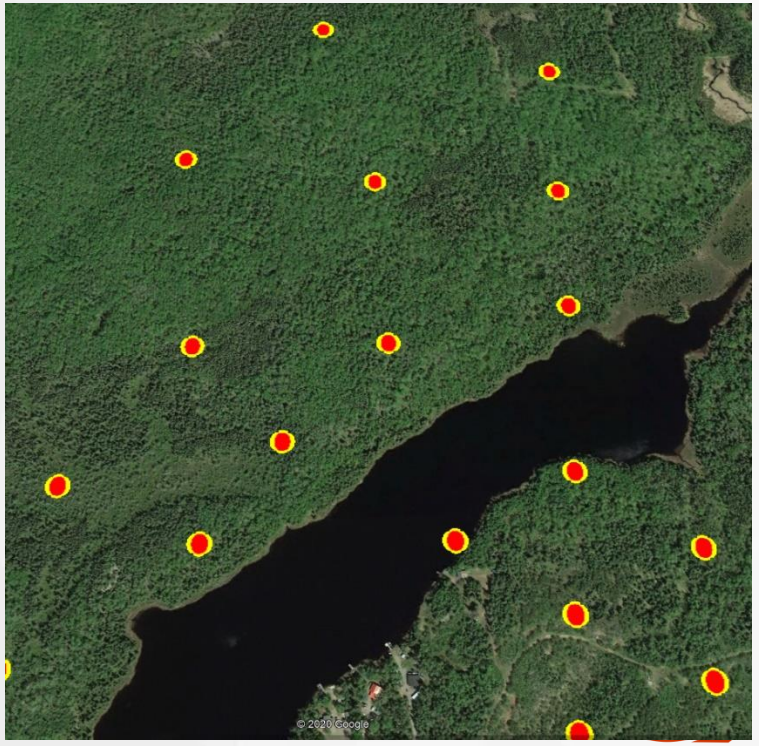
- approx. 205 sites
- 35 days
- $ k /day
  - Crew size dependant

Typical survey plan

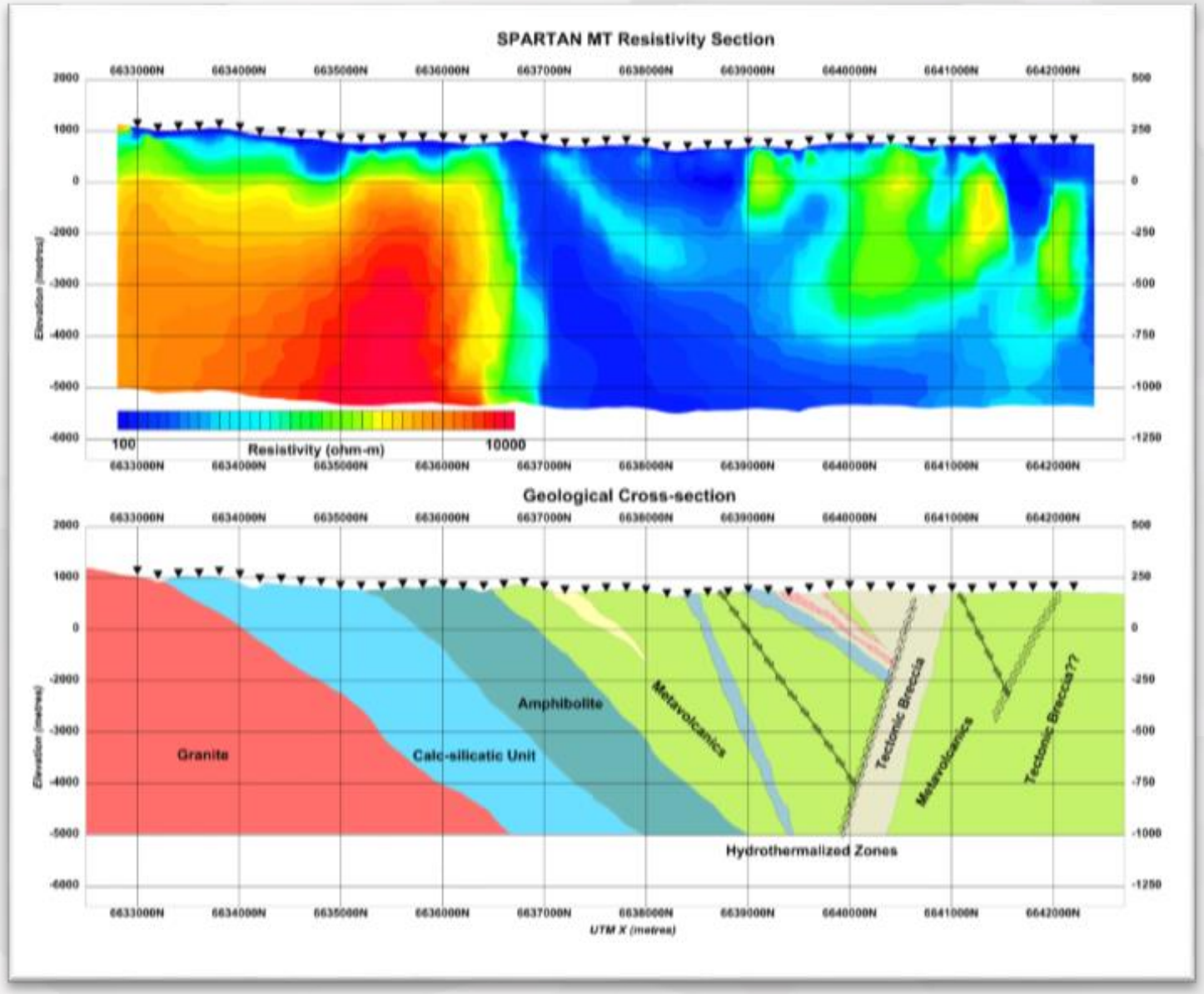
- approx. 90 sites
- covering 2.5 x 2.5 km
- 21 days for 5 man crew
- $ k





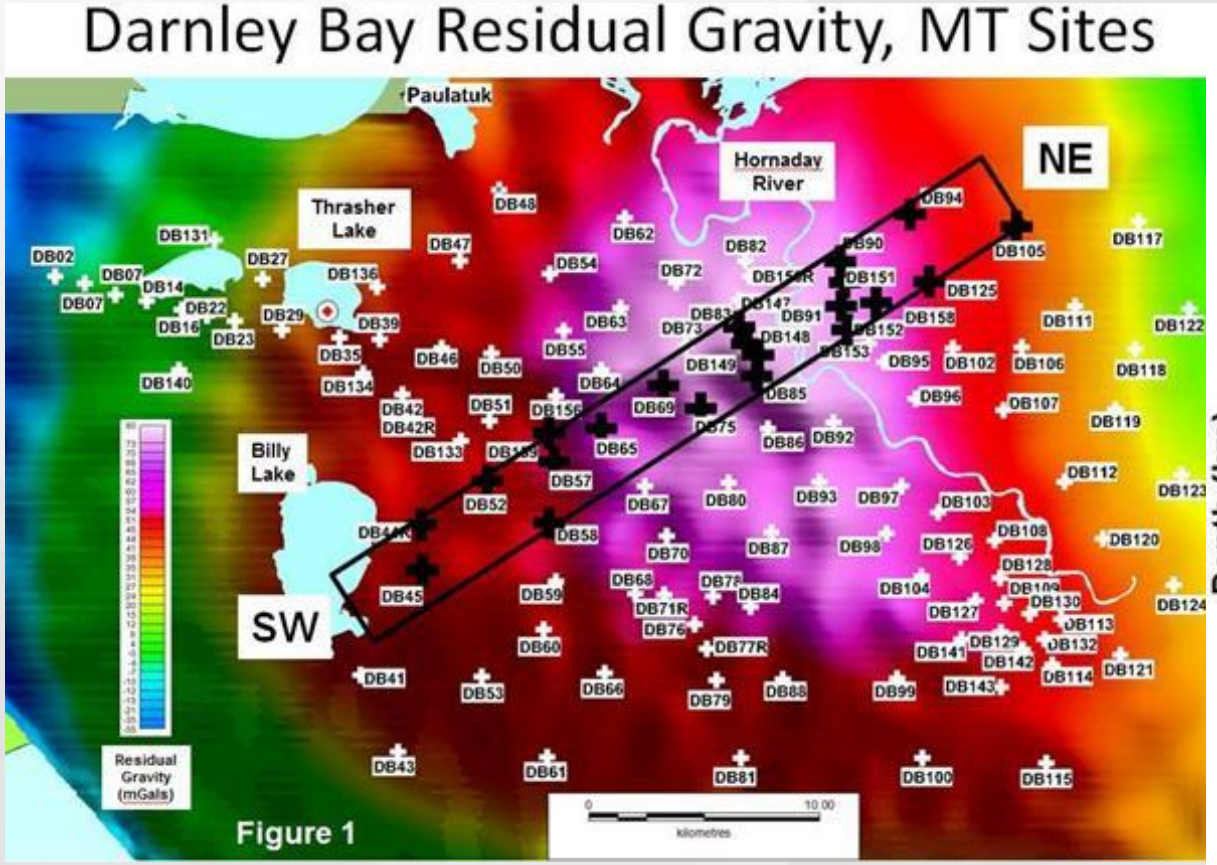


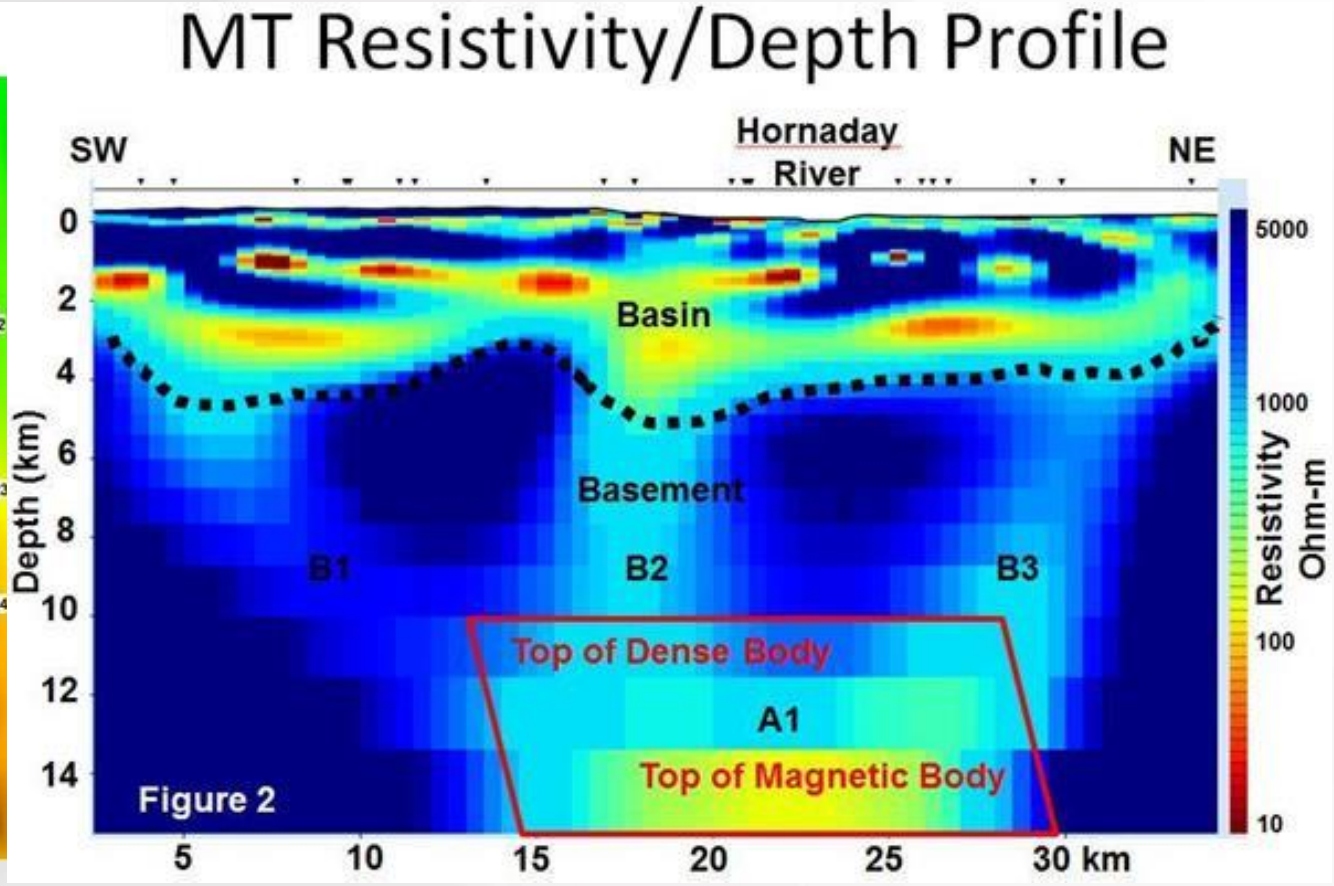
Single line transects



- 2D Inversion shown

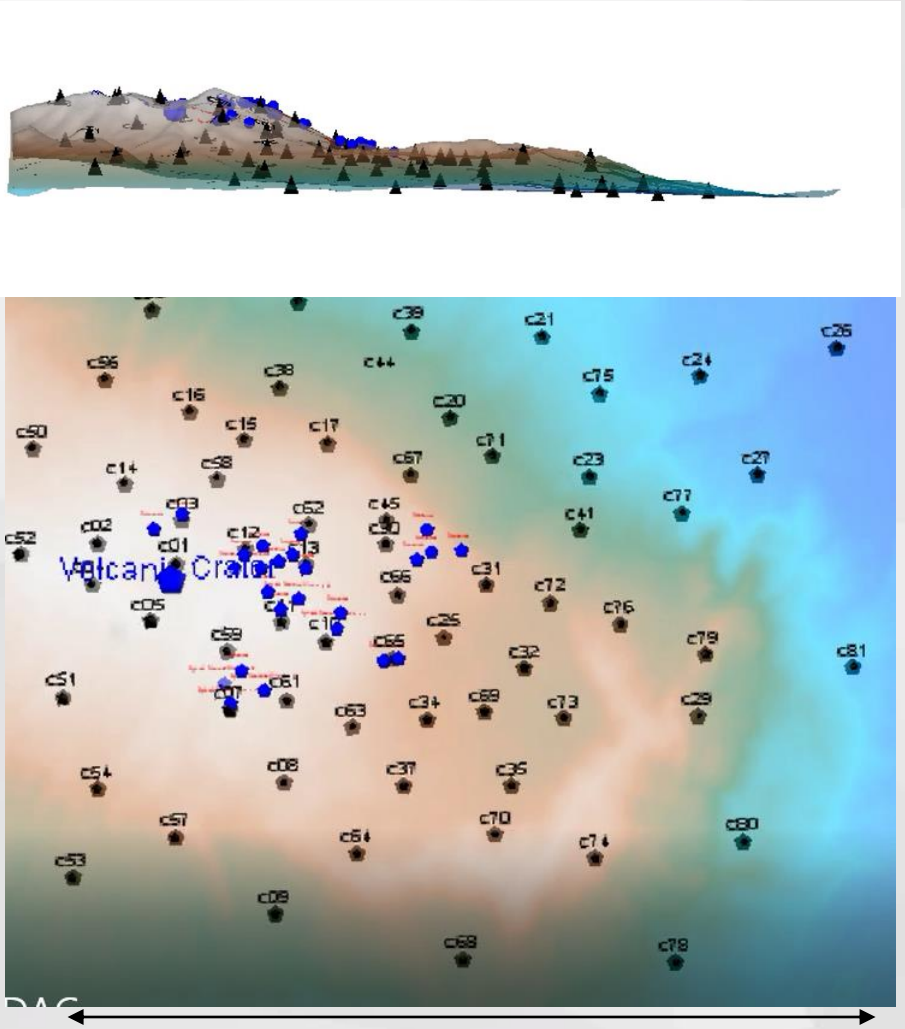
Generation Mining - regional survey (NWT 2018)

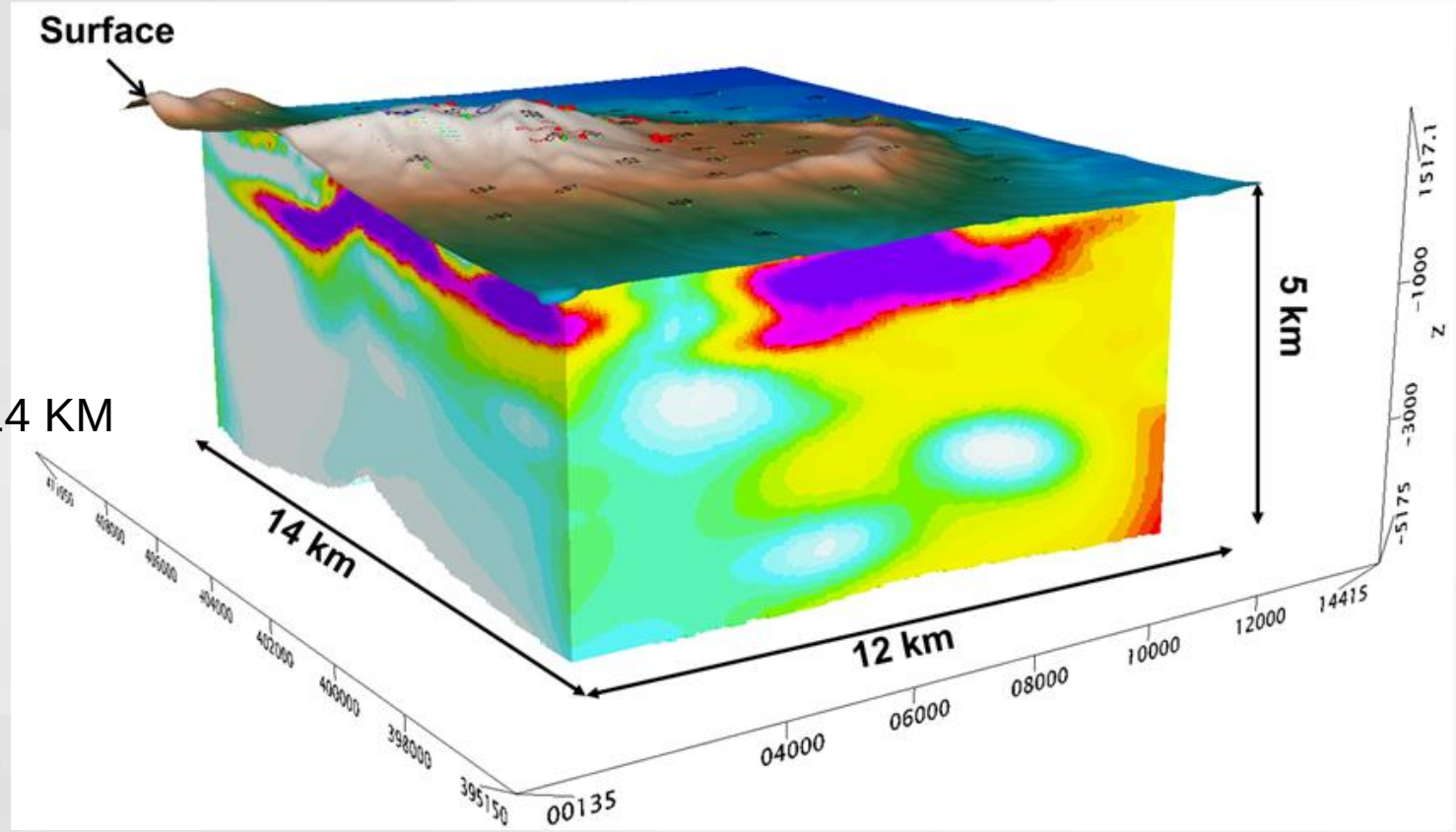




SPARTAN MT

SPARTAN MT survey - plan & results for regional study

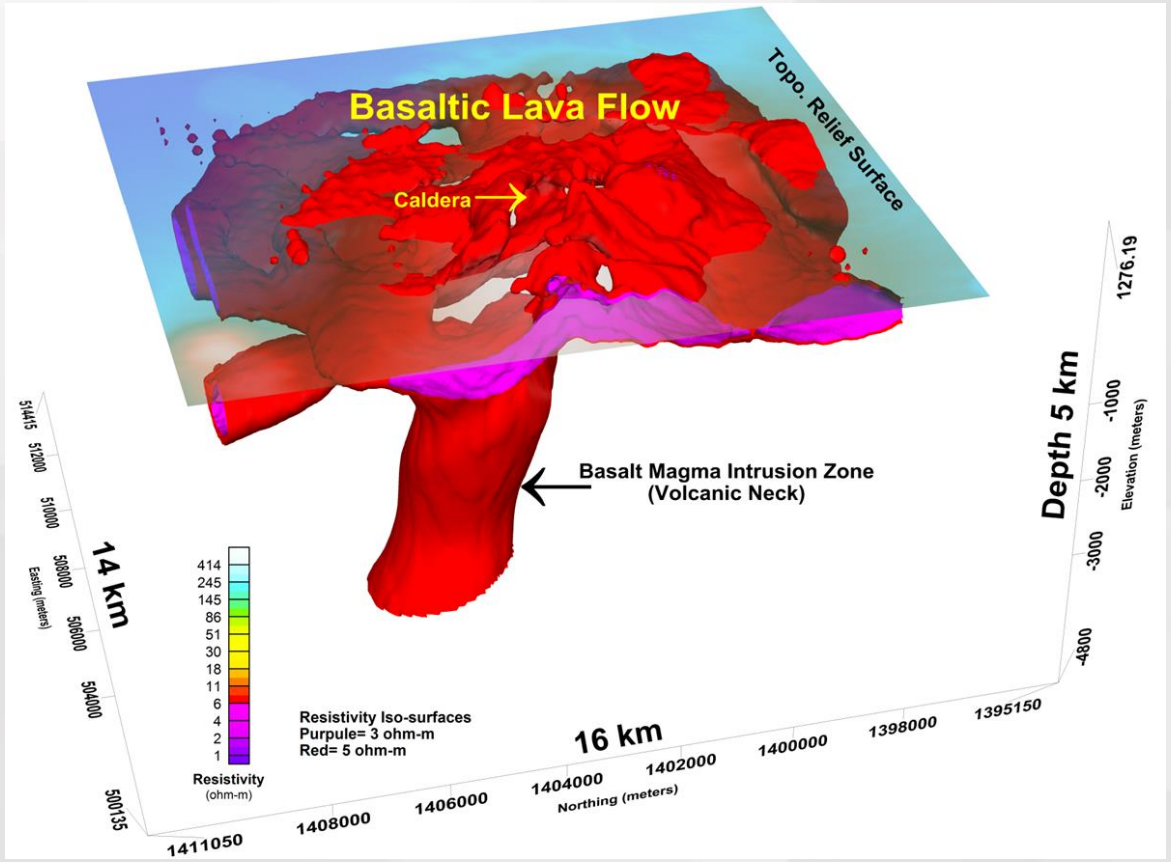


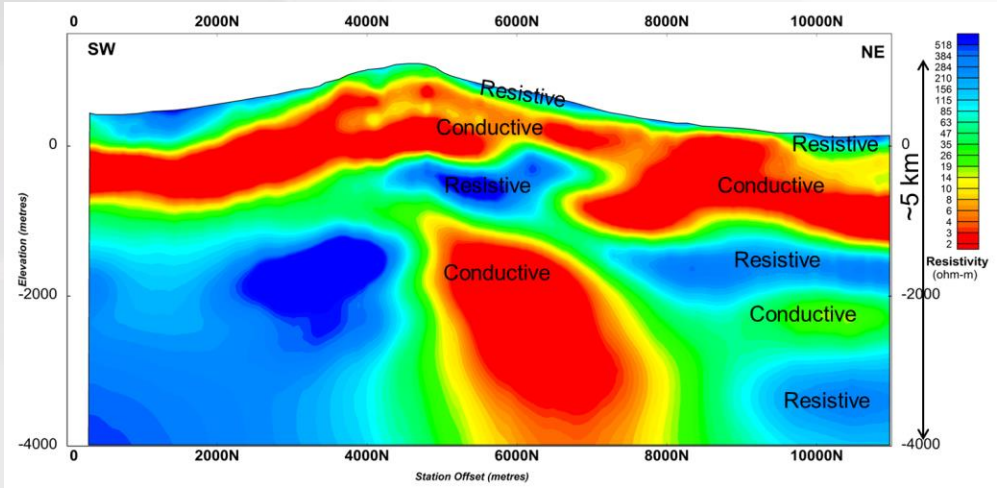


3D Resistivity model

SPARTAN MT

Iso shells depicting low resistivity (volcanics)





- 2D resistivity slice from 3D model

- Iso shell depicting low resistivity range

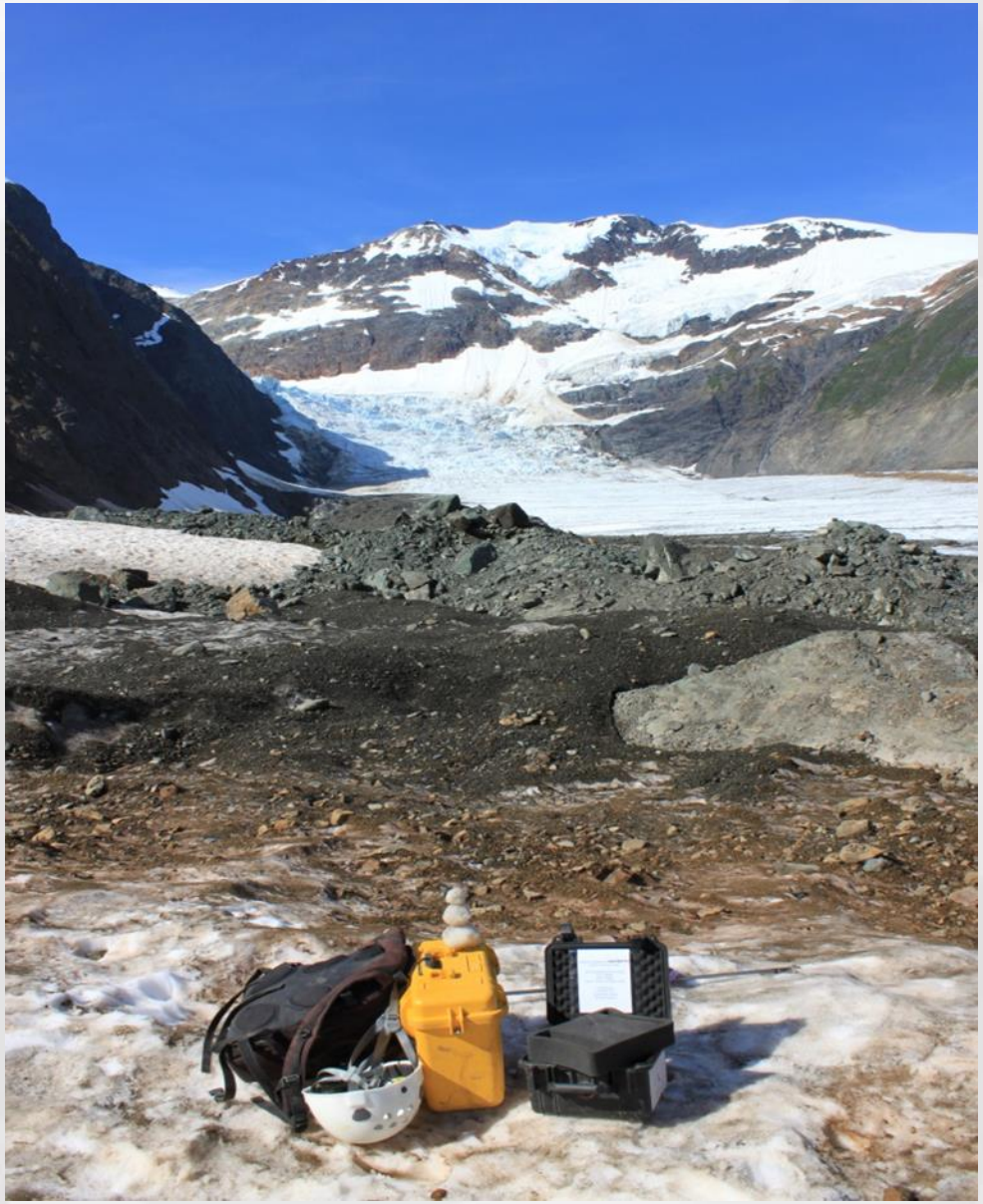
SPARTAN MT

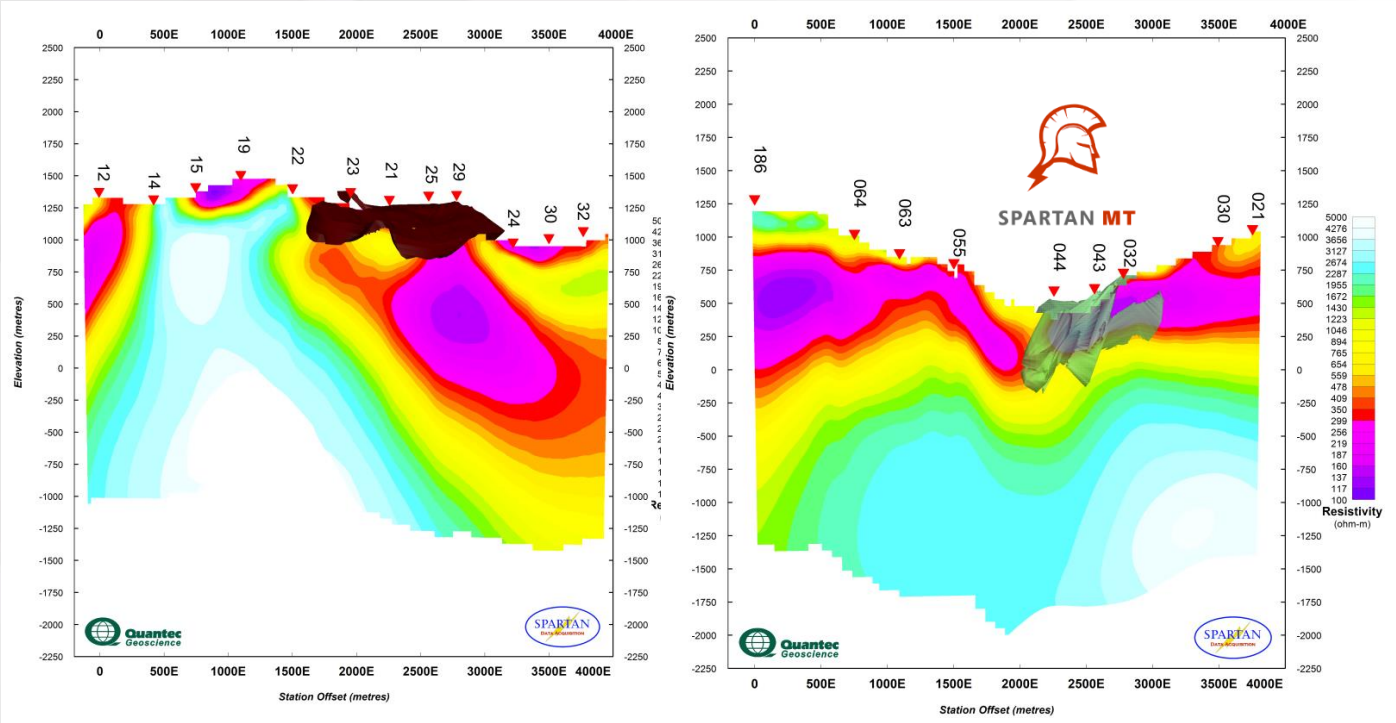
Seabridge Gold, British Columbia
Kerr-Sulphurets-Mitchell property: porphyry exploration

Exploration Objectives:

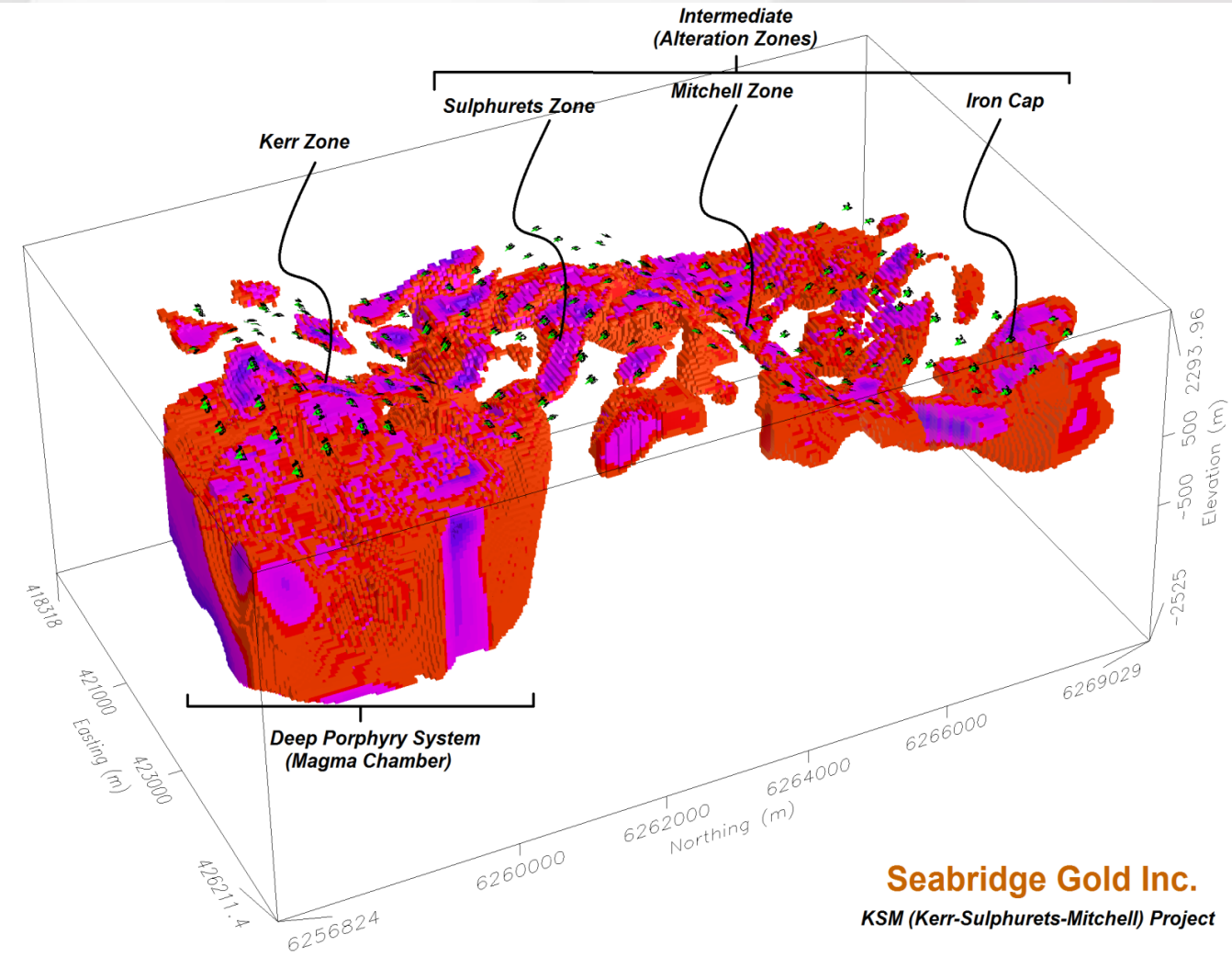
- **Map potential targets to depths of 2000m and greater with increased resolution.**
- **Establish an understanding of the geological system and fluid pathways to great depth within the KSM survey area.**
- **Detect porphyry rich mineralization and/or associated alteration zones to depth for drill targeting.**
- **Complete an orientation survey to identify additional conductive zones or 'blind' conductors in the area.**

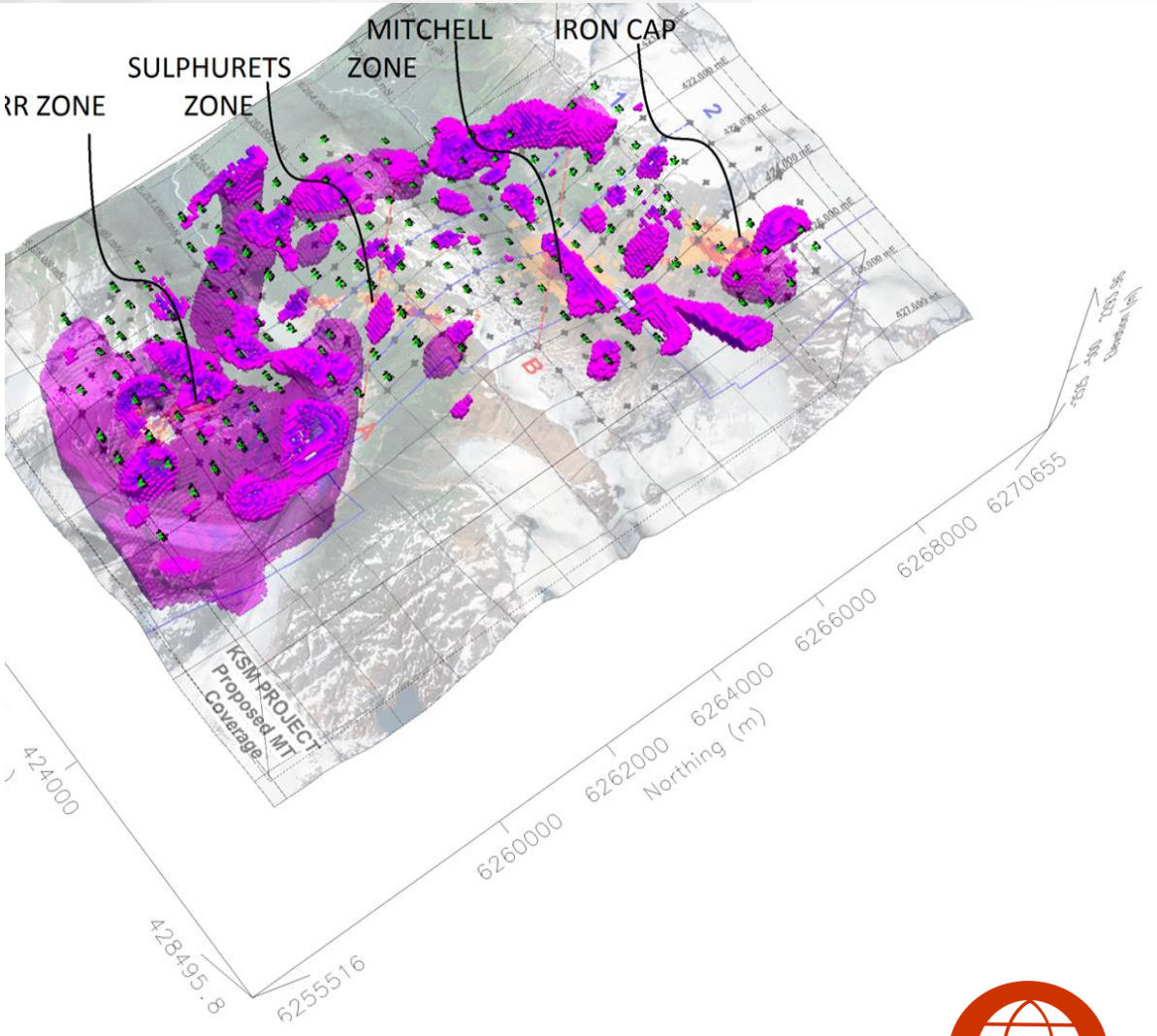
Seabridge Gold- SPARTAN MT results





Resistivity results in 3D

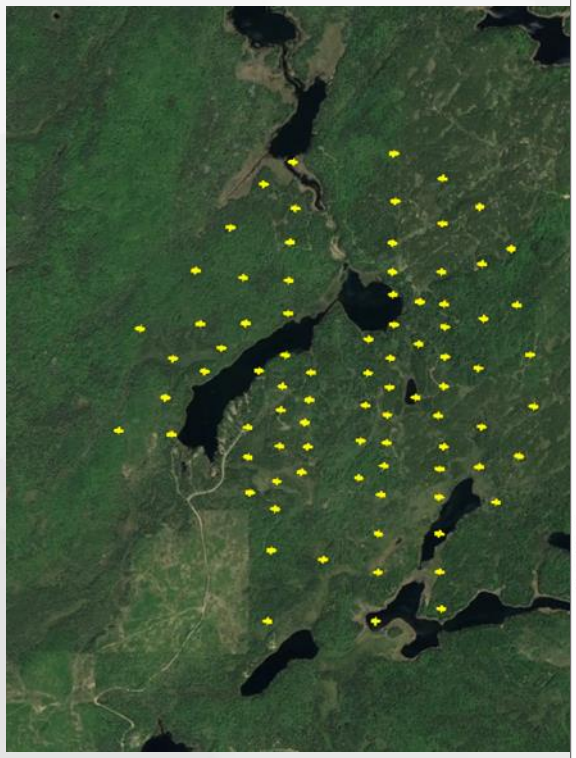


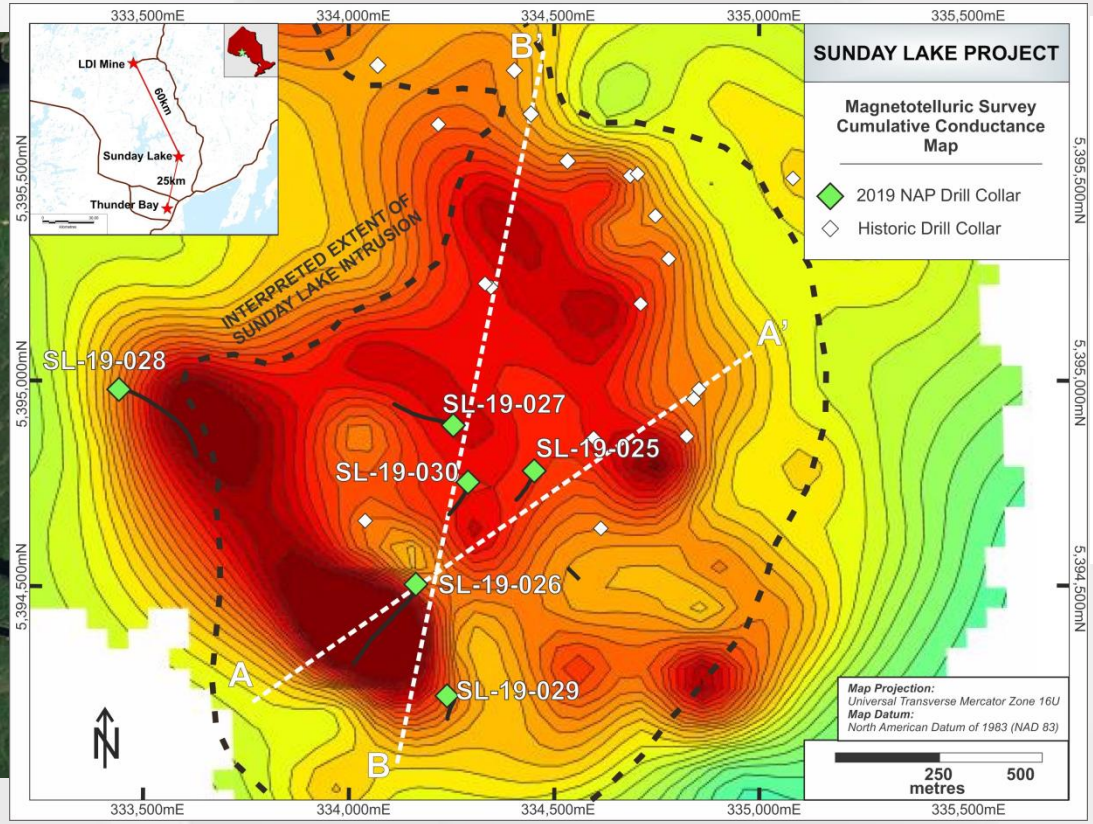


Seabridge Gold Inc.

KSM (Kerr-Sulphurets-Mitchell) Project

Sunday Lake - Pt/Pd exploration





Hole#	Area	Target		From (m)	To (m)	Length (m)	Pt (g/t)	Pd (g/t)
19-025	Central	BHEM		1013.00	1027.80	14.80	1.33	0.90
"	"	"	inc.	1020.00	1022.30	2.30	2.47	1.48
"	"	"	and	1026.20	1027.80	1.60	2.95	1.93
19-026	West	MT		1392.00	1433.20	41.20	3.22	2.08
"	"	"	incl.	1417.40	1433.20	15.80	5.42	3.35
"	"	"	with	1418.85	1427.15	8.30	7.67	4.97
"	"	"	and	1425.24	1427.15	1.91	9.29	7.12
"	"	"	and	1425.24	1425.90	0.66	9.90	9.27
19-029	West	MT		1405.00	1466.00	61.00	1.23	0.82
"	"	"	inc.	1433.00	1465.00	32.00	1.89	1.23
"	"	"	inc.	1443.00	1449.00	6.00	2.87	1.94
"	"	"	and	1454.00	1465.00	11.00	2.73	1.72
"	"	"	inc.	1455.46	1463.63	8.17	3.16	1.96
"	"	"	and	1461.00	1463.00	2.00	3.46	2.17
19-030	Central	BHEM		1067.39	1088.00	20.61	1.04	0.76
"	"	"	inc.	1067.39	1079.00	11.61	0.79	0.59
"	"	"	and	1082.50	1088.00	5.50	2.05	1.50

- Intersections at 1000 – 1460 metres

https://impalacanada.com/investors/news/news-details/2019/North-American-Palladium-Announces-Major-Expansion-to-Sunday-Lake-PGM-Zone-and-Best-Drilling-Results-to-Date/default.aspx

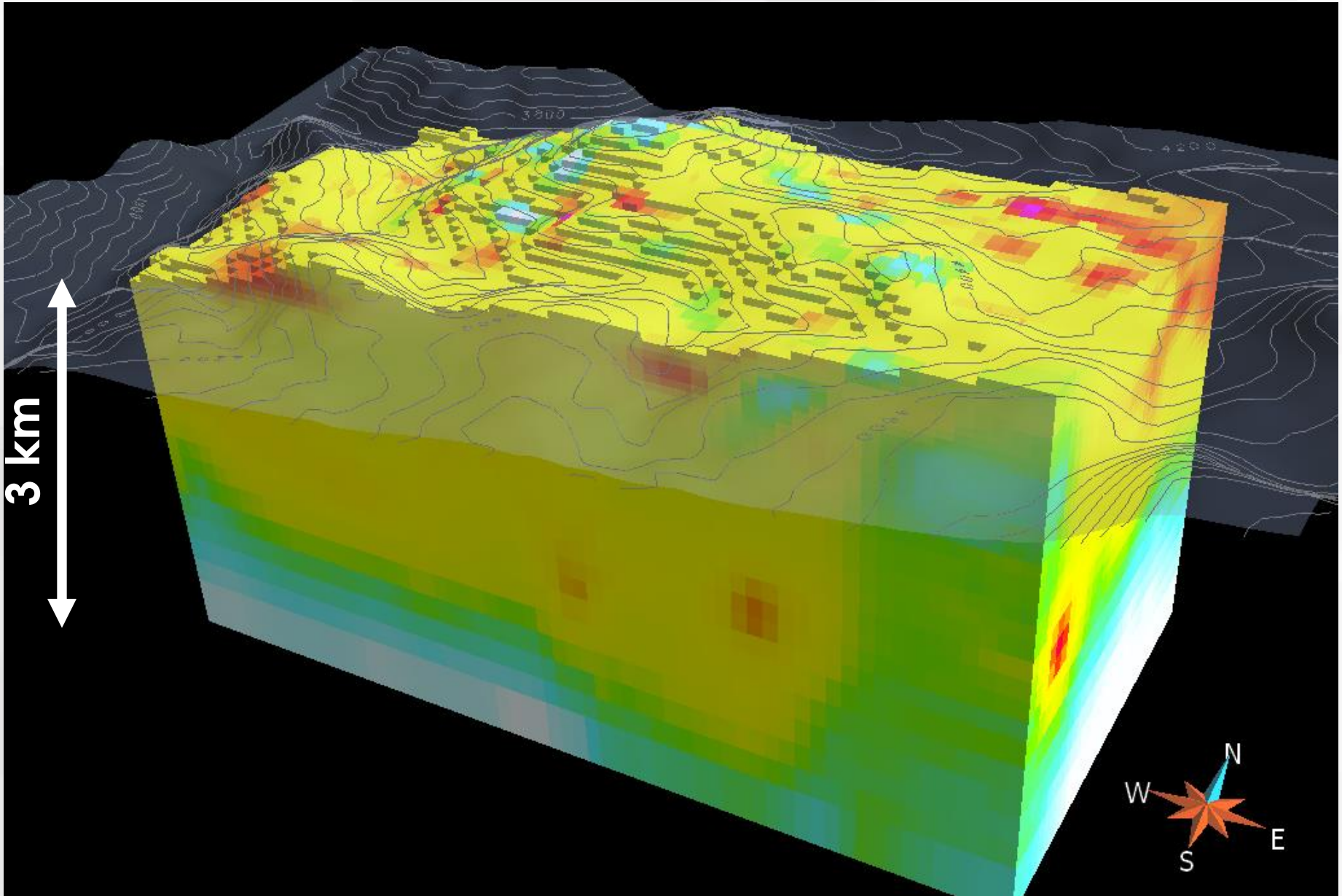
Santa Cecilia

- Location, High Western Cordillera,

  Maricunga Belt.
- Intensive Hydrothermal alteration.
- Magnetic, CSAMT and ORION 3D DCIP/MT.

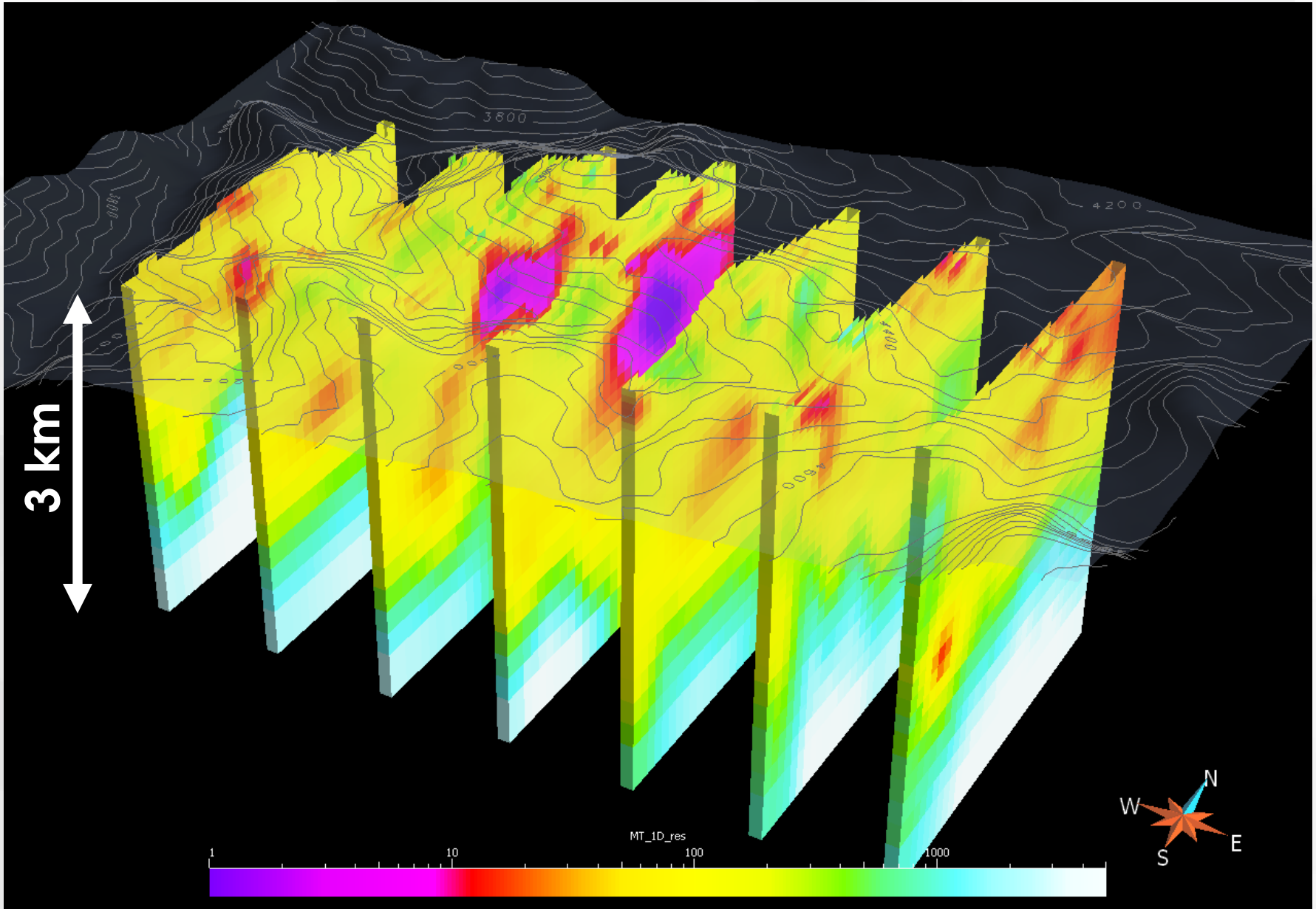
ORION 3D

3D MT Model



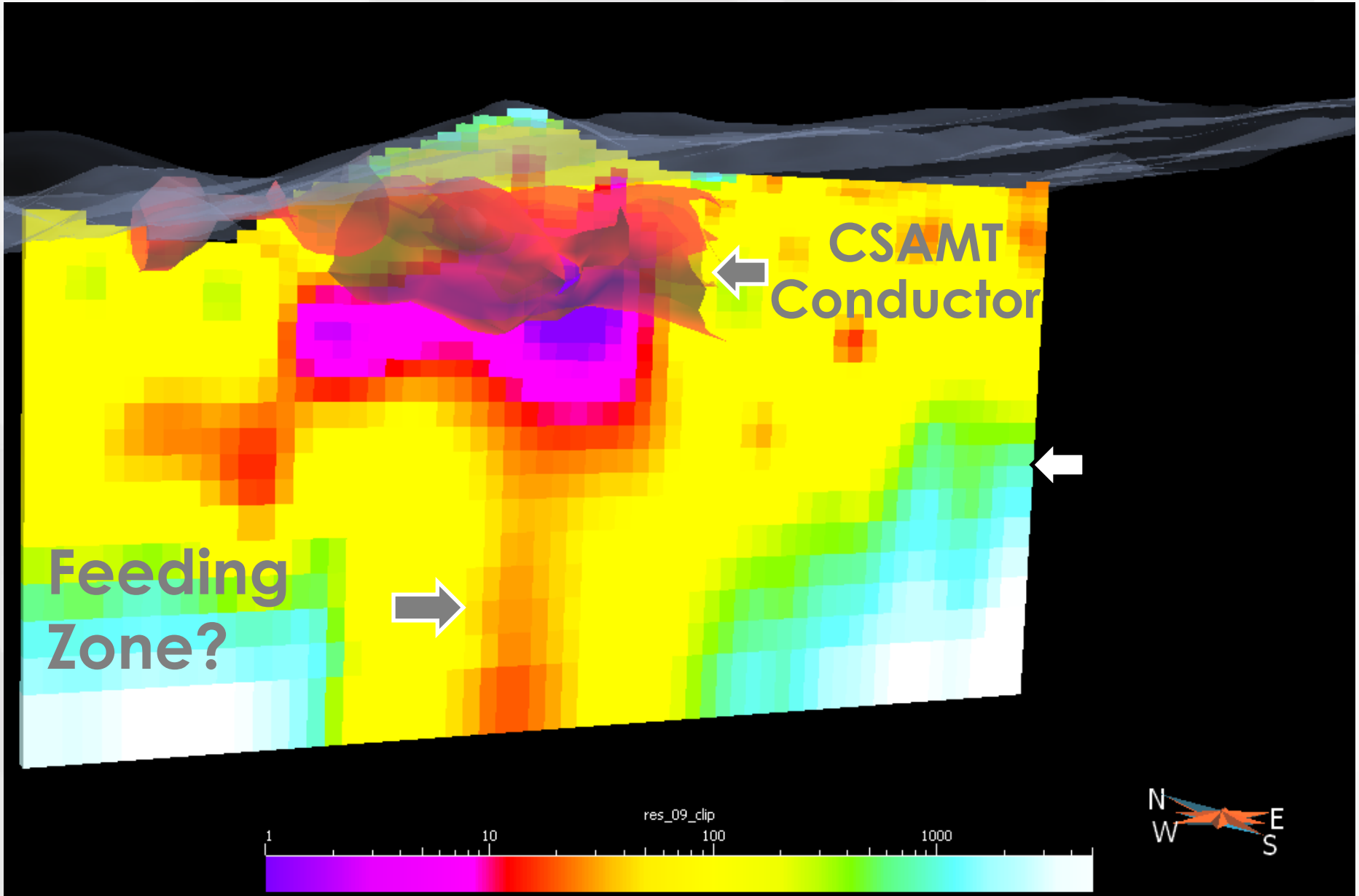
ORION 3D

3D MT Model



ORION 3D

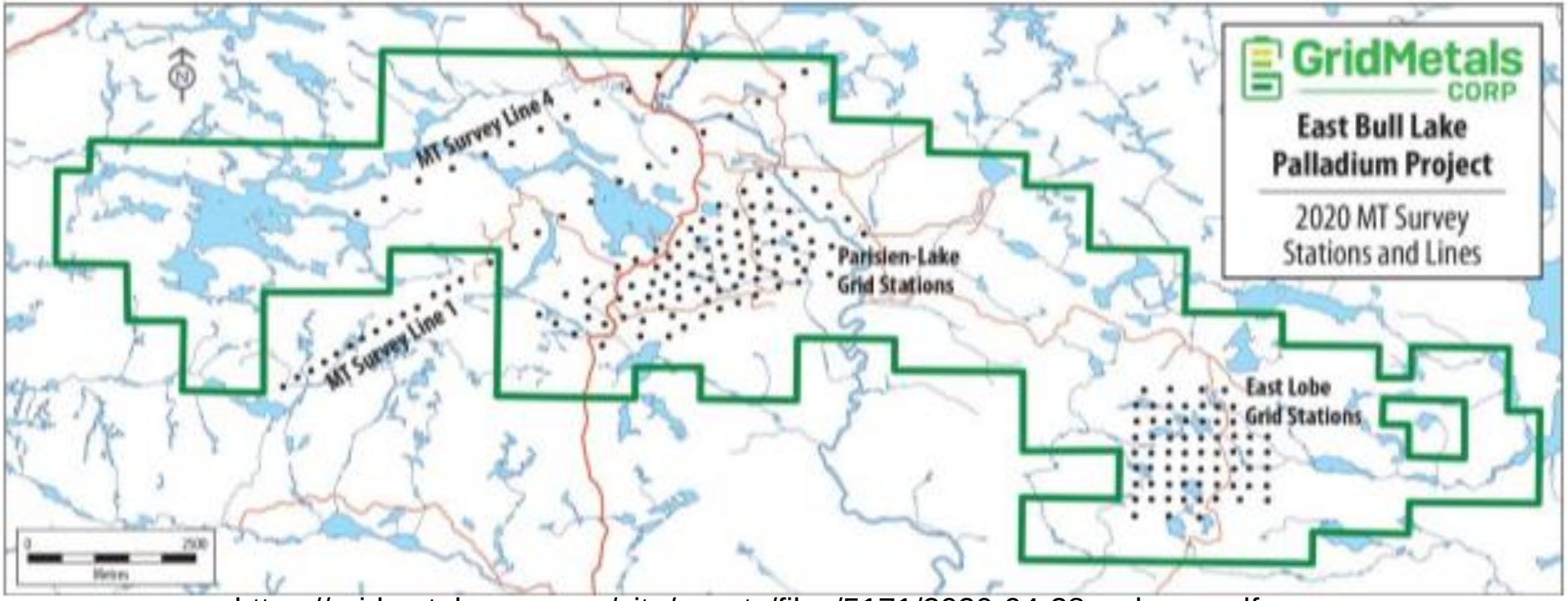
3D MT plus CSAMT conductive zone



ORION 3D

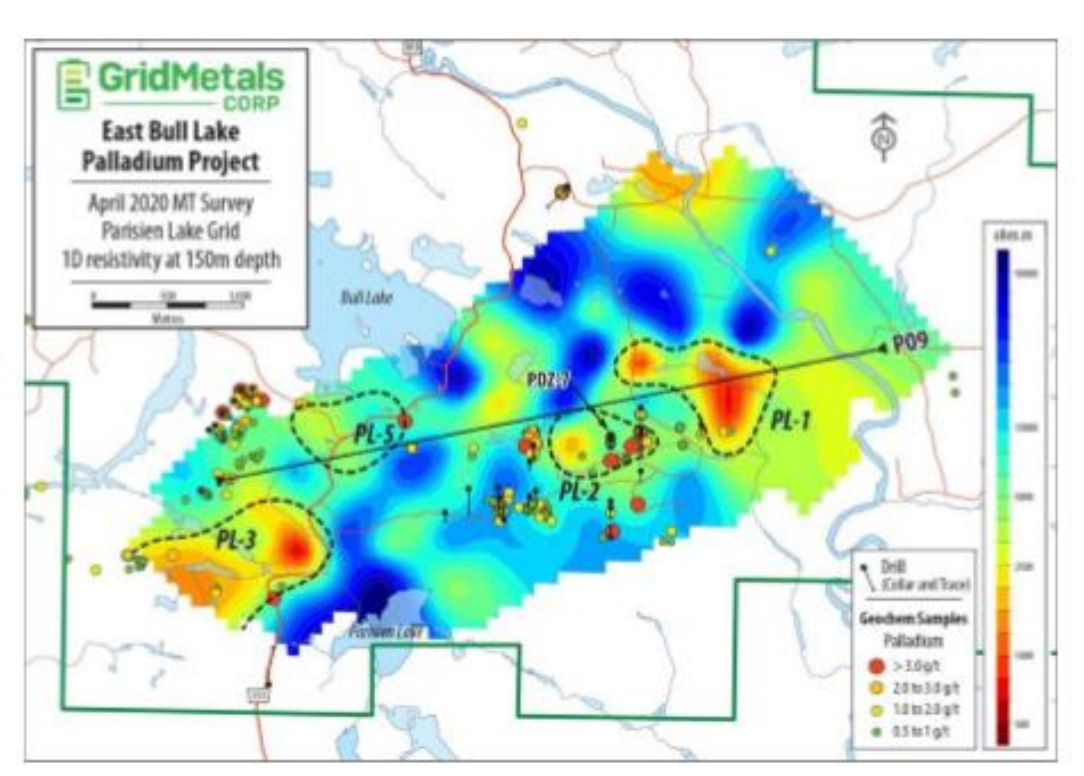
Grid Metals Exploration - ongoing

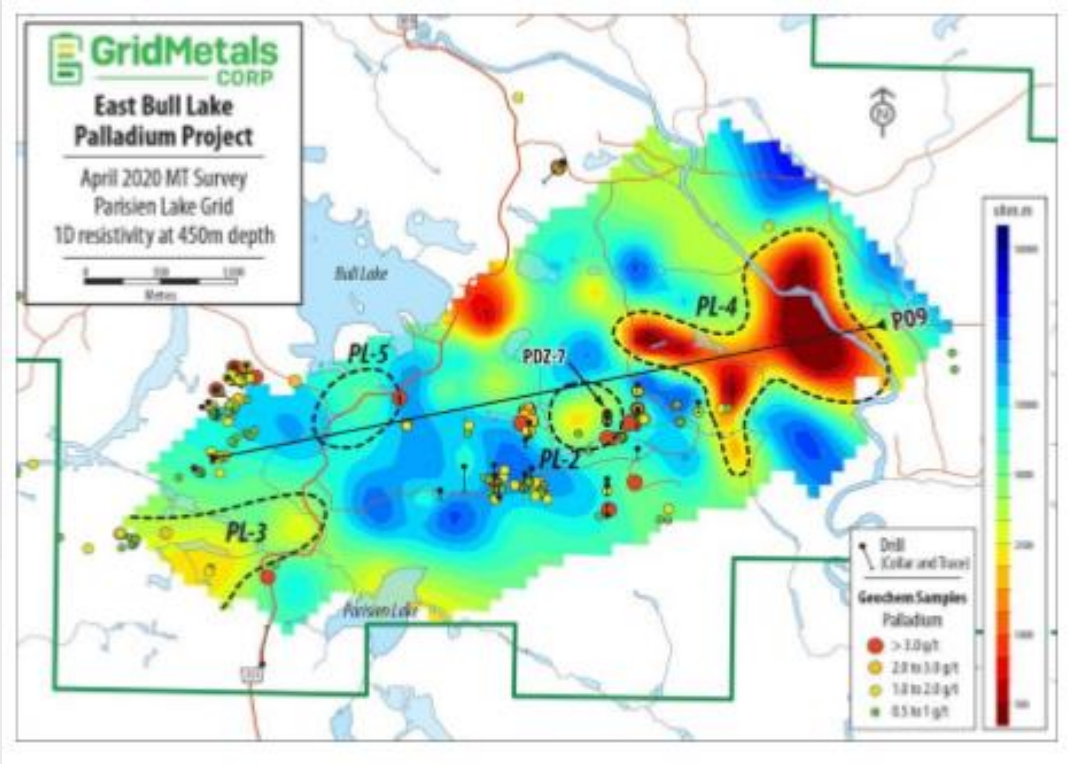
Figure 2. Location of planned magnetotelluric survey station sites on the East Bull Lake property with mapped extent of the East Bull Lake intrusion (filled blue polygon). Both the Parisien Lake and the East Lobe grids are have been completed.



https://gridmetalscorp.com/site/assets/files/5171/2020-04-28-grdm-nr.pdf

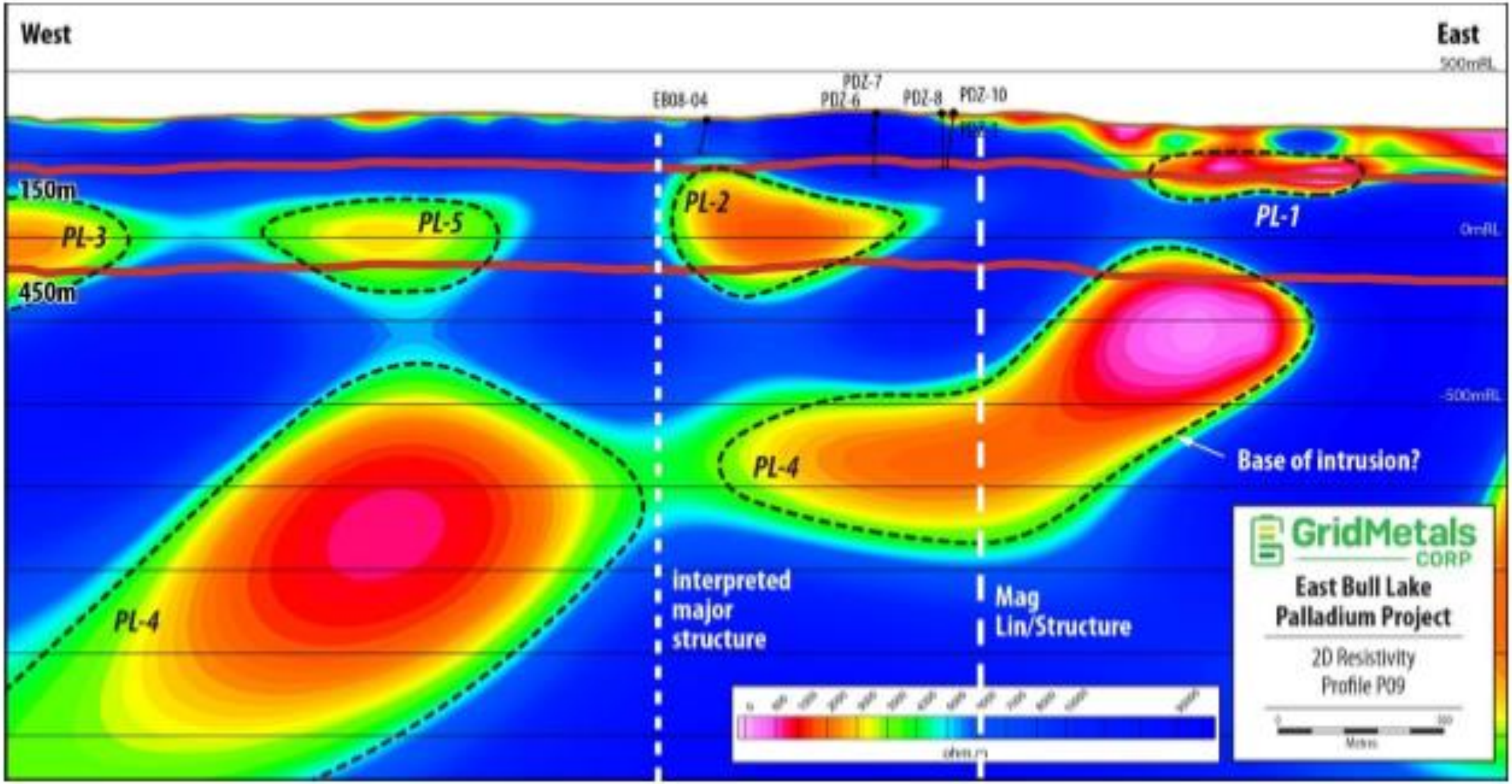
Resistivity depth slices at 150m and 450m





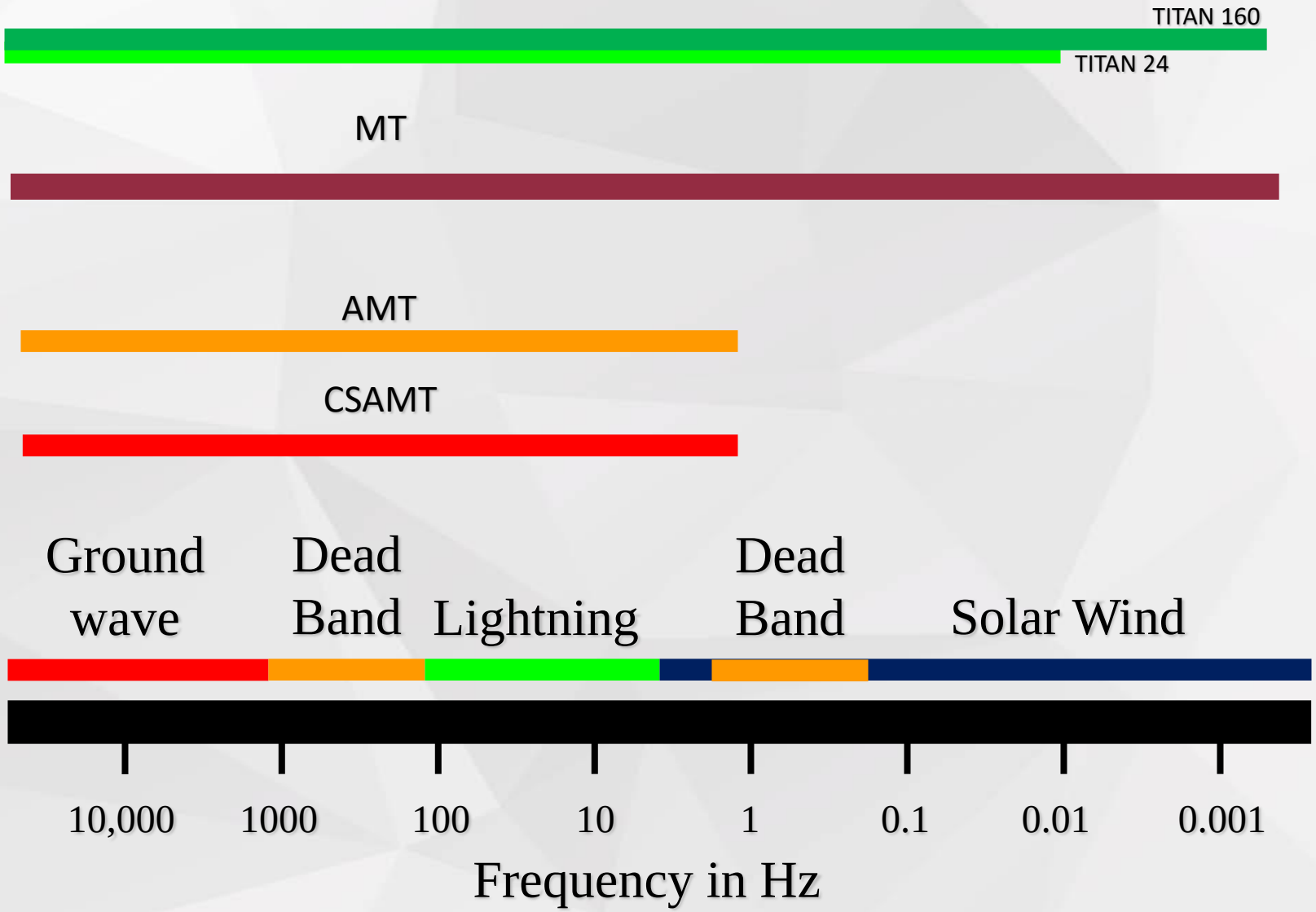
"The MT survey is an electromagnetic geophysical method with excellent depth penetration and a proven ability to detect, directly or indirectly, the type of palladium mineralization (high palladium tenor disseminated sulfide) that is found at EBL. Initial results from the completed portions of the survey have delineated several high priority geophysical targets proximal to known palladium rich mineralization. "

Resistivity section



Distributed Array – Detailed MT Profiling surveys

MT – frequency bandwidth & survey types

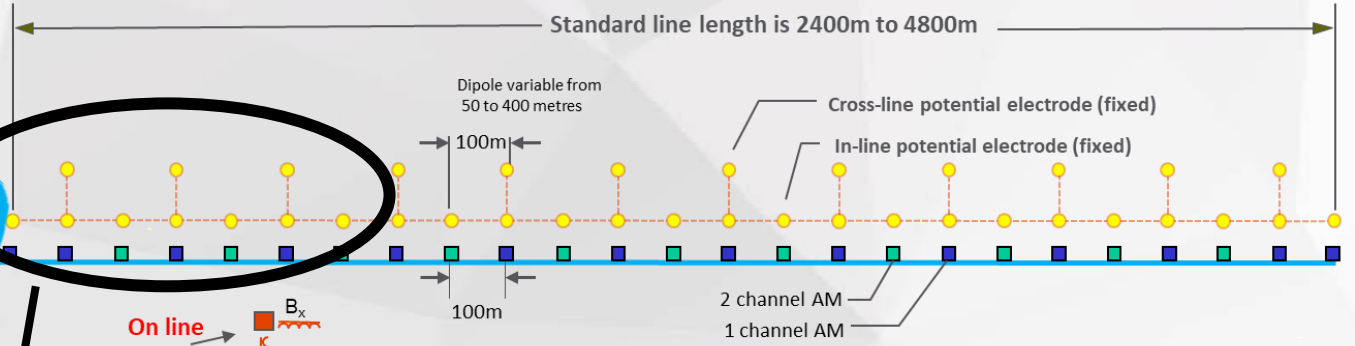


TITAN MT
(distributed array /close spacing)

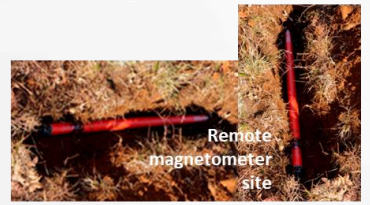
TITAN MT (distributed system) and detailed

Typical station set up

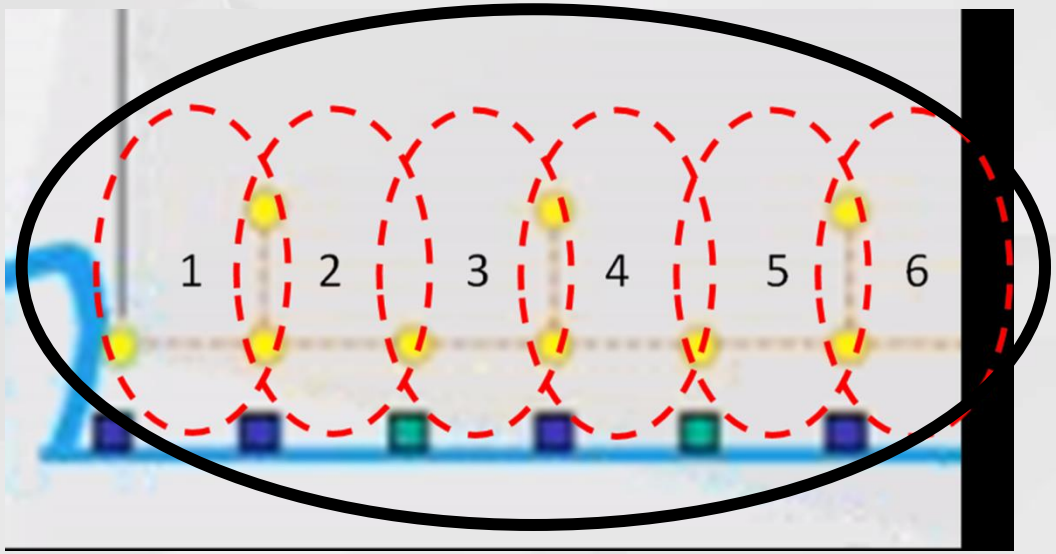
LAN link to Data harvesting centre



This example: line length: 2400 m
24 E_x 100m dipoles
12 E_y 100m dipoles
25 current stations
2 B_x/B_y magnetometer sites



B_x
B_y
>20 km from line

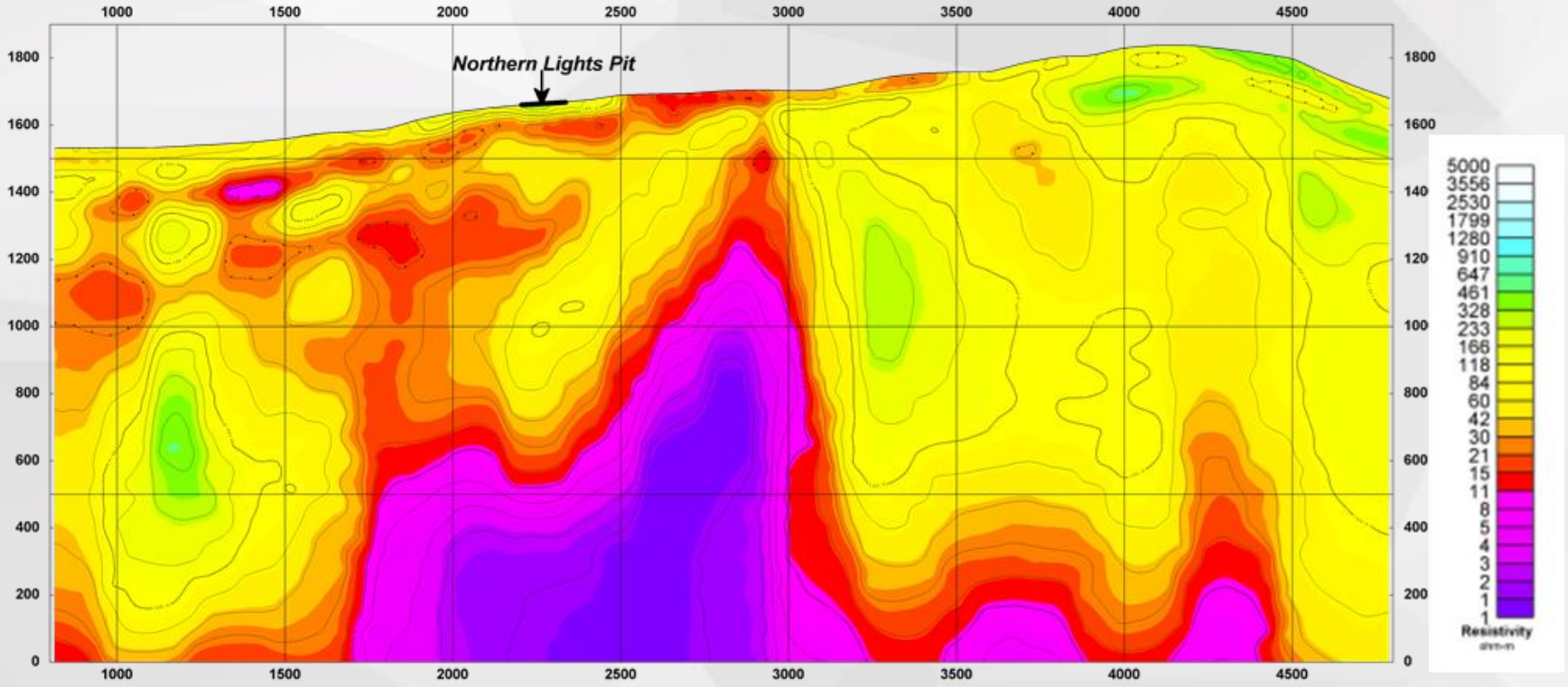


Effectively 24 - 100m spaced sites

Collected simultaneously

TITAN 24

Detailed Resistivity



MT Resistivity

PW 2D inversion;

Typically 1500 metres

TITAN 24

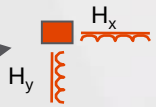
TITAN 160 MT (*TE/TM*)

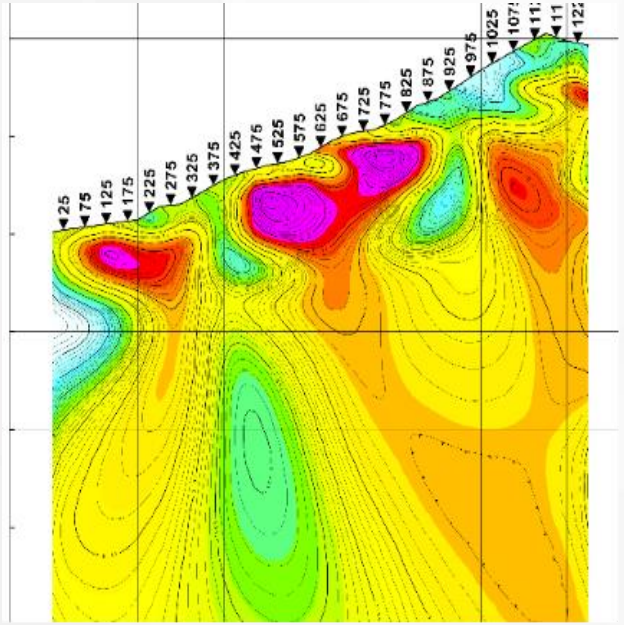
Typical station set up

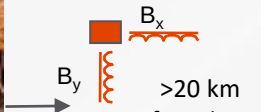
Multi channel acquisition module

Battery

On line magnetometer site per 2 profile spread



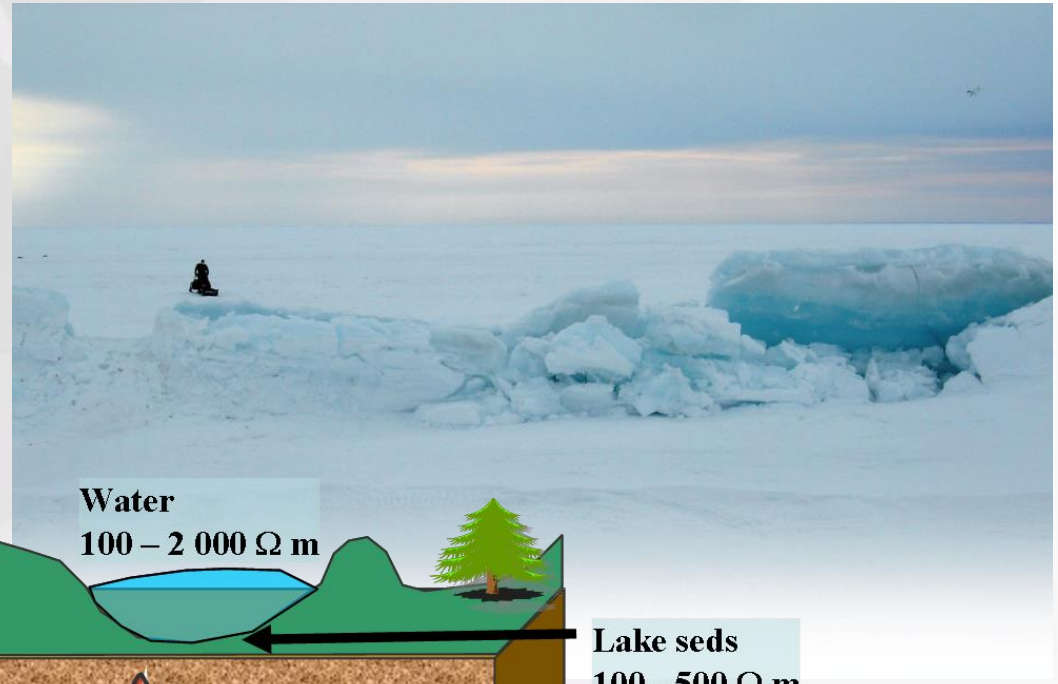


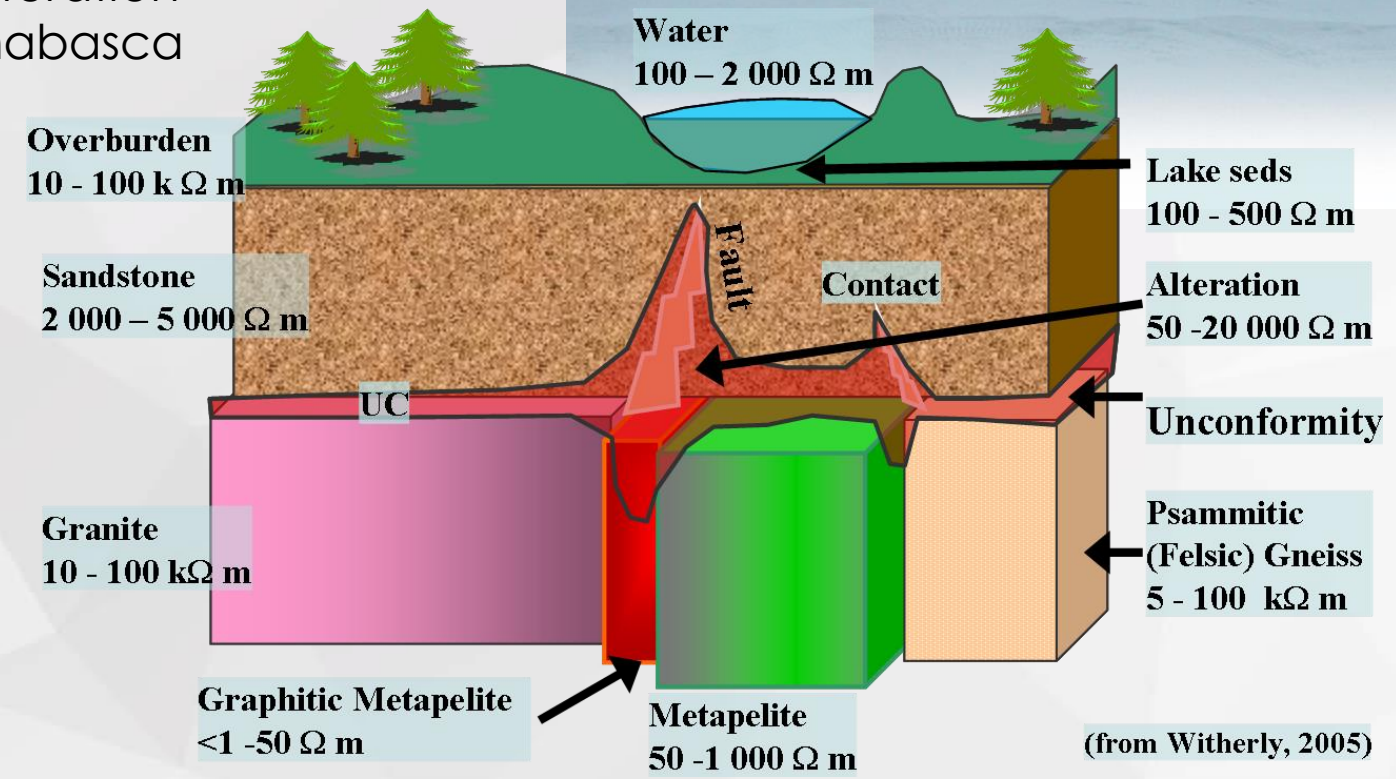


>20 km from line

Athabasca Basin, Beartooth Island: Uranium

- Penetrate below the thick conductive Wolverine Point sediments to delineate at depth (> 600m) geophysical signatures associated with possible unconformity type uranium deposits, specifically graphitic conductors and fault structures in the basement, as well as alteration zones within the overlying Athabasca sandstones.

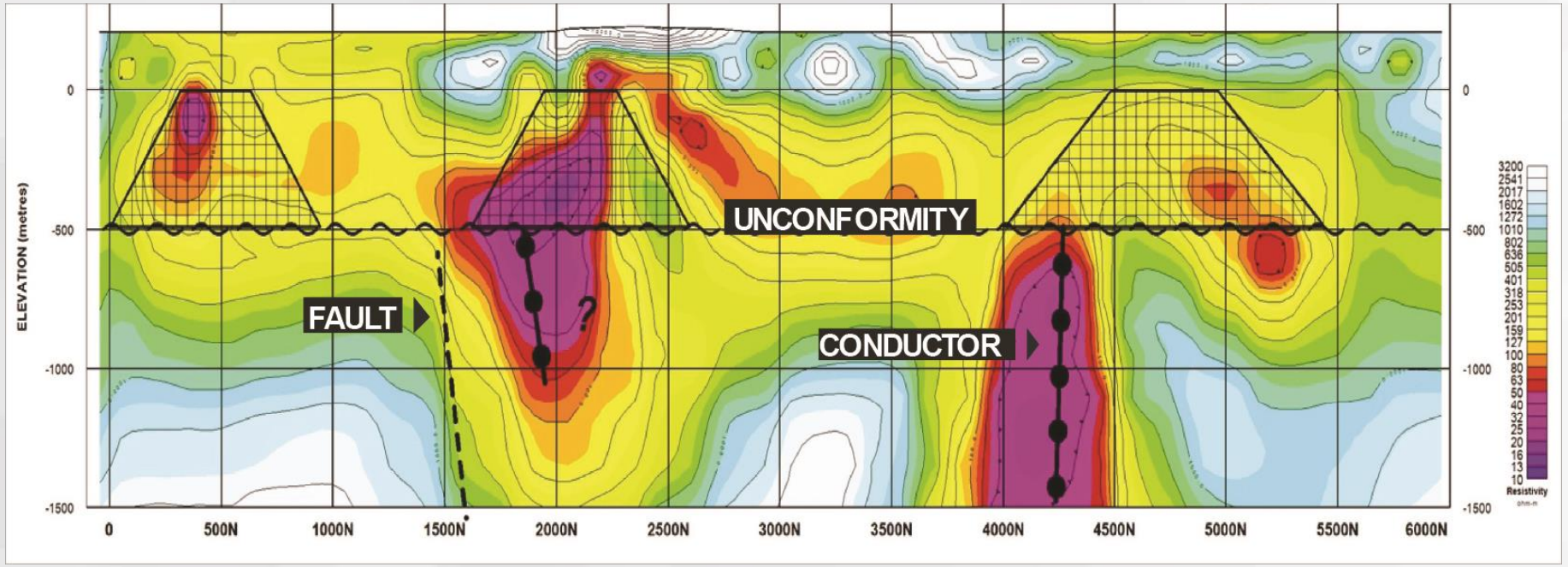




Golden Valley Mines Ltd.
Mines de la Vallée de l'Or ltée

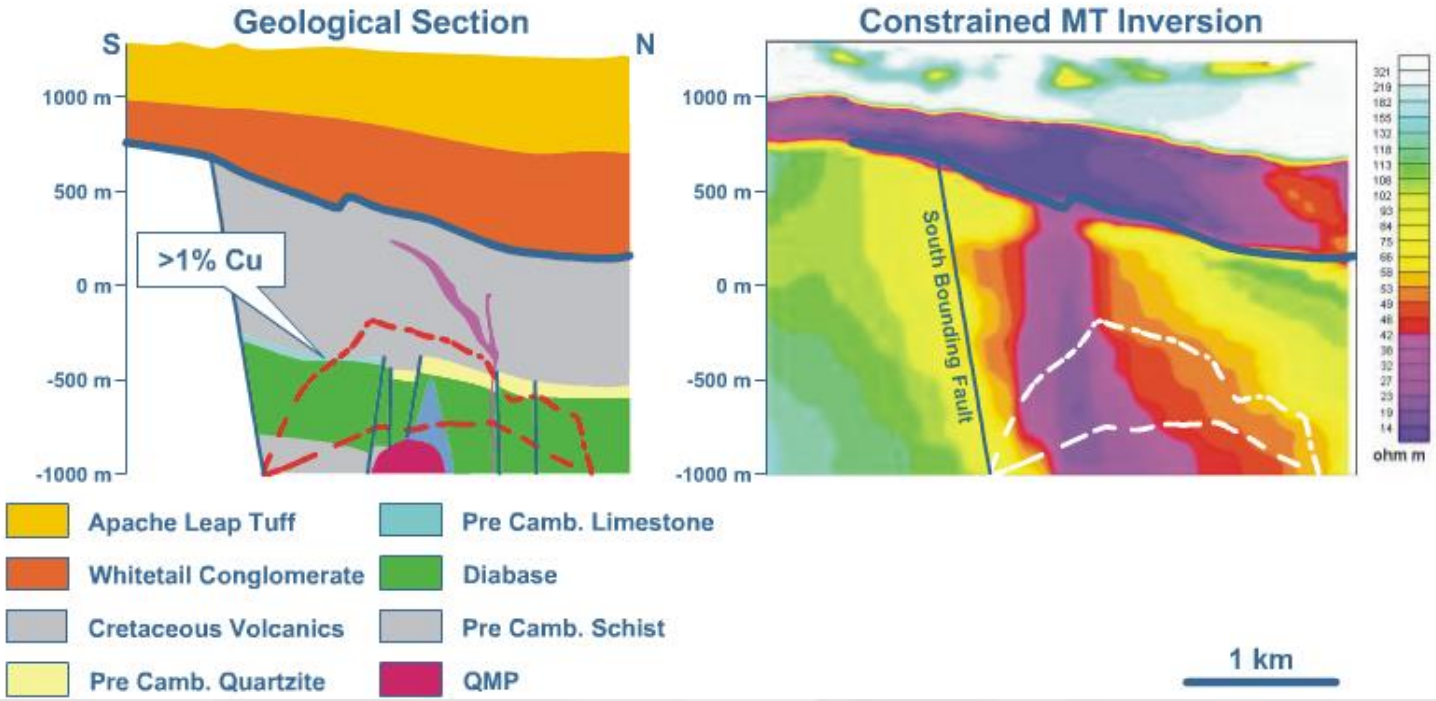
Beartooth Island- Survey Results

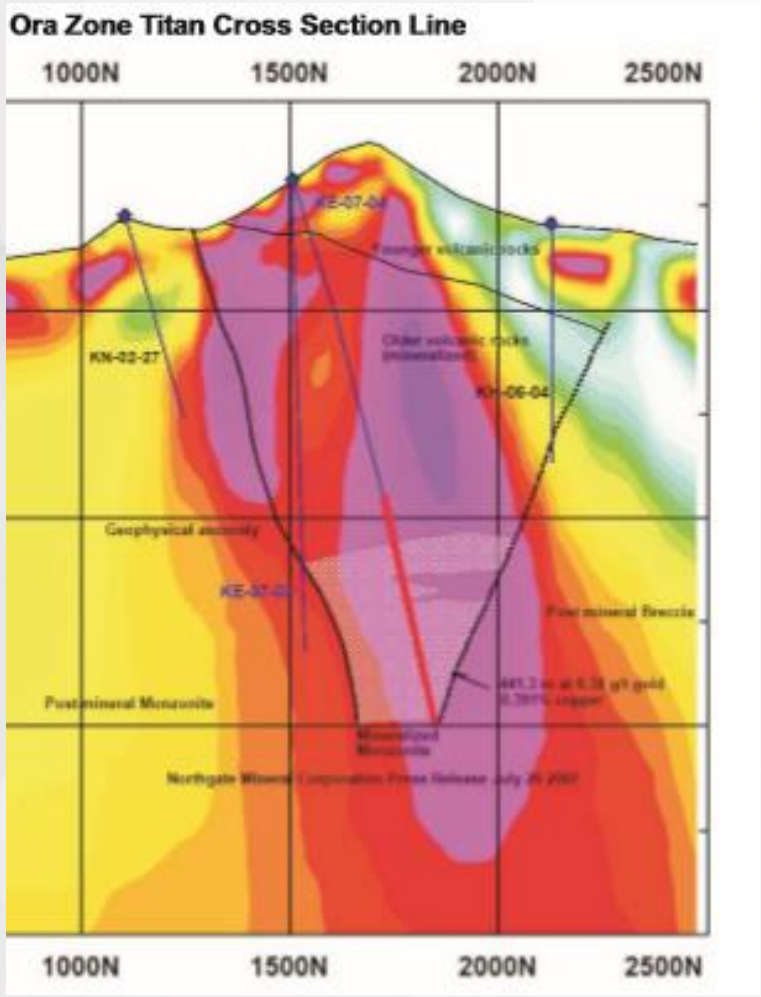
- Several near vertical basement conducts were detected below the Athabasca unconformity.
- Mapped the unconformity at depths of approximately 700m.
- Identification of LOW RESISTIVITY zones in the sandstone sediments and CONDUCTIVE structures in the basement.



Cu porphyry examples

MT Inversion - Resolution, Arizona – Porphyry Copper

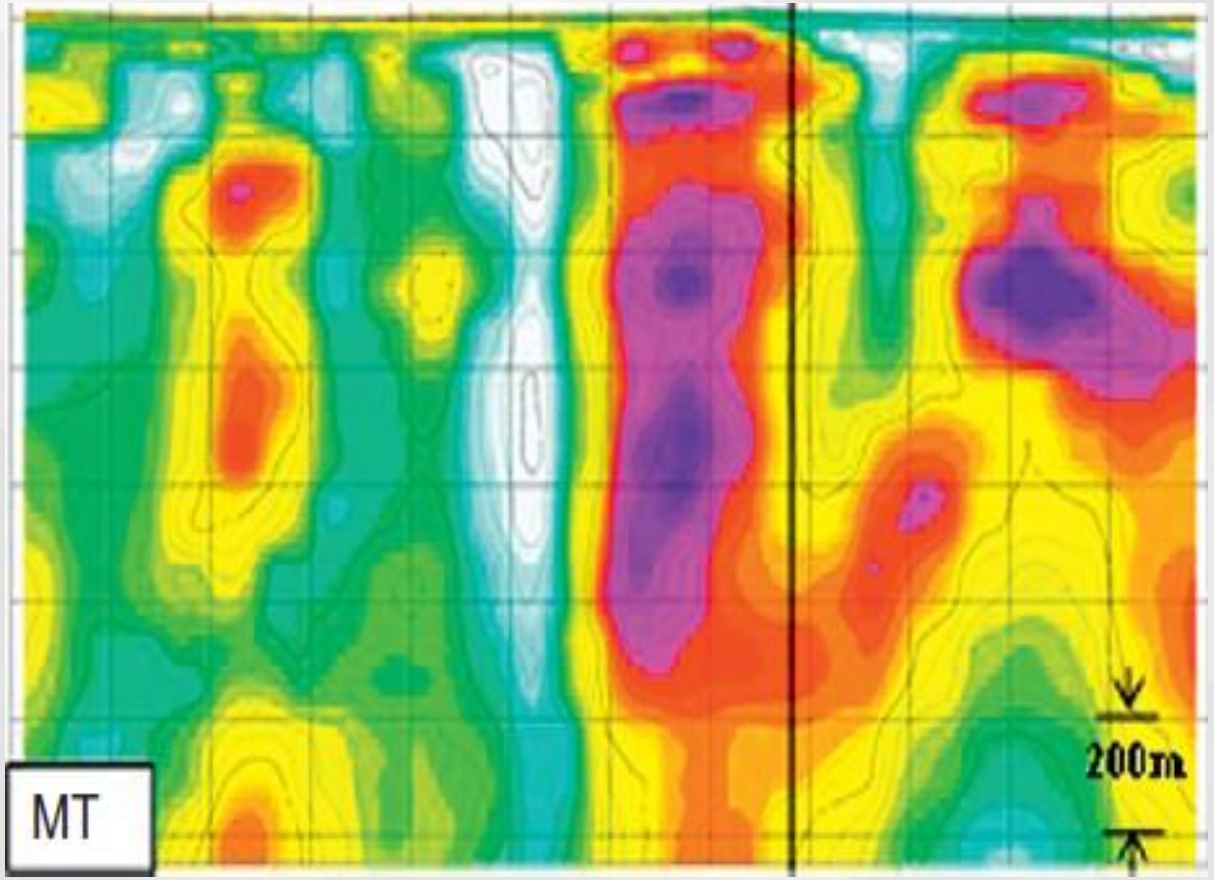




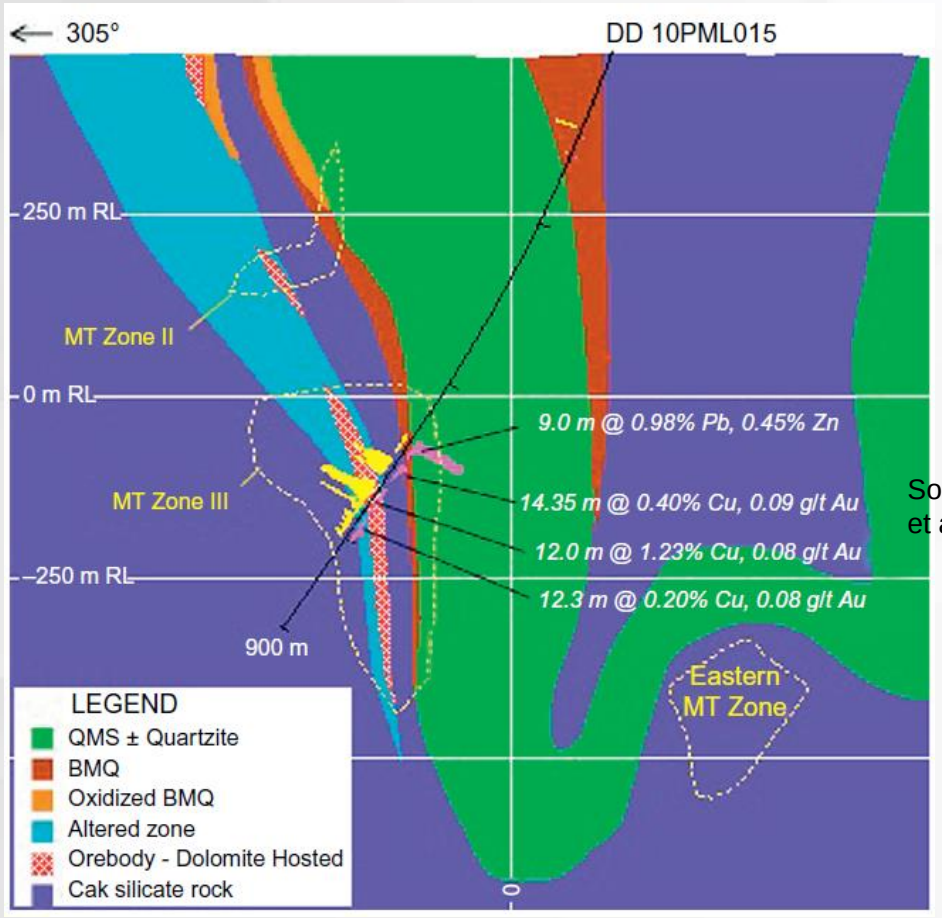
TITAN 24

Deep targeting

- Deep structural resistivity highs



- Pur-Banera Prospect, Rajasthan, India



Source: From Kavdia et al. (2015).

(Kavdia et al., 2015).

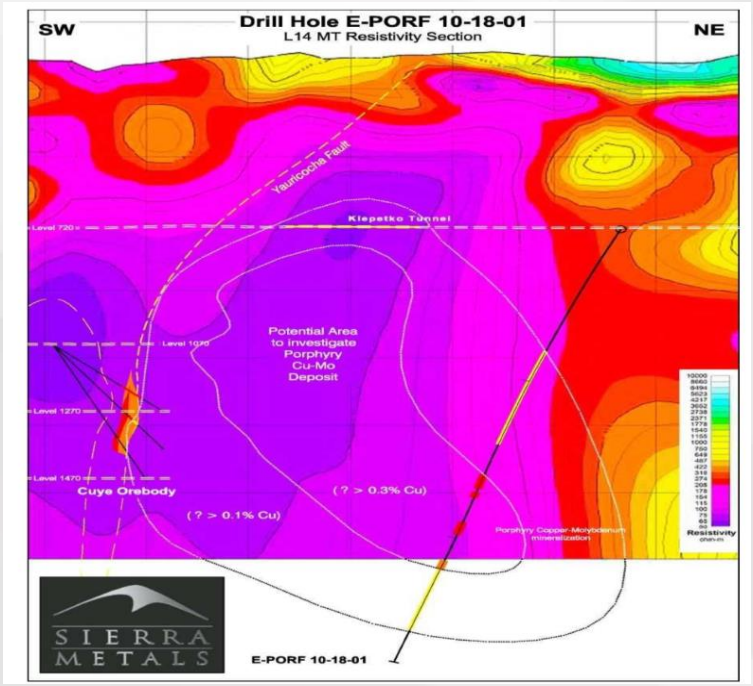
Near mine exploration

SIERRA METALS

PARA SU PUBLICACION INMEDIATA
Bolsa de Toronto: SMT
Bolsa de Lima: SMT
Bolsa NYSE American: SMTS

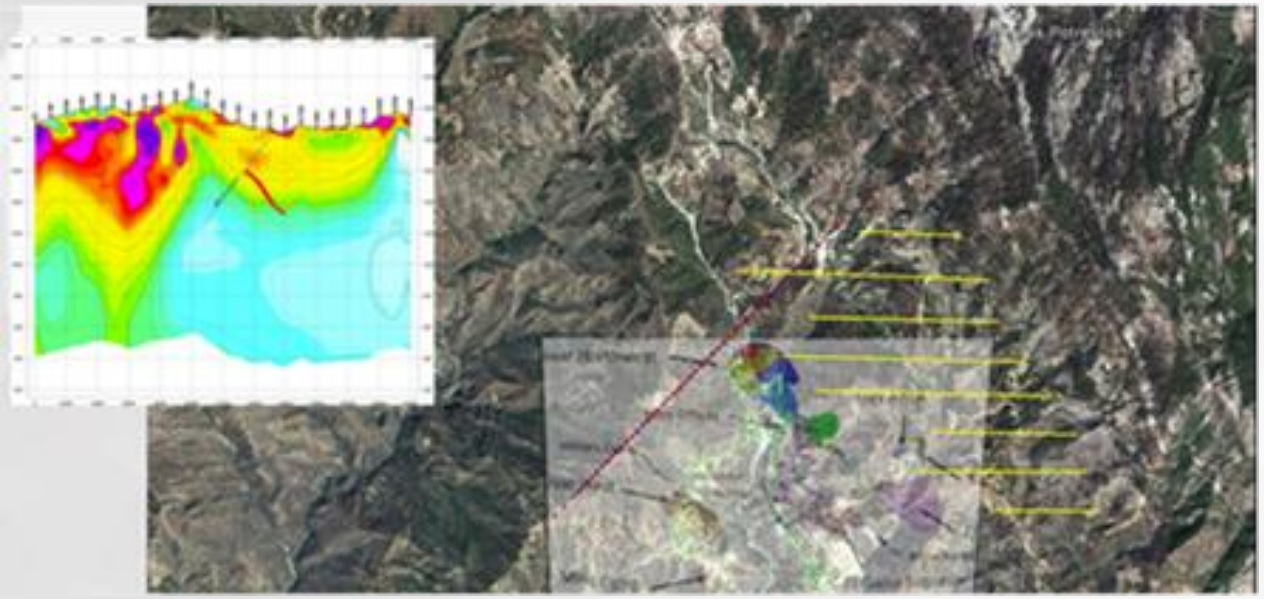
No. 32-2018

SIERRA METALS CONFIRMA MINERALIZACION PORFIDICA EN SU MINA YAURICOCHA EN PERU, RESULTADOS POSITIVOS INCLUYEN 22 METROS DE 0.46% DE COBRE, 134 PPM DE MOLIBDENO, Y 10.73 PPM DE COBALTO

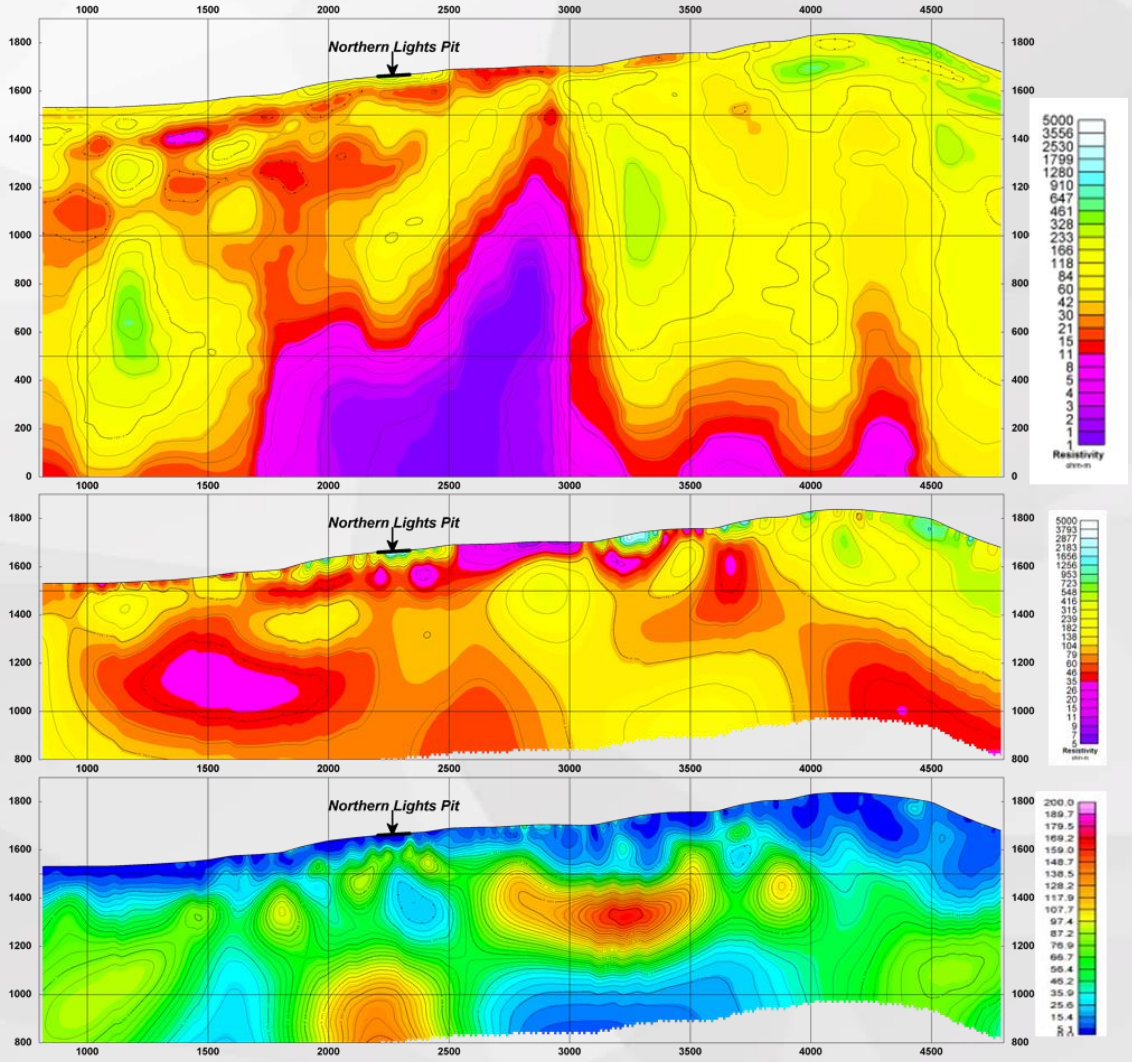


- Drilled from 720 level to 1394 metres deep
- Intersections from 798m through 980m

- Near mine deep resistivity mapping



How does MT Resistivity compare to DC resistivity ?



Top panel: MT Resistivity

PW 2D inversion;

Typically 1500 metres

Middle panel: DC Resistivity

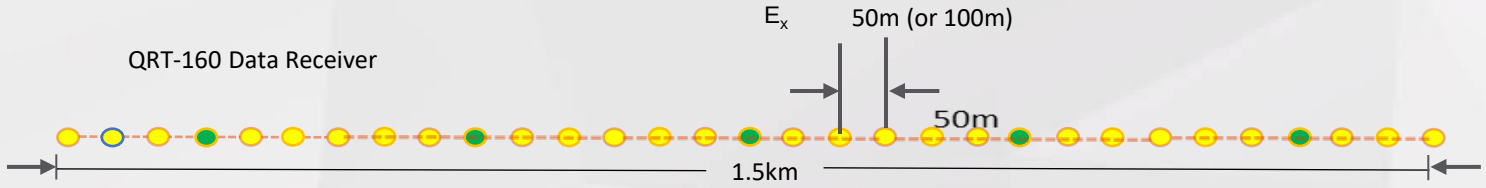
Typically 500-750 metres

Bottom panel: Chargeability

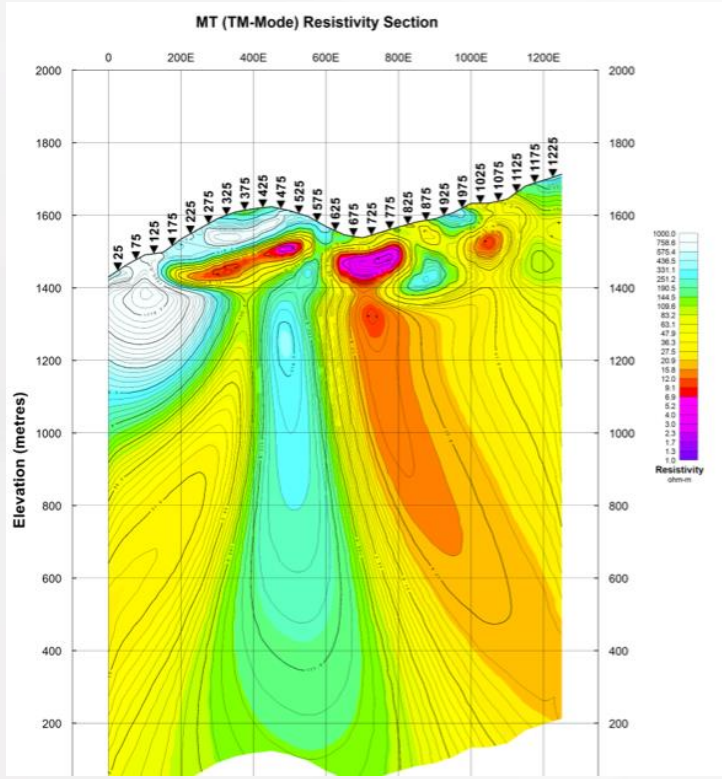
TITAN 24

What is an EMAP survey

Typical station set up



On line magnetometer site typically 1 per profile spread



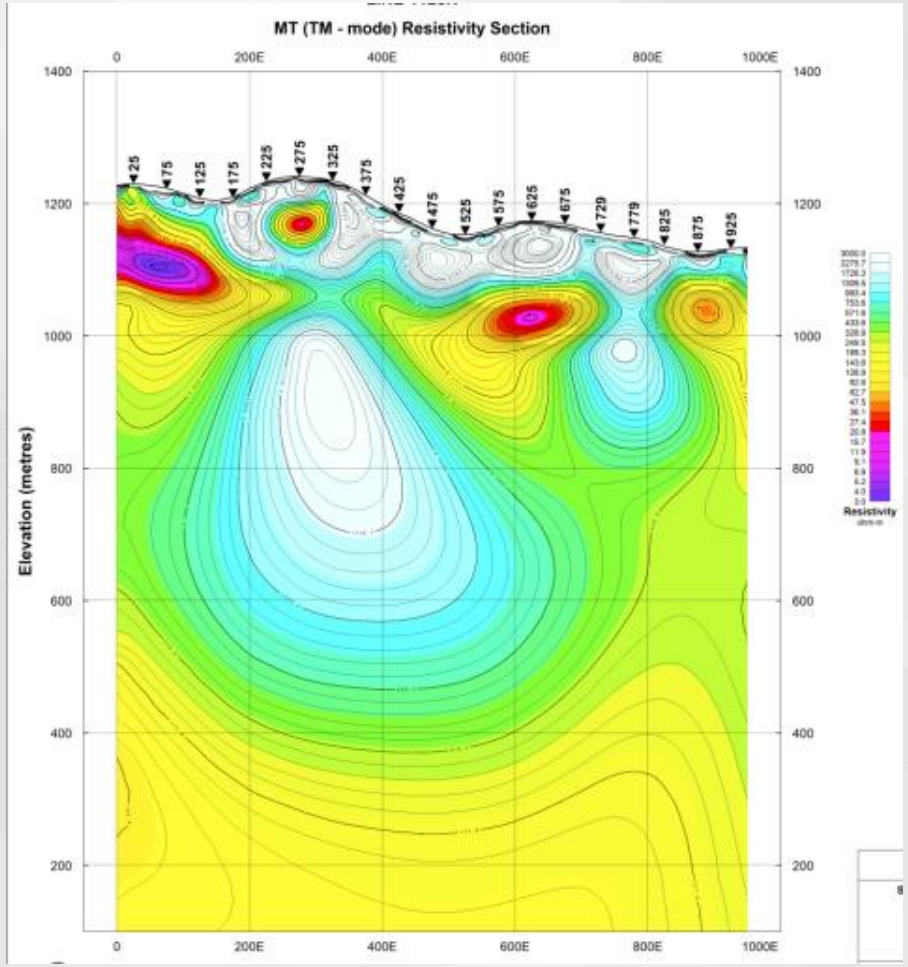
Remote magnetometer site

H_y

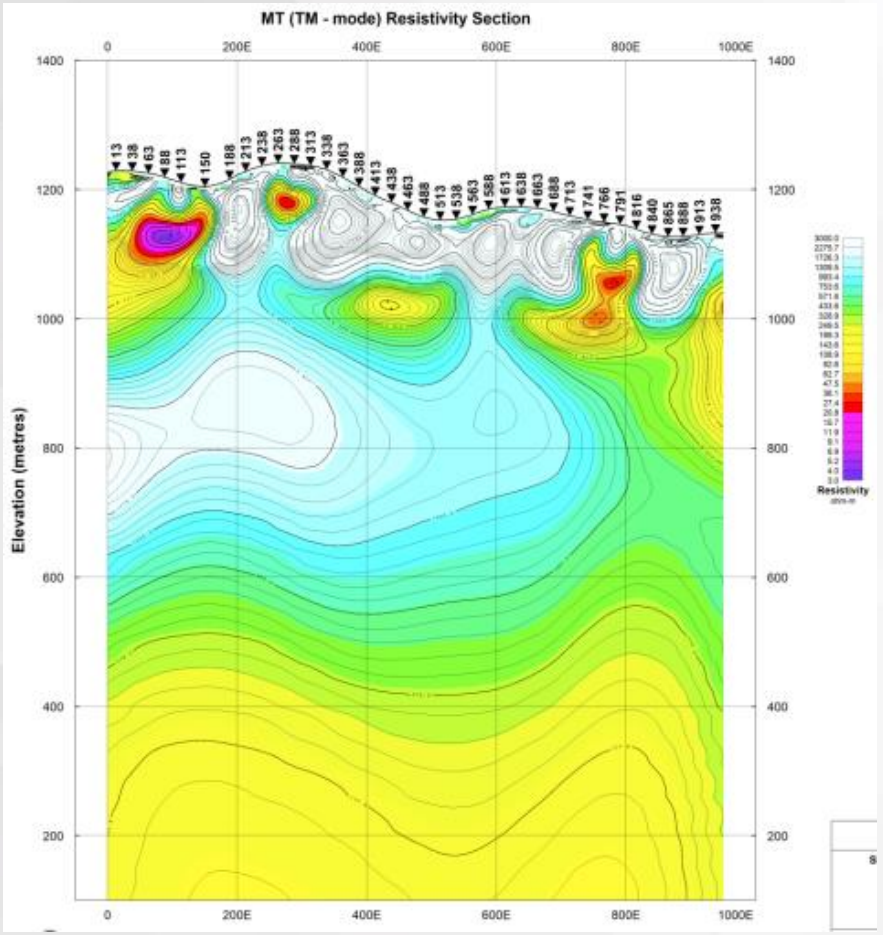
>20 km from line

EMAP 50 m dipole vs. 25 m dipole

- Profile MT - Emap mode (2D Inversion)50m dipoles

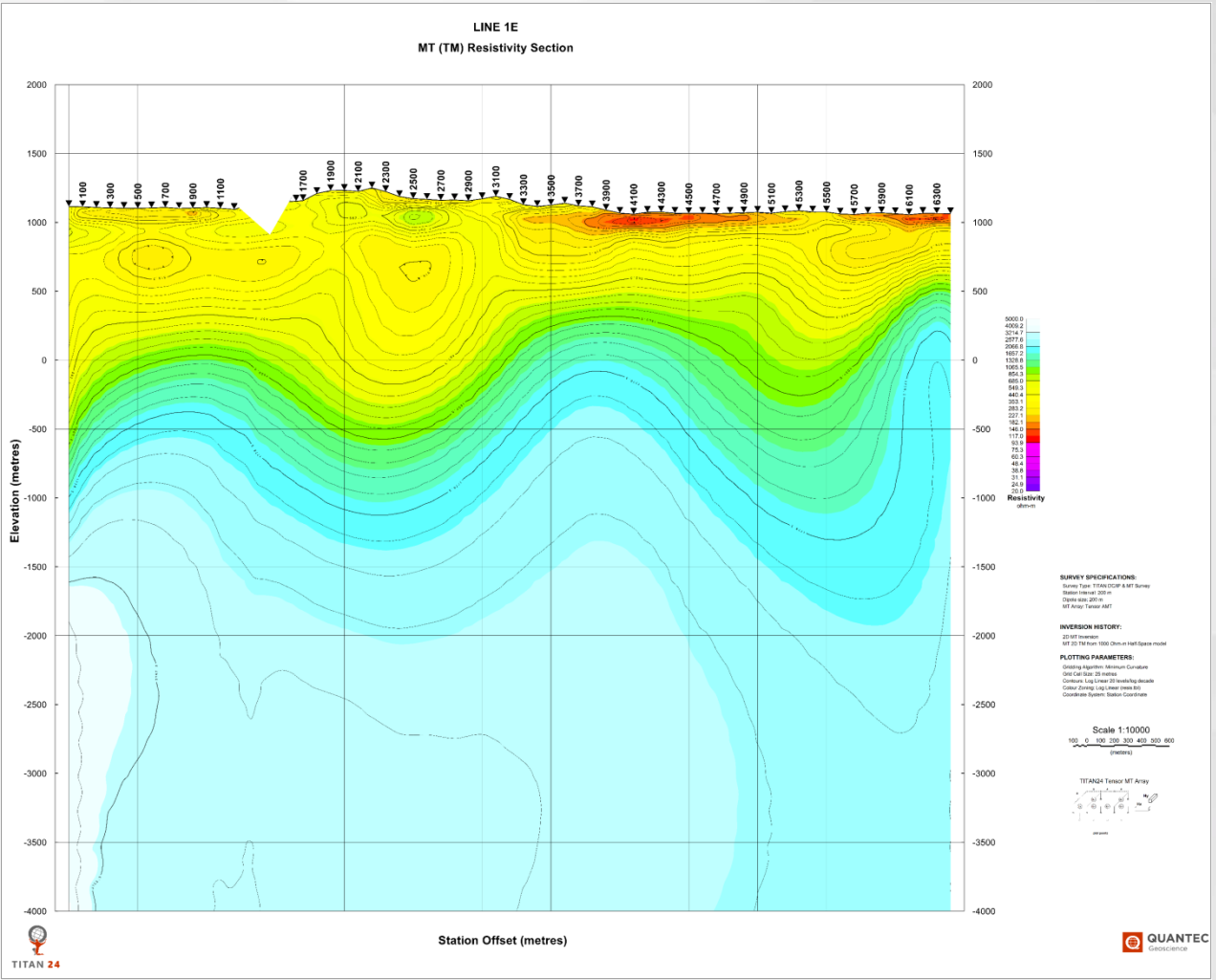


- Profile MT - Emap (2D Inversion)25m dipoles

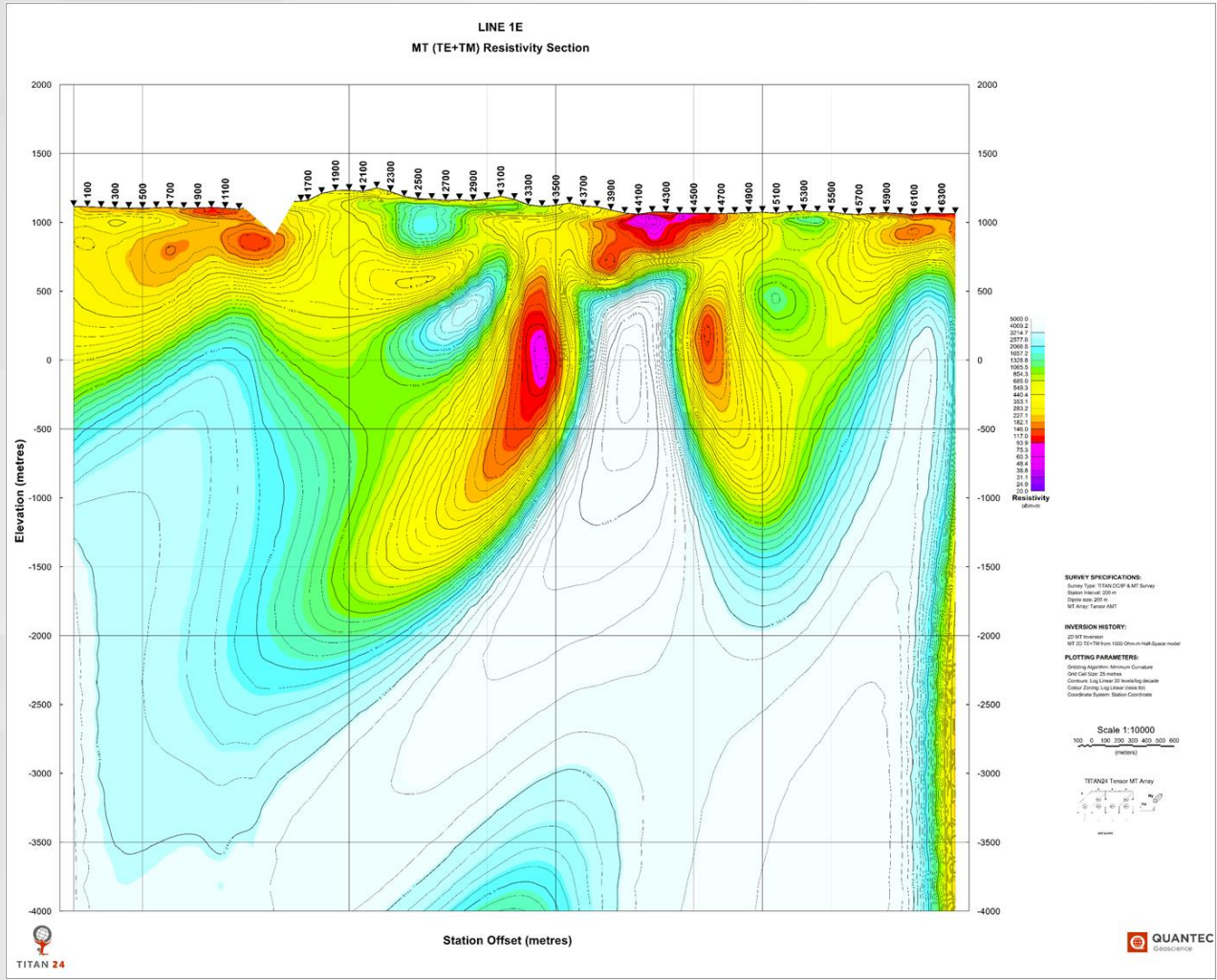


What benefit are the cross dipoles (TE)

- Profile MT or Emap mode (2D Inversion)



- Profile MT (TE&TM) (cross dipoles) (2D Inversion)



Summary

MT or Magnetotellurics

- Provides resistivity information about the subsurface
  - typically related to Geology and structure but also sensitive to buried conductors
- Regional and local applications
- Effective 1D, 2D and 3D imaging for exploration across commodity types
  - Porphyry exploration
  - Gold exploration
  - Base Metals, Ni, PGE
- Near mine & pre-mine applications (recent discovery at Yauricocha)

Thank you !

Ref. Karen R. Christopherson, *Chinook Geoconsulting, Inc*

QUANTEC
Geoscience

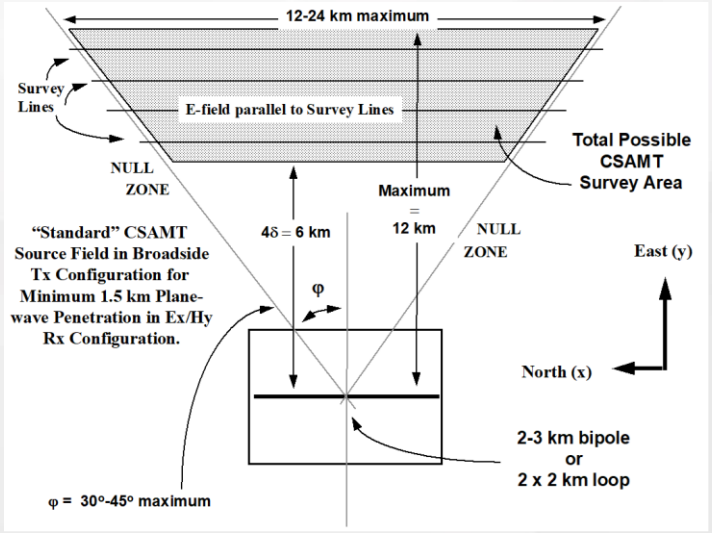
Questions ?

rgordon@quantecgeoscience.com
cmaudet@quantecgeoscience.com

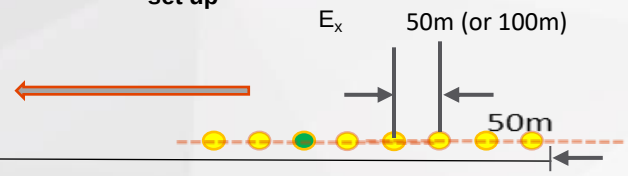
www.quantecgeoscience.com

Karen R. Christopherson, *Chinook Geoconsulting, Inc*

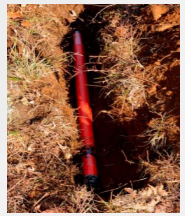
How does CSAMT work?



Typical station set up



On line magnetometer site typically 1 per set up



CSAMT - near field / far field - distortions

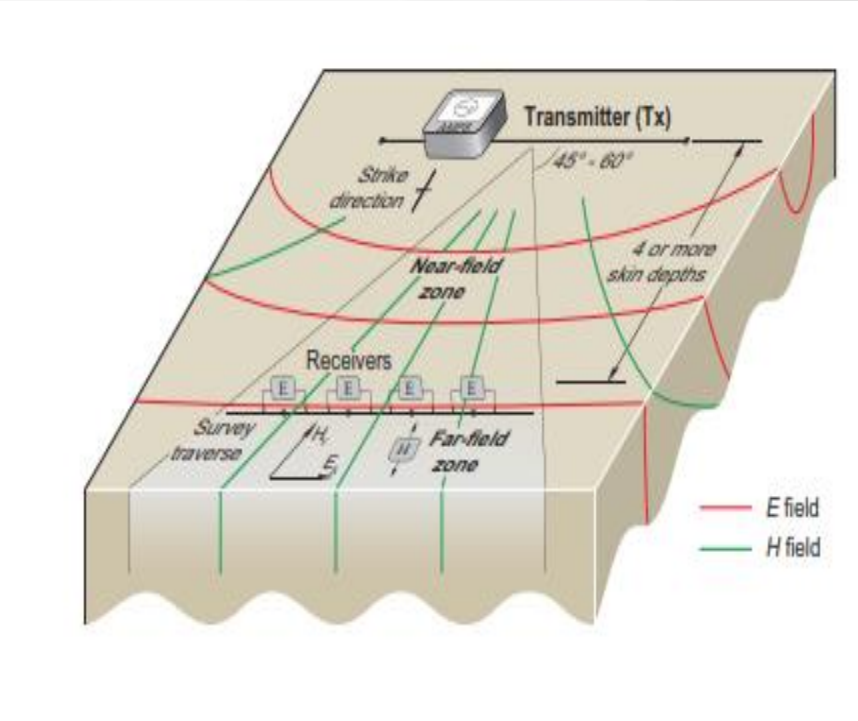
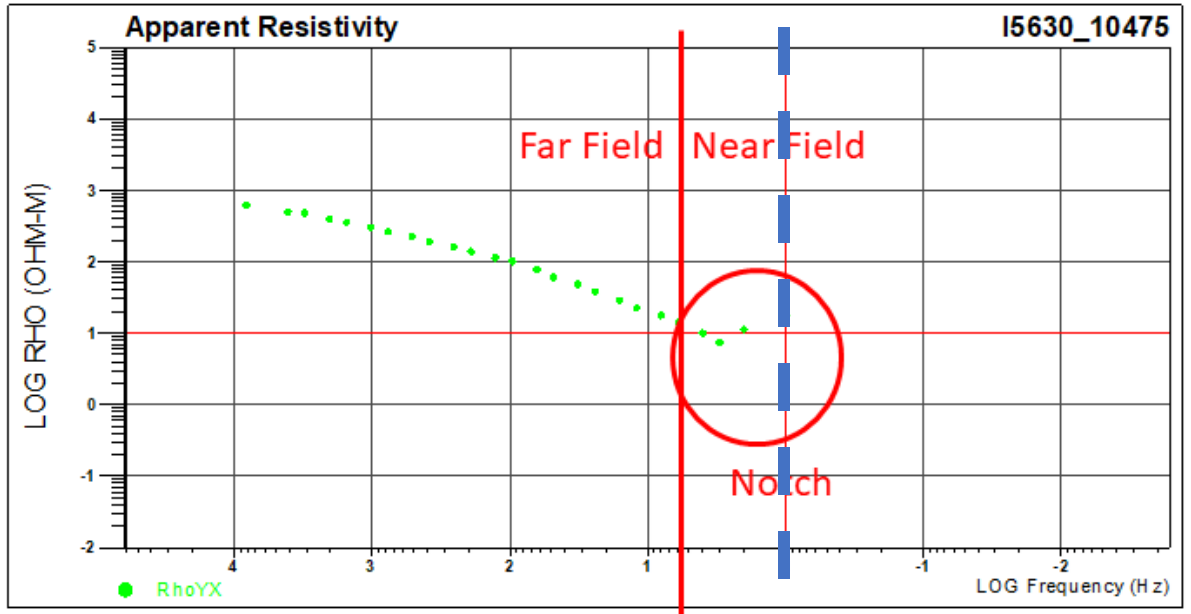
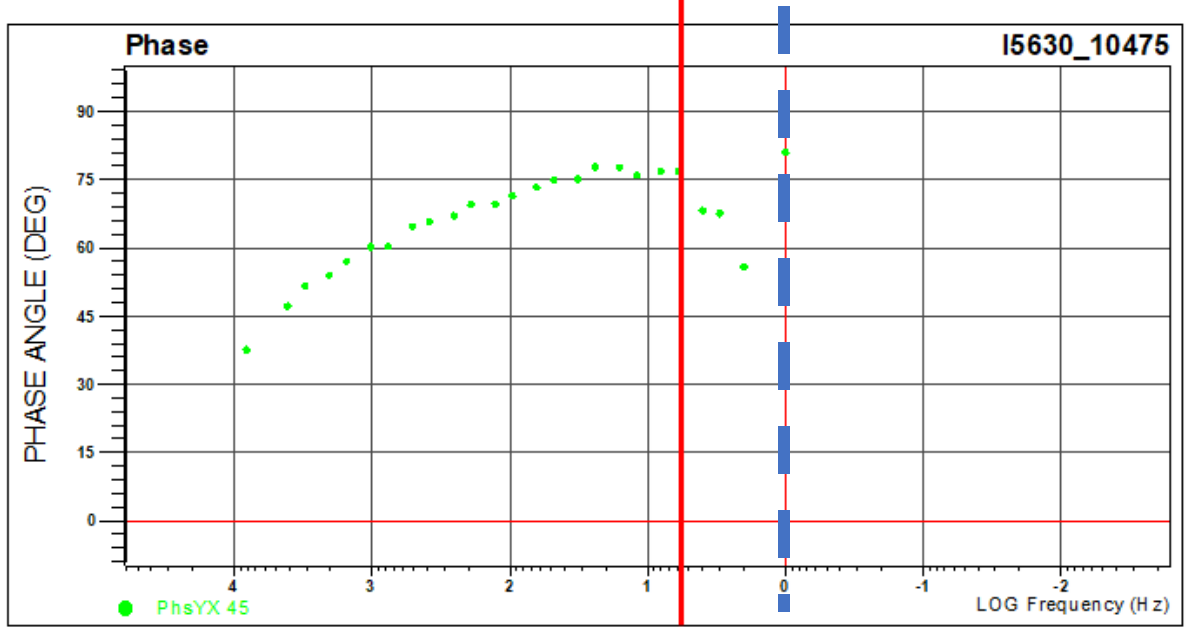


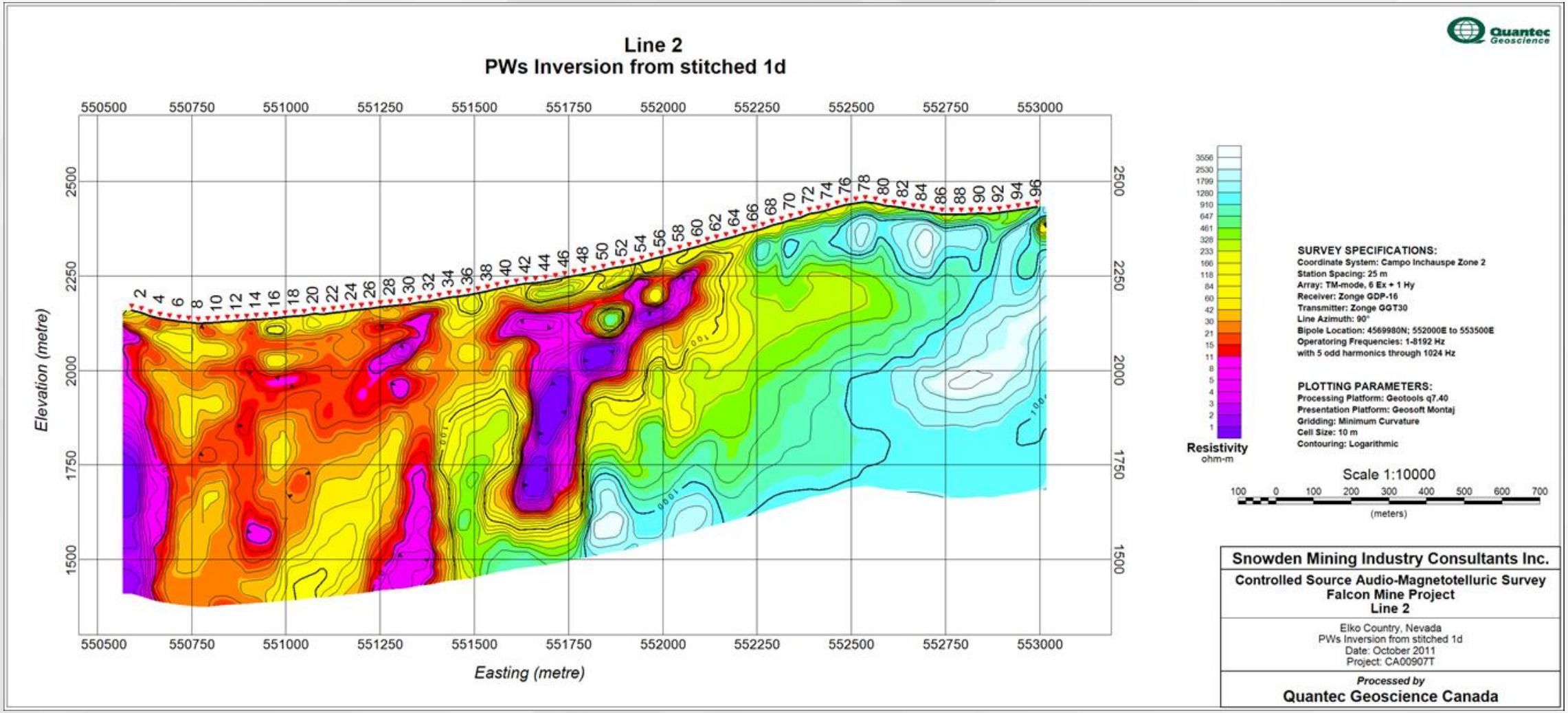
Figure A4.1 CSAMT survey arrangement. The transmitter dipole is oriented perpendicular to the geological strike (TM mode). Electric (E_X) and magnetic (H_Y) fields are measured in far-field zone.

http://www.cambridge.org/ae/files/6713/9643/1711/Online_appendix_04.pdf



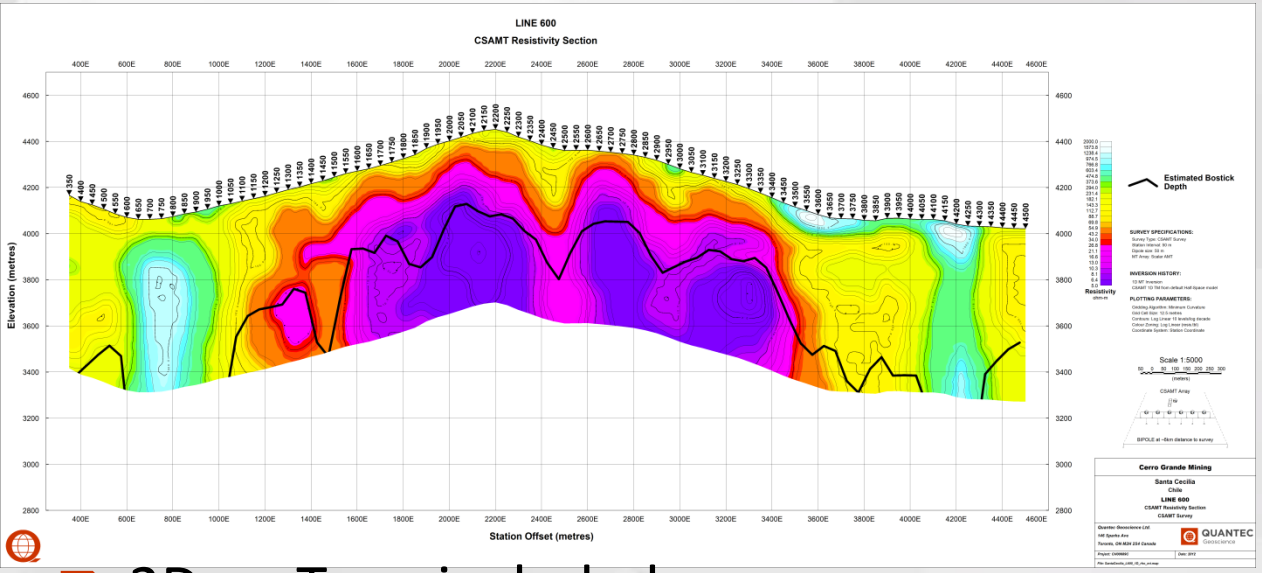


CSAMT section from South America

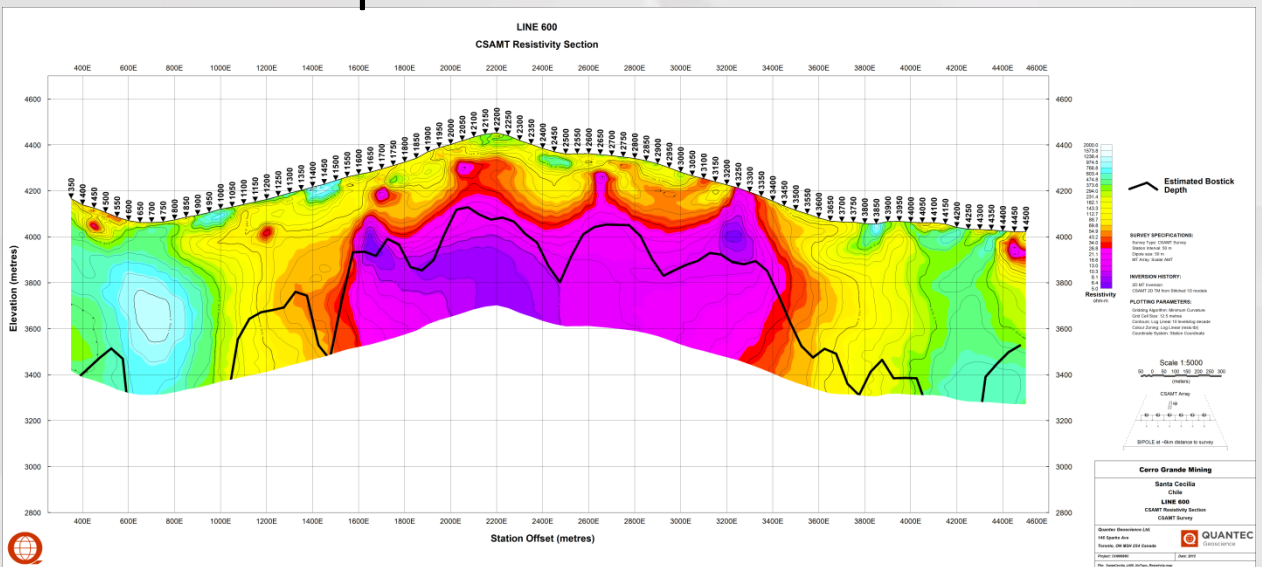


Traditional CSAMT – Effects from topo

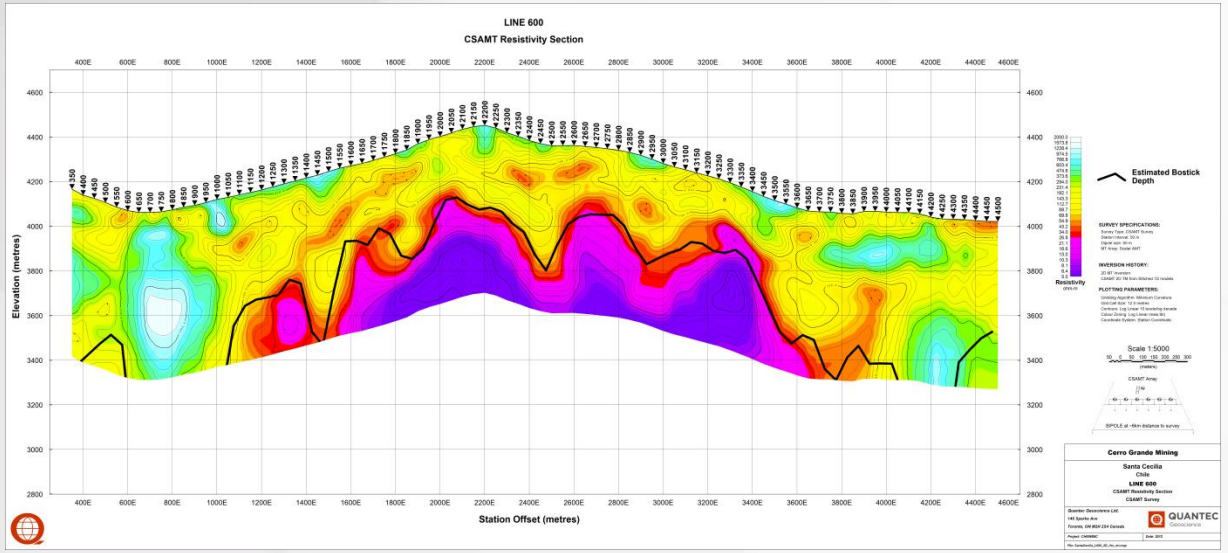
- 1D no topo included



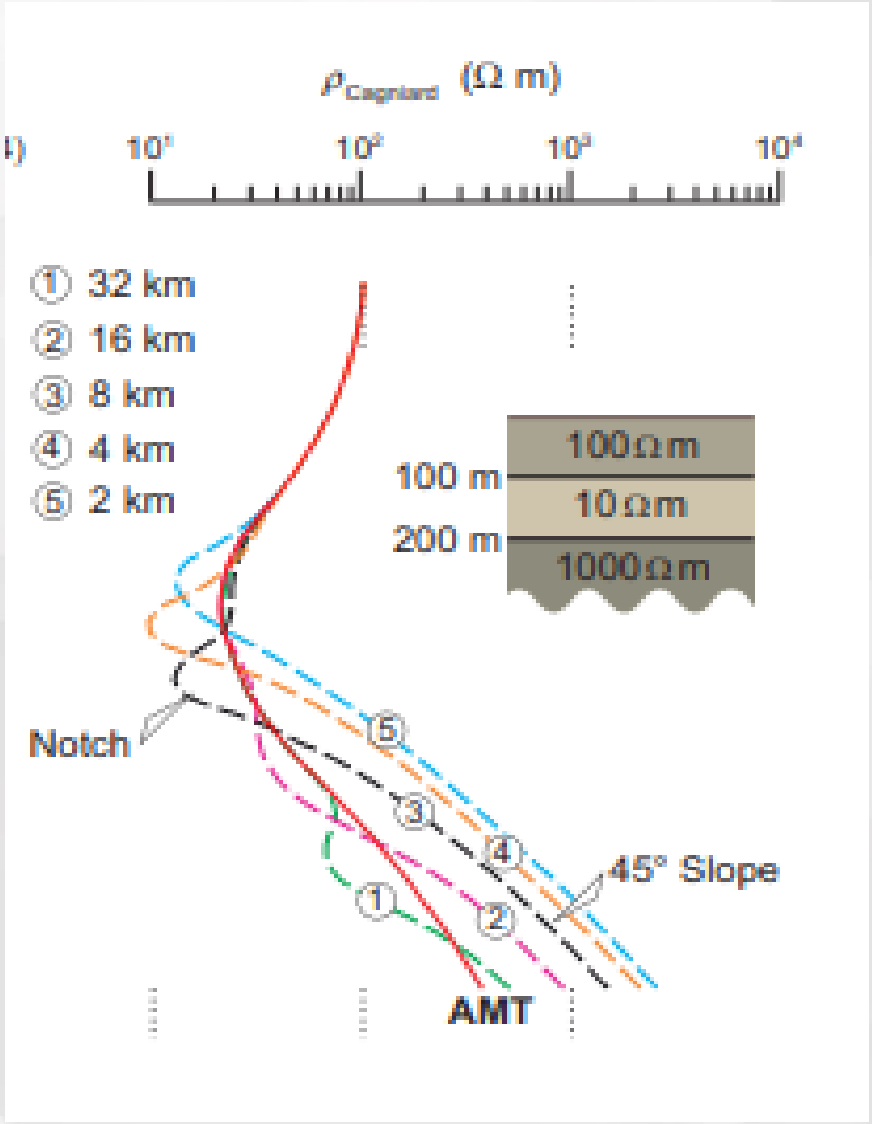
- 2D no Topo included



- 2D Topo correction included



AMT/ CSAMT Near field/far field



CSAMT/AMT/MT

- CSAMT for different Transmitter receiver distances show the onset of non-Far field responses at increasingly higher frequencies for closer source receiver separations
  - Although the match is better when the transmitter is very far away, signal strength goes way down , making the sensitivity relative poor.
- AMT represents an entirely “Far Field” response for a consistent curve

MT/AMT/ CSAMT for exploration Pros and Cons

MT

- Provides 1d/2d &3d resistivity solutions
- Great depth of penetration (surface to > 1000m)
- 3D information achieved
- Regional and local applications
- Provides info on poor and good conductors
- Natural signal can be irregular but problems alleviated by over night longer reads
- Light-weight equipment --very portable
- Can access almost anywhere
- No transmitter required
- Little impact on environment
- Multi-parameter surveys can be incorporated

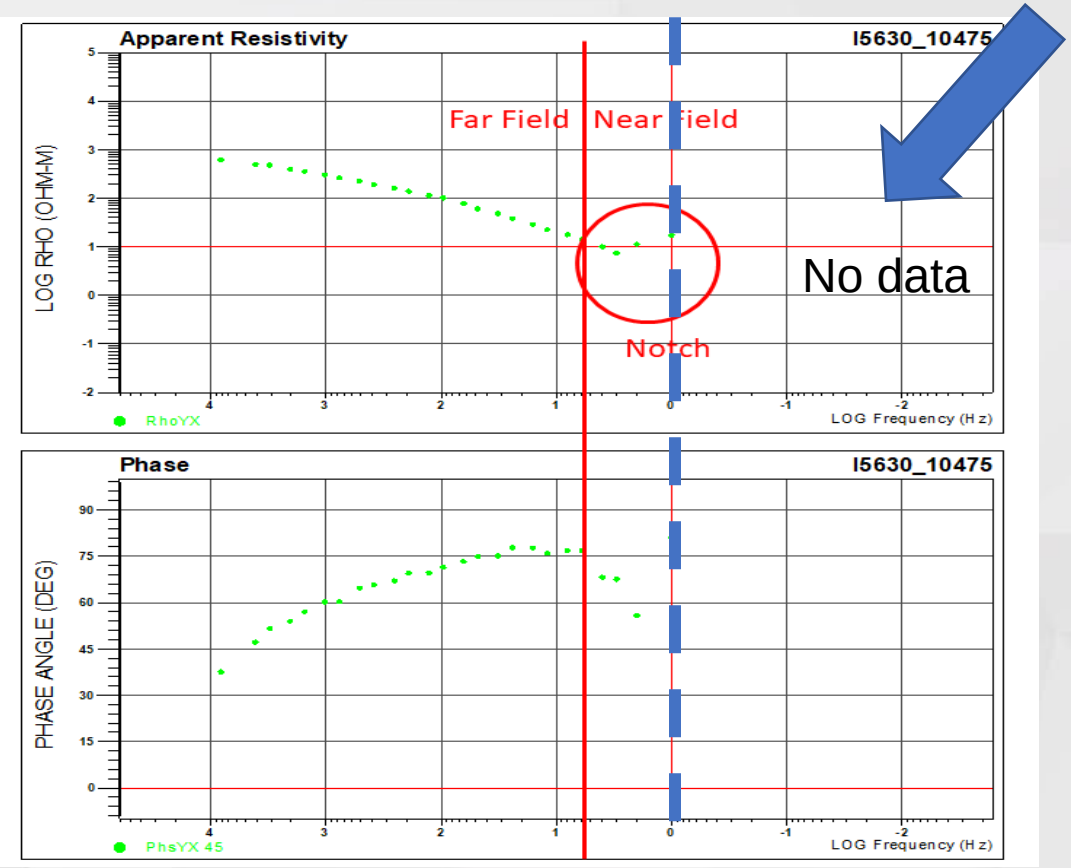
CSAMT

- Provides 2d resistivity sections
- Depth limited (typically < 1000m (500m))
- Typically only runs in TM mode, so not best for dealing with anisotropy
- Issues related to the effects of near field / far field effects.
- Requires large motor generator and transmitter

Summary

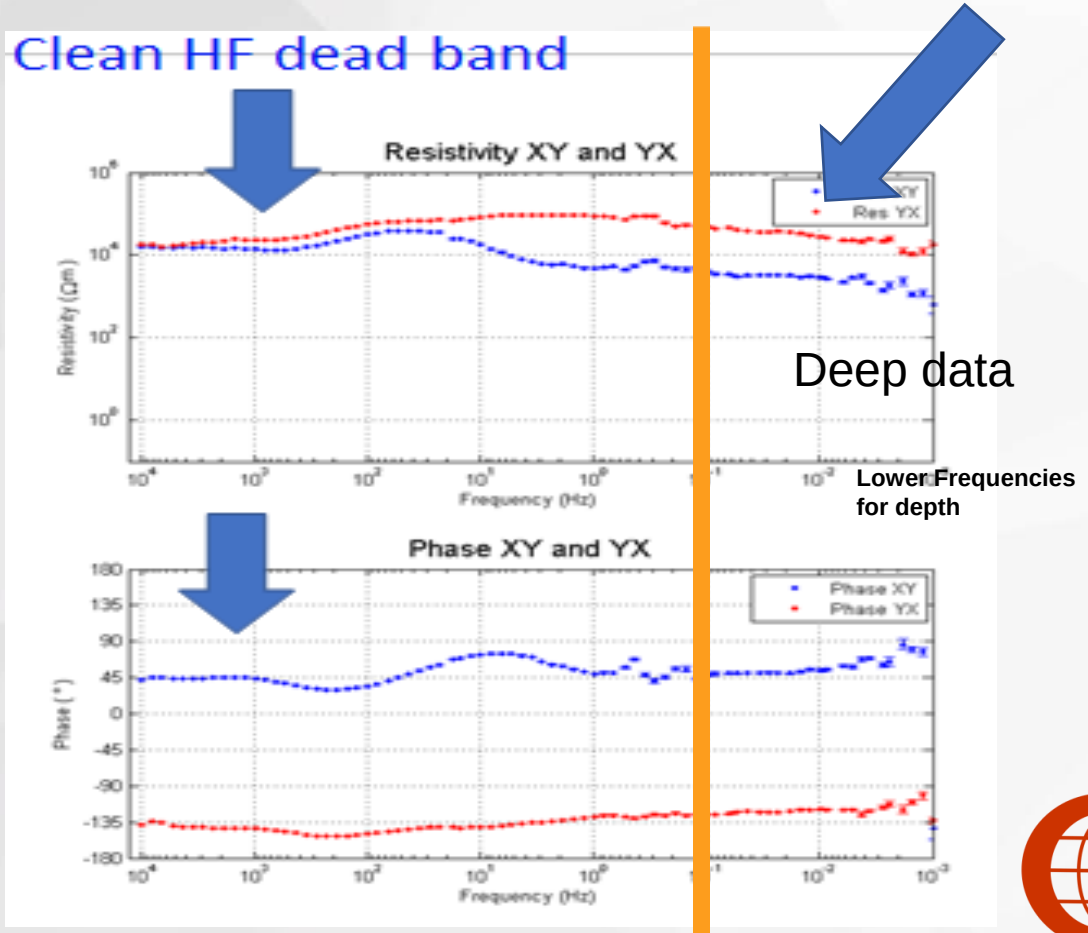
CS-AMT

- Captures good signal in deadband
- No lower frequencies
- Depth limited



MT– overnight read

- Captures good signal in deadband and lower frequencies for depth



What is the difference between ZTEM & MT

ZTEM

- Measures Hz in the air over a line or grid at 100 km/hr
- Measures Hx & Hy in one location, near the grid
- Frequency range is 30Hz to 720 Hz

MT

- Measures Hx, Hy & Hz AND Ex and Ey at single stations in on a line/grid – over a period of 3-20 hrs
- Measures Hx, Hy & Hz plus Ex and Ey at a reference station 30+km away over course of survey
- Frequency Range is .001Hz to 10,000Hz

What is ZTEM ?

- ZTEM
- MT

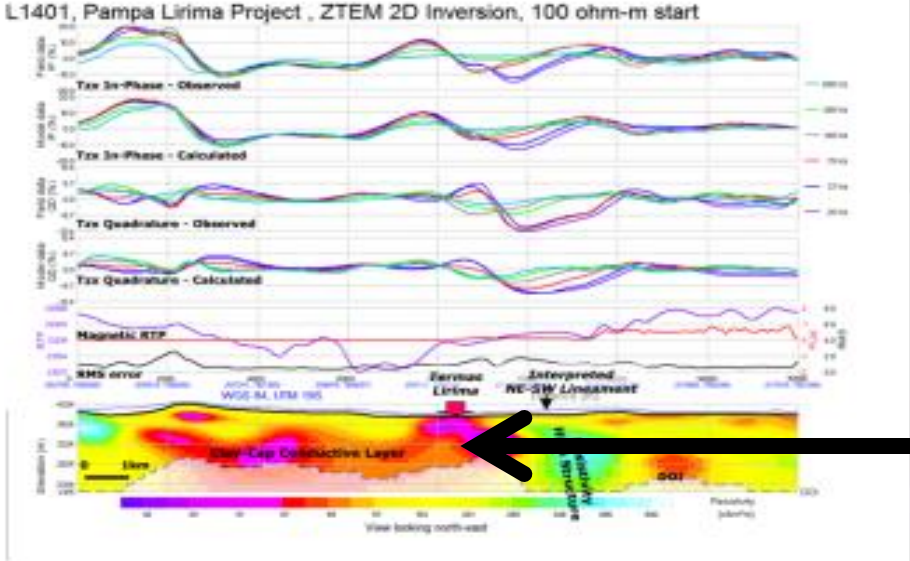


Figure 11: 2D ZTEM inversion for L1401 across the Lirima geothermal field that roughly coincides with the NW-SE trending 3D MT inversion section in Figure 7b.

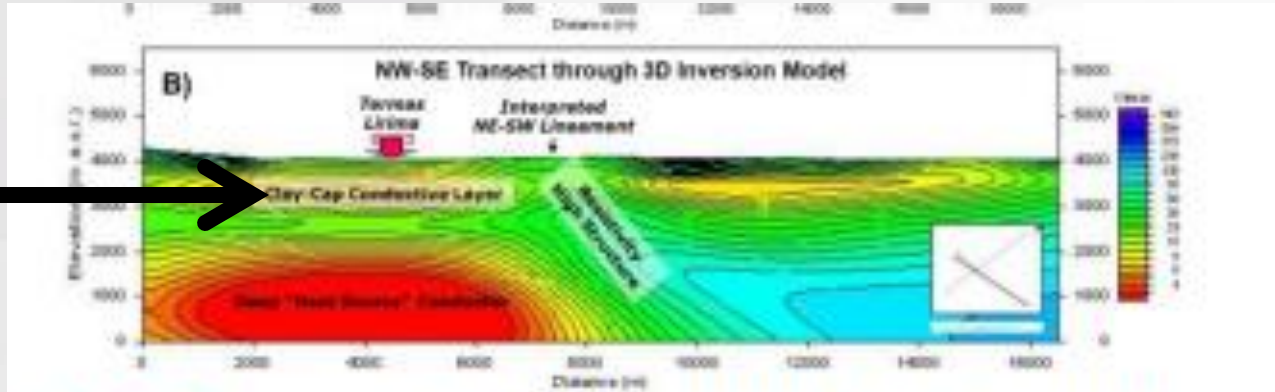


Figure 7: 3D Magnetotelluric inversion results, showing: a) NE-SW and b) NW-SE oriented sections across the 3D model (after Arcos ET AL., 2011). Their location is approximately by the 2D ZTEM inversion lines presented in Figure 8.

http://geotech.ca/wp-content/uploads/2016/10/042-Pampa-Lirima-ZTEM-MT-case-study_GRC_final-with-revisions_28-May-2012.pdf

Arrow shows feature at 500m
(MT sites widely spaced)