Exploration '07 plus 5: A half-decade of mineral exploration developments

Ten years of passive airborne EM development for mineral exploration

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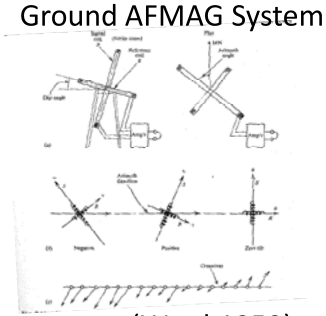
Outline

- Introduction
- Overview Geotech Passive AEM systems
- AFMAG Development from 2001 to 2011
- Field Survey Examples
  - ZTEM vs. FW-ZTEM over Arizona porphyry target
  - ZTEM vs. AirMt over Nebo-Babel Ni-Cu-PGE
- Conclusions (what's new for 2012 and beyond)

AFMAG - Background

- AFMAG stands for "Audio Frequency Magnetics", 1ST proposed by Ward (1959) as scalar (Hz=TxHx), redefined by Vozoff (1972) as complex vector, further developed by Labson et al (1985).

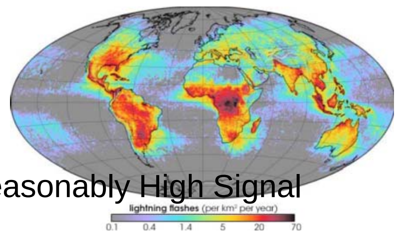
Ground AFMAG System



(Ward,1959)

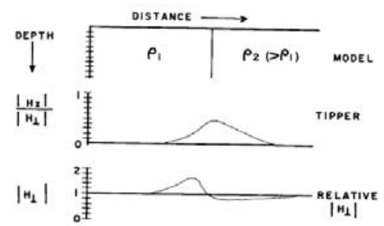
- **Passive EM** (Electromagnetic) technique – in same family as **Audio-Magneto-tellurics (MT),** but measures magnetic fields only (E-fields not easily measured in air).

- The EM source is the natural field of Earth caused by Lightning Strikes– mainly equatorial thunderstorms and other electrical storms 1000's of km away – create horizontal planar primary fields, available year-round.



- ELF "Extra Low Frequency" range" between from 30 to 360Hz +/- 720Hz (provides for reasonably High Signal Strengths <u>and</u> Significant Penetration <u>and</u> Year Round Surveys)

- Basic Principle: Lateral resistivity contrasts cause horizontal EM fields to Tilt Vertically. Vertical secondary H-field vector called "Tipper" (aka Weiss-Parkinson Vector).



- . The relationship between vertical (Hz) & horizontal (Hx-Hy)-fields is:

$$Hz(f)= Tx\,(f)*Hx(f)+ Ty(f)*Hy(f) \quad \text{Vozoff (1972)}$$

Tipper vector (Tx, Ty) is determined using FFT processing of time-series.

AFMAG – Background

Mcphar AFMAG 1959

- AFMAG **first used in the late 1950's** by McPhar Geophysics for mineral exploration in ground & airborne surveys.
- In spite of its many positives, poor data quality and repeatability were major impediments to its application/acceptance in mineral exploration industry (Ref. Ward et al., 1968), i.e. scalar approximation was incorrect.
- Technique was essentially abandoned in 70's-80's-90's as an exploration tool (replaced by upcoming inductive EM systems).
- Academic research in AFMAG continued (Ref. Labson et al., 1985) more efforts applied to VLF (Europe – Ex. Pedersen, 1998).
- Geotech re-embarked on AFMAG development in 2000, lead to ZTEM (Z-axis Tipper EM) system in 2005-06, first commercially available passive AEM system for mineral exploration in 30 years.

Mcphar H400 AFMAG 1973

- ZTEM is Variant of AFMAG – only Hz receiver mobile, Hx-Hy fixed base-station as per:

$$H_z(\mathbf{r}) = W_{zx}(\mathbf{r},\mathbf{r}_0)H_x(\mathbf{r}_0) + W_{zy}(\mathbf{r},\mathbf{r}_0)H_y(\mathbf{r}_0).$$

- AirMt (Airborne Magnetic Tipper), first introduced by Geotech in 2009, compares all 3 components of Magnetic Field at receiver and base, according to the following:

Geotech AFMAG 2002

$$\begin{bmatrix} H_x(\mathbf{r}) \\ H_y(\mathbf{r}) \\ H_z(\mathbf{r}) \end{bmatrix} = \begin{bmatrix} W_{xx}(\mathbf{r},\mathbf{r}_0) & W_{xy}(\mathbf{r},\mathbf{r}_0) & 0 \\ W_{yx}(\mathbf{r},\mathbf{r}_0) & W_{yy}(\mathbf{r},\mathbf{r}_0) & 0 \\ W_{zx}(\mathbf{r},\mathbf{r}_0) & W_{zy}(\mathbf{r},\mathbf{r}_0) & 0 \end{bmatrix} \begin{bmatrix} H_x(\mathbf{r}_0) \\ H_y(\mathbf{r}_0) \\ H_z(\mathbf{r}_0) \end{bmatrix}.$$

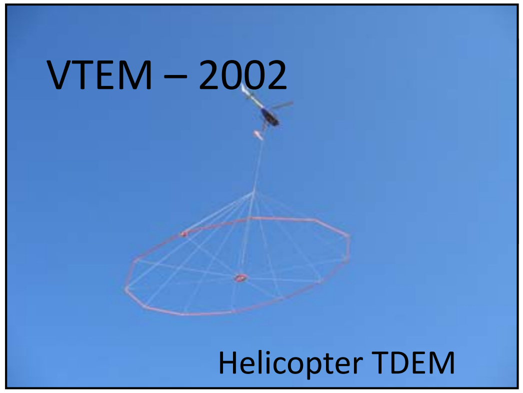
- The 3x3 matrix |W| can be re-written to obtain the complex scalar: called the "*Amplification Parameter*" AP which is rotationally invariant.

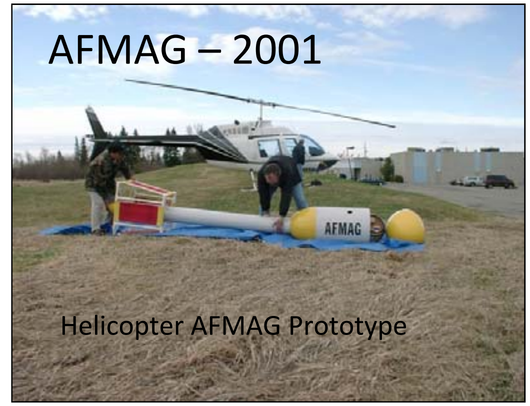
$$K = \mathbf{K} \cdot \frac{Re(\mathbf{K})}{|Re(\mathbf{K})|}$$

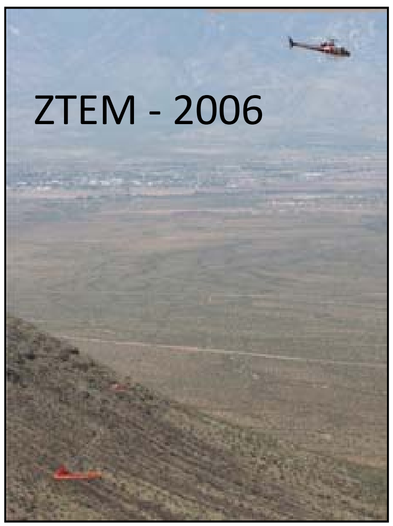
Geotech Passive Airborne EM Systems: >10 years of Development

Helicopter AFMAG - 2002

From Fountain
(2008)







Geotech currently has 10 passive AEM system in operation around the world (8-ZTEM, 1-FWZTEM,1-AirMt)

AFMAG System Development

- Geotech revisited AFMAG starting in 2000 using modern technology, and digital signal processing tools.

- Test results using the system as shown on the right, were encouraging, but showed that the receiver coils were not sensitive enough – i.e. too small, too few windings.

  It only had a rudimentary suspension system to damp out vibrational noise

AFMAG System in 2001

From Lo and Kuzmin (AEM 2008)

AFMAG Development

AFMAG DAS System (2002)

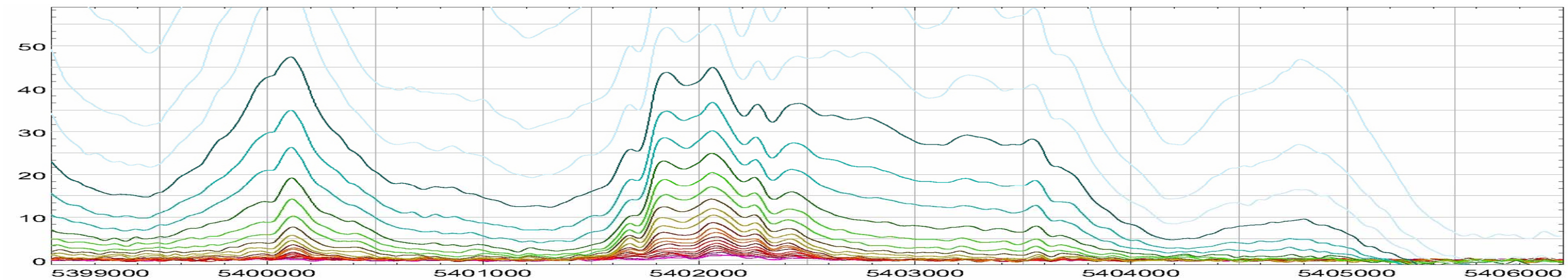
AFMAG Receiver Bird (2002)

- With funding and support from INCO and MIM, Geotech obtained a OMET grant to significantly upgrade the airborne AFMAG system.
- New coils, suspension system, base stations, orientation sensors, numerical simulation, field trials, data processing techniques and reporting were accomplished.
- Geotech undertook testing at Reid Mahaffy in 2002 and also patented the system.

From Lo and Kuzmin (AEM 2008)

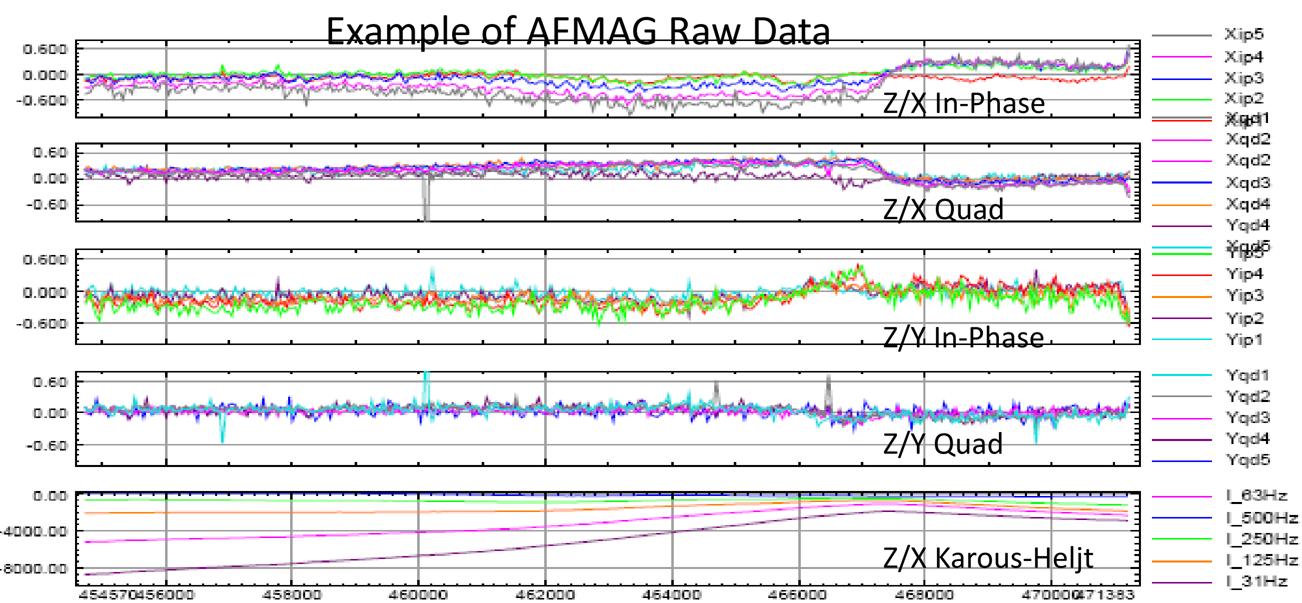
Reid Mahaffy Test Range circa 2002, comparison with early VTEM results

VTEM results – line 20



Geoelectric section from VTEM

Karous-Heljt Relative Depth Filtered XIP



AFMAG results – line 20

8

From Lo, Kuzmin and Morrison (2005)

AFMAG Development

AFMAG Base-Station (2004)

AFMAG Receiver Bird (2005)

- Following the results of 2002, Geotech took time to assess the data and modified the electronics and suspension of the airborne system.
- A tail and drag skirt assembly were added to the bird to give it greater stability in the air.
- As well, a base station unit was built.
- A set of ground tests of the new and redesigned equipment in the Sudbury area was successful.
- This was immediately followed by airborne trials over the Sudbury area in 2004
- These results were presented to in OMET (2005) & KEGS (2005), and at ASEG (2006)

From Lo and Kuzmin (AEM 2008)

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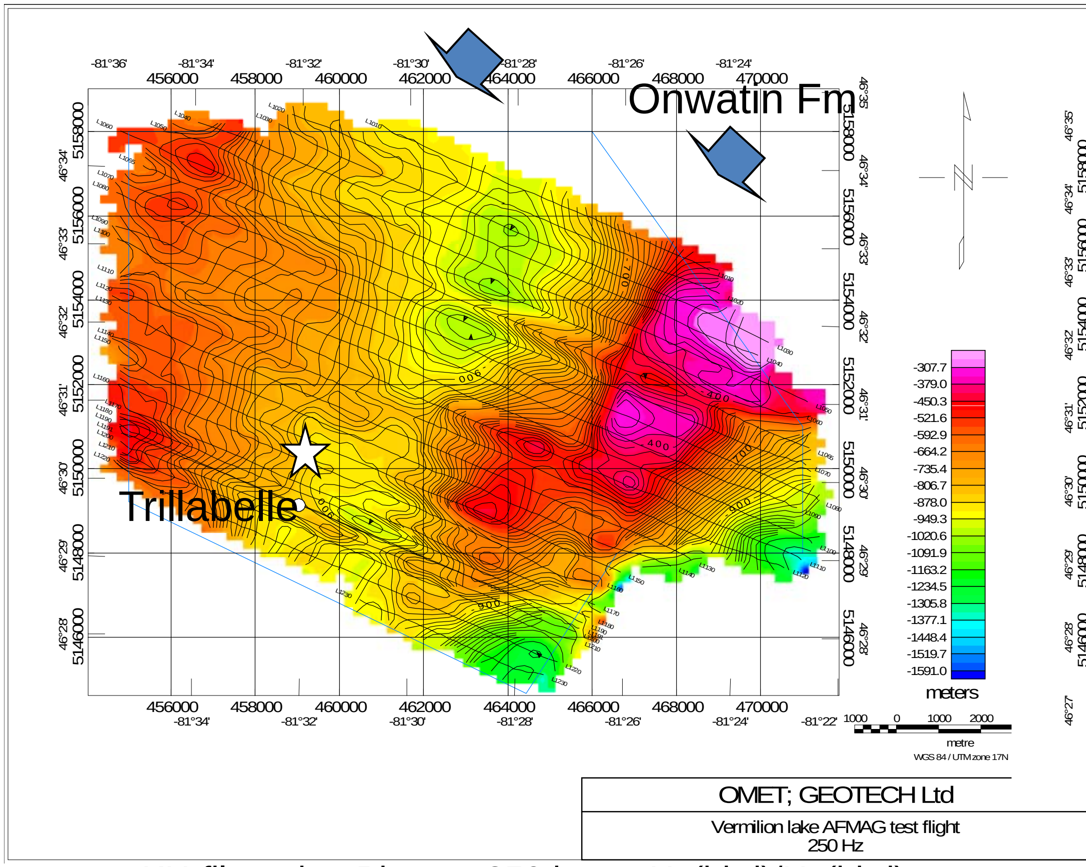
Base Station vs Local Receiver (2004)

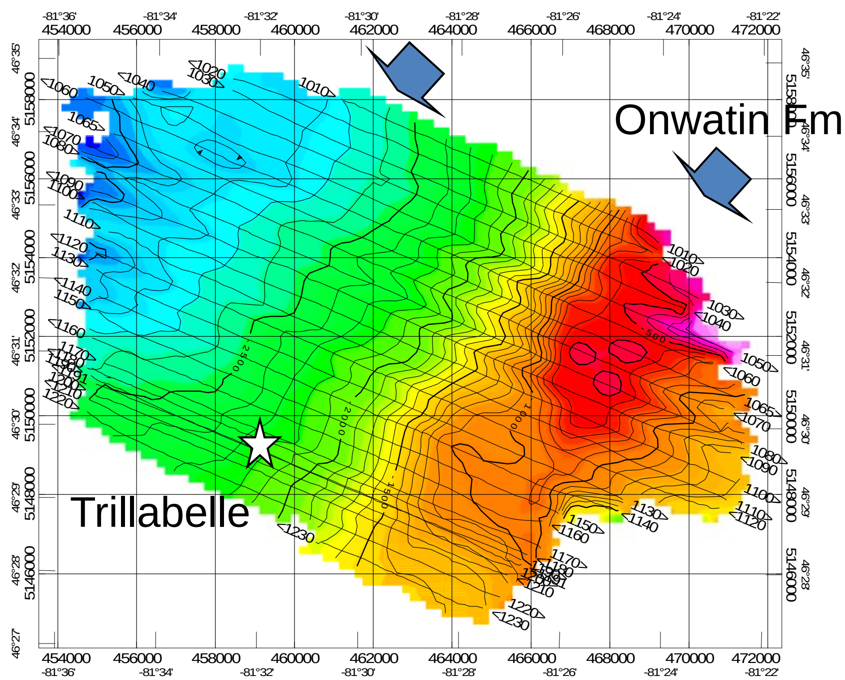
Tx Tipper using Hx-Hy in Receiver bird   SIC Contact?



KH-filtered In-Phase - 250 hertz Hz(bird)/Hx(bird)

Tx Tipper using Hx-Hy at Fixed Base station

SIC Contact?



KH-filtered In-Phase 250 hertz Hz(bird)/Hx(base)

Survey trials show that use of base-station leads to improvement in Signal/Noise yet not all anomalous responses (i.e. SIC) relating to geology are defined.

From Lo, Kuzmin and Morrison (2005)

Lessons from AFMAG Field trials

- The system developed for the OMET subsidized project was a very workable system …. but …. Need to....
- Improve the suspension system as the Signal to Noise ratio is 10X better on the ground.
- Increase size of sensor - improves signal to noise.
- Maximize distance between aircraft & receiver, by using long tow cable - fixed-wing “stinger” sensor concept proves unworkable.
- Use base station data for horizontal fields instead of airborne receiver – results in acceptable and interpretable data.
- Added benefits include the ability to increase the size of the base-station magnetometers and place them far from man-made culture, in order to improve their signal to noise
- R&D development eventually leads to conception of ZTEM system in 2006

From Lo and Kuzmin (AEM 2008)

ZTEM – 2006

System in 2006

- Onboard Hz-Hx-Hy receiver coils in AFMAG bird replaced by combination of:
  a) larger single vertical aircoil & b) fixed base station receiver coils.
- New configuration called “ZTEM” (Z-axis Tipper EM) system.
- Early ZTEM airborne coil was 7.4 m (same size now)
- Early ZTEM had base station coils same size as airborne coil at 7.4 metres diameter
- This proved impractical and smaller base stations were built.

From Lo and Kuzmin (AEM 2008)

ZTEM base station - 2007

- Base station was now smaller – about 3.5 metres square,
- Braced to be perpendicular to each other
- Internal suspension system
- Air-core loops
- Yet, difficult to transport and set-up easily
- Still currently in use

ZTEM base-station - 2007

From Lo and Kuzmin (AEM 2008)

ZTEM base station (2009)

- ZTEM started to use the AirMt receiver coil as its ZTEM base station in 2009
- Still about 3.0 metres square
- Easily deployed (using helicopter) & mobile, minimum set up time are important advantages.
- Currently used when more than on base-station emplacement required (large surveys with >20km distances)

Geotech Passive AEM Systems

ZTEM (Z-axis Tipper Electromagnetic)

Key System Parameters

- Natural magnetic (AFMAG EM) field measurement (30-720Hz)
- Fixed Base Station
- Airborne Z axis loop sensor that acquires vertical magnetic field data.
- Receiver loop-tilt correction via use of onboard GPS sensors
- Rx loop diameter: 7.2 m
- Rx height: 50-100 m nominal

Data Acquired

- Measures Tzx (in-line) and Tzy (cross-line) Tipper vectors (via FFT of time-series)
- Magnetics: Caesium Sensor
- Production: 150-600km day

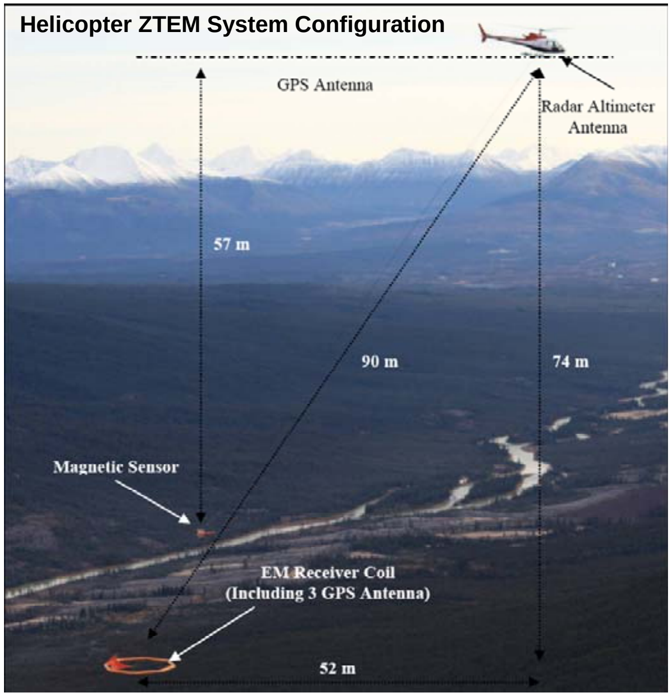
Applications

Resistivity Mapping – Mineral Industry

Porphyry Copper

Geothermal

Hydrocarbon



ZTEM is the deepest penetrating airborne EM system, proven to below 1-2km Depths, with demonstrated success for mapping Porphyry Coppers and other large mineralized systems.

ZTEM Base Station (Hx-Hy horizontal)

Geotech Passive AEM Systems

FW (Fixed Wing)-ZTEM

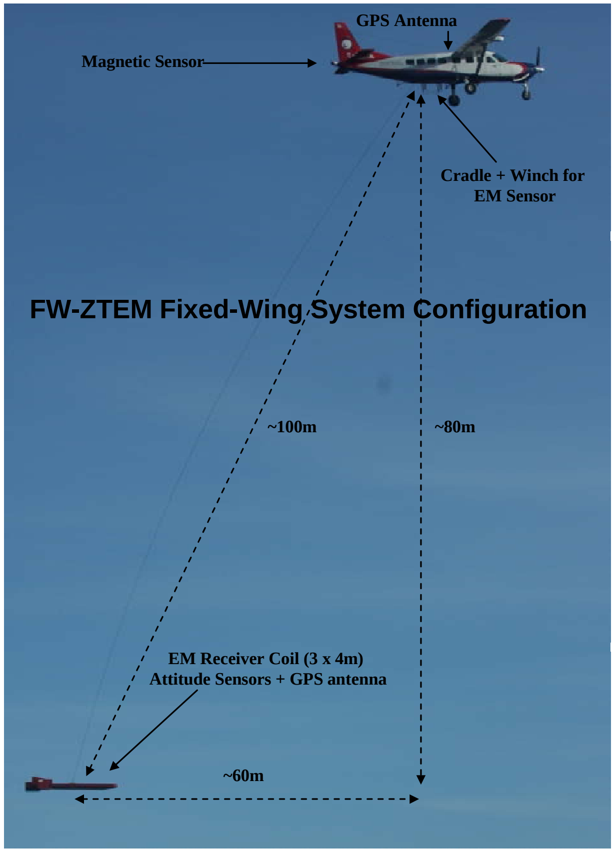
Key System Parameters

•Natural magnetic (AFMAG EM) field measurement (30-720Hz)
• Fixed Base Station
• Airborne Z axis loop sensor that acquires vertical magnetic field data (Retractable vs Sling-load)
• Receiver loop-tilt correction via use of onboard GPS sensors & inclinometers
•Rx loop dimensions: 3m x 4m
•Rx height: 50-100 m nominal

Data Acquired

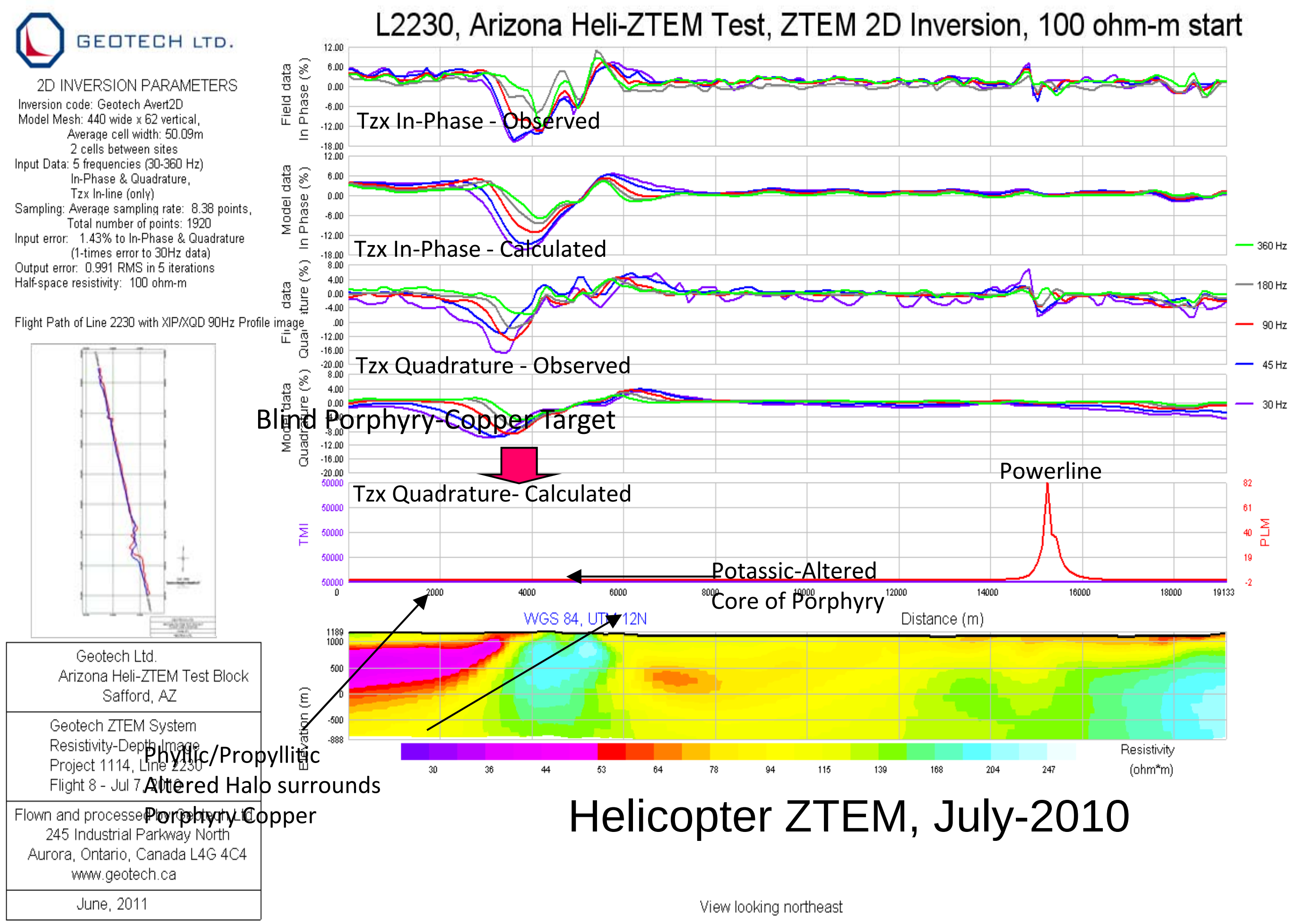
•Measures Tzx (in-line) and Tzy (cross-line) Tippers
•Magnetics: Cs Sensor
•Optional Grav-gradiometry, Spectrometry.
•Production: ~1000km/day projected

Applications
Low Cost Regional Resistivity Mapping
Porphyry Copper
Hydrocarbon
Geothermal

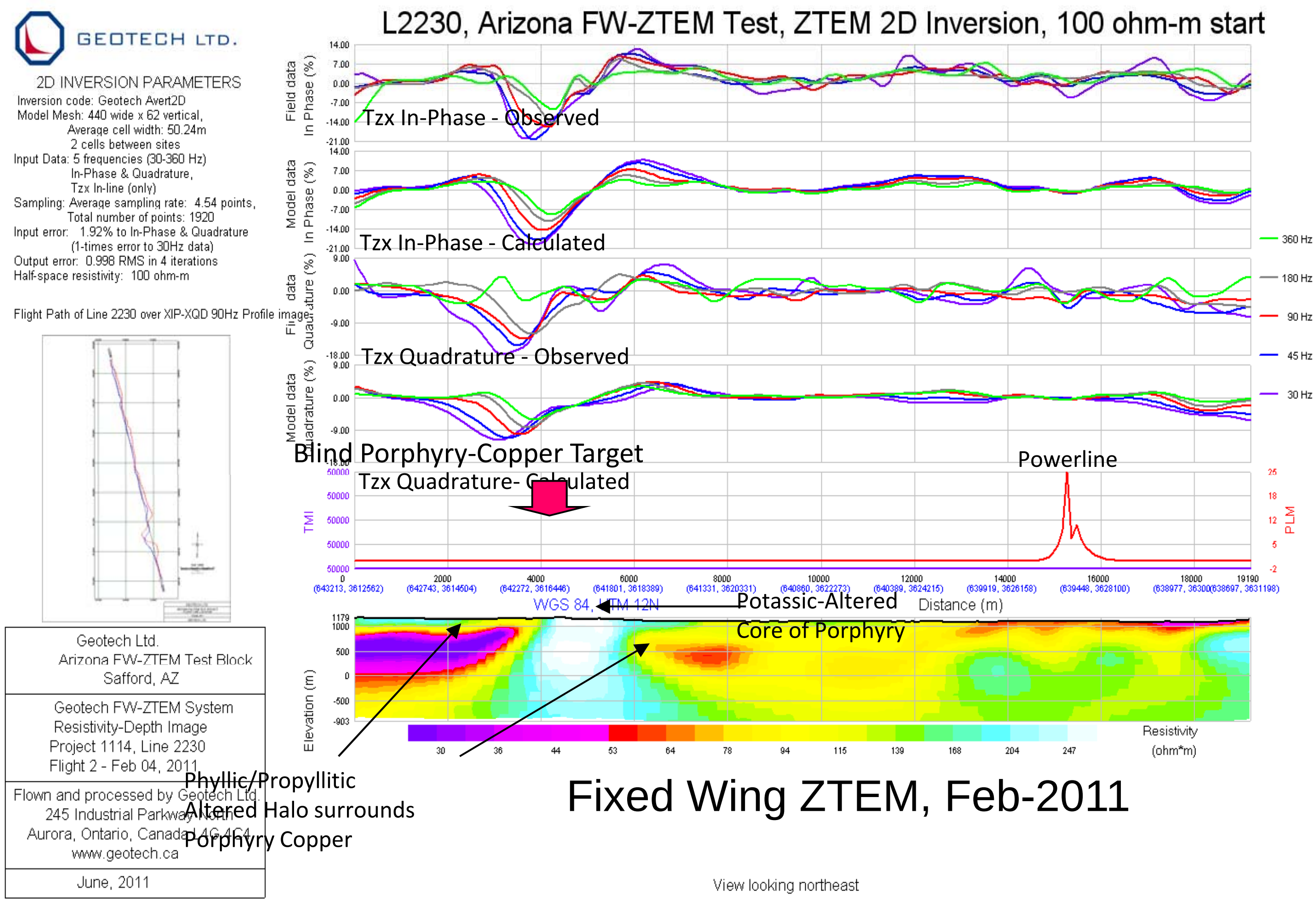


Fixed-Wing ZTEM is equivalent system for more regional geologic mapping using a longer range/ endurance platform. Designed to be deployed with add'l sensors for complete multi-parameter characterization

FW- vs Heli-ZTEM Tests, '11

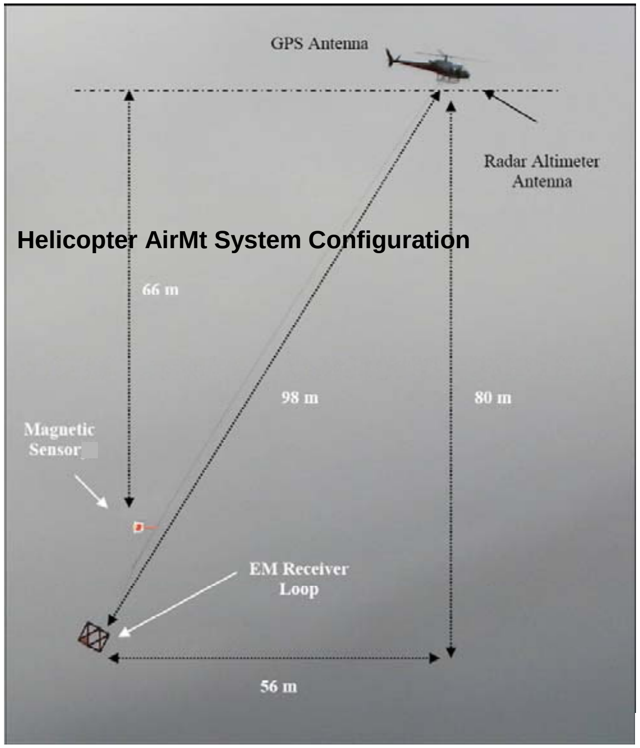


Notice close fit between observed and modeled data, and resulting resistivity model from 2D inversion, highlighting alteration phases over buried Porphyry, Safford Az



Notice close fit between previous Heli-ZTEM & FW-ZTEM data and 2D inversions prove that FW-ZTEM can be cost-effective alternative for regional reconnaissance surveys.

Geotech Passive AEM Systems



AirMt (Airborne Magnetic Tensor)

Key System Parameters

•Natural magnetic (AFMAG EM) field measurement (45-720Hz +/- 30Hz)
• 3-axis loop sensor with identical base station
• No Receiver loop-tilt correction necessary (GPS for positioning only)
•In-Phase and Quadrature transfer functions
•Peak responses over lateral varying resistivity structure
•Rx loop dimensions: 3m x 3m
•Rx height: 50 m nominal

Data Acquired

• Measures rotationally invariant Amplitude Parameter (AP)
• Magnetics: Cs Sensor
•Production: 120-500km/day
Applications
Resistivity Mapping – Mineral Industry
Porphyry Copper
Hydrocarbon
Geothermal

AirMt is innovative next step in passive AEM design, features improved signal/noise (3x) & increased depth-penetration vs ZTEM - In R&D/design-testing.


AirMt Sensor as Base Station

AirMt-ZTEM system Comparison

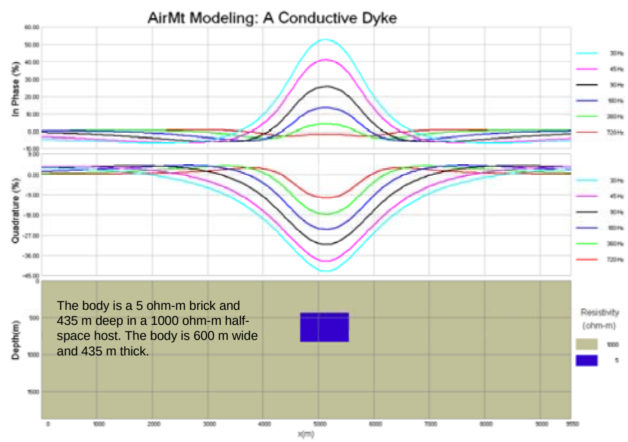
AirMt

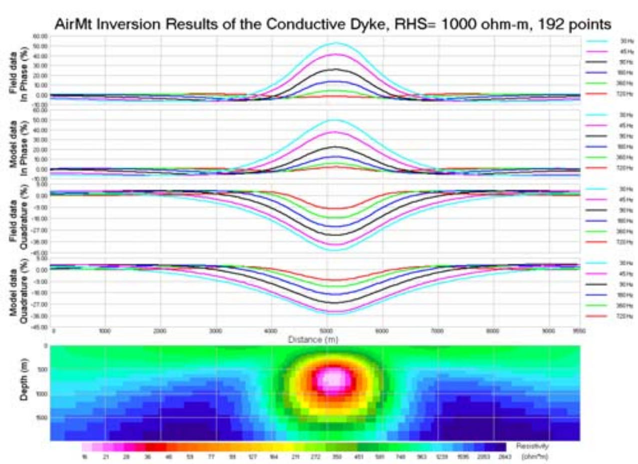
- Natural magnetic (AFMAG EM) field measurement (45-720Hz)
- 3-axis loop sensor with identical base station
- No Receiver loop-tilt correction necessary (GPS for positioning only) – improves S/N
- Measures rotationally invariant Amplitude Parameter (AP)
- In-Phase and Quadrature transfer functions
- Peak responses over lateral variations in resistivity structure
- Interpretation in plan directly from raw data
- Resistivity cross-sections via 2D-3D inversion

ZTEM

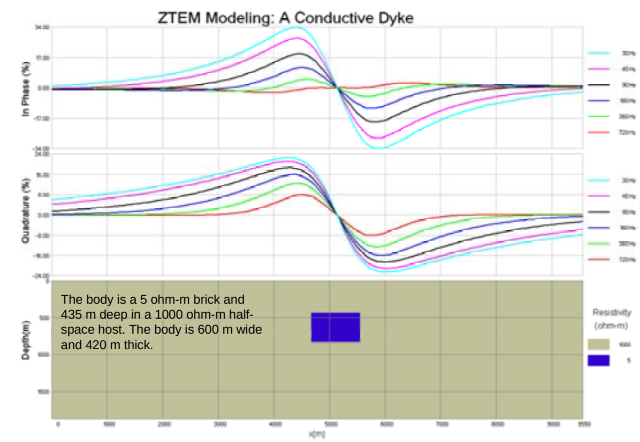
- Natural magnetic (AFMAG EM) field measurement (30-720Hz)
- Z-axis sensor with 2 or 3-axis base-station (AirMt coils)
- Receiver loop-tilt correction via use of onboard GPS sensors – reduces S/N
- Measures Tzx (in-line) and Tzy (cross-line) Tipper vectors
- In-Phase and Quadrature transfer functions
- Cross-over responses over lateral variations in resistivity structure
- Interpretation in plan using DT or Phase-Rotation of Tippers
- Resistivity cross-sections via 2D-3D inversion

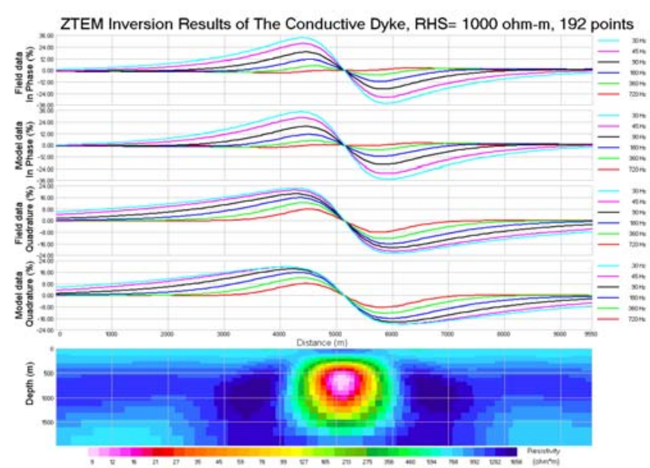
AirMt 2D Synthetic Modeling





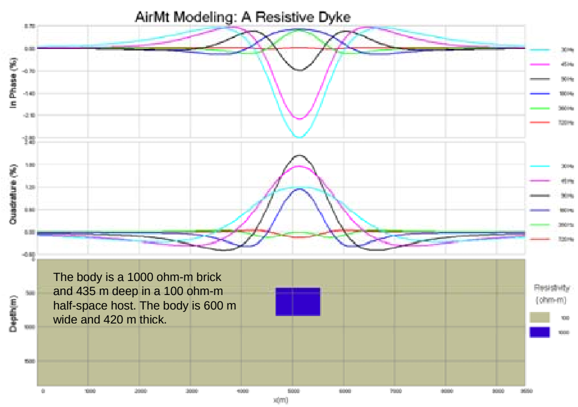
ZTEM 2D Synthetic Modeling

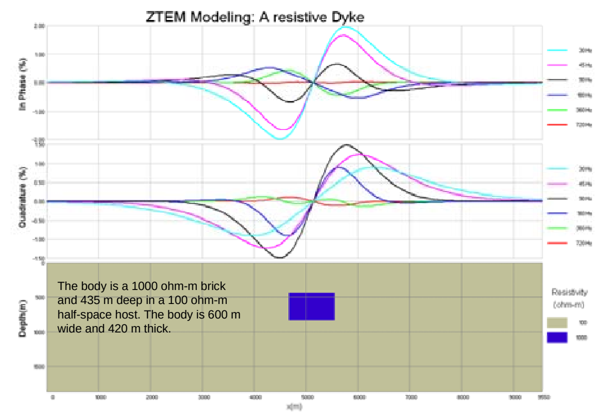


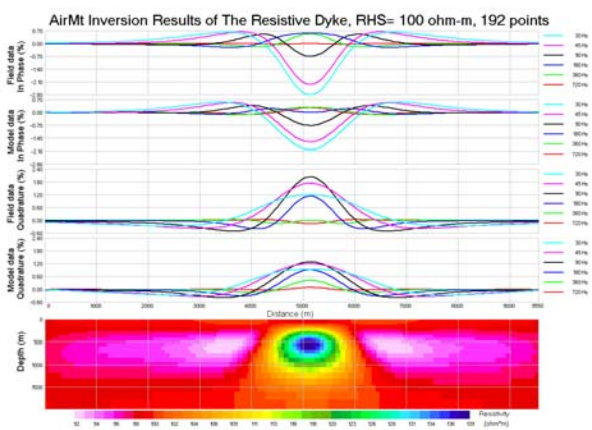


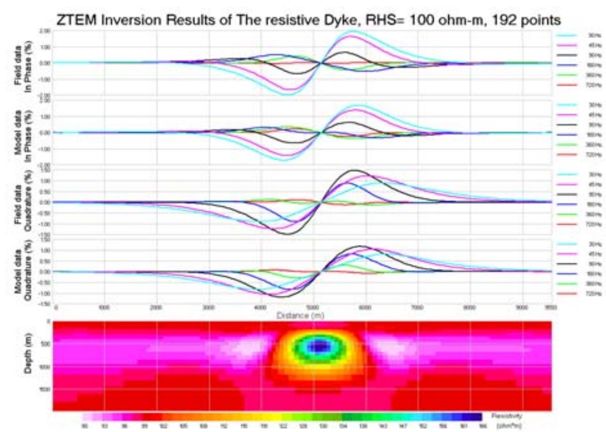
AirMt 2D Synthetic Modeling

ZTEM 2D Synthetic Modeling





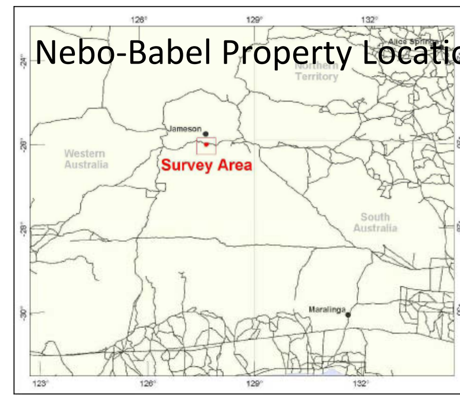


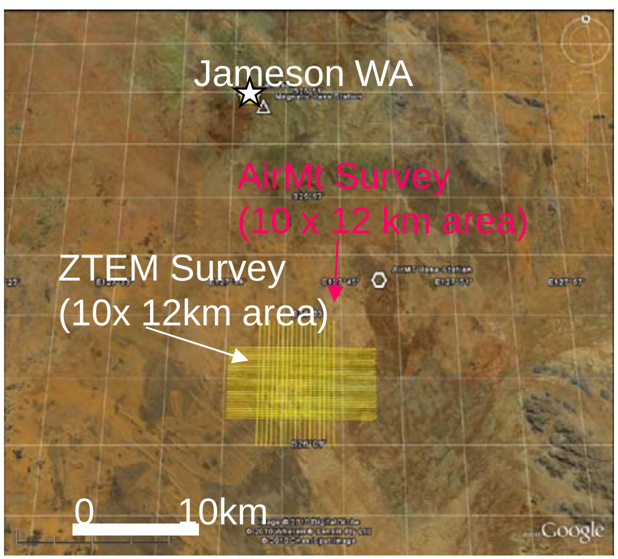


Case History Example:

ZTEM & AirMt survey results over the Nebo-Babel Ni-Cu-PGE Deposit, West Musgrave, WA (2010).

- Discovered in 2000 using surface geochemistry
- Drill intersections include 106m at 2.4% Ni, 2.67% Cu & 0.2g/t PGE
- Resource of 1Mt Ni + 1Mt Cu+Co contained
- Hosted in tube-like gabbro-norite that intrude ortho-gneissic country rocks and offset along north-south Jameson Fault
- Babel is large, low grade disseminated deposit, subcrop-600m
- Nebo is smaller, but higher grade MS pods, shallow buried-600m?



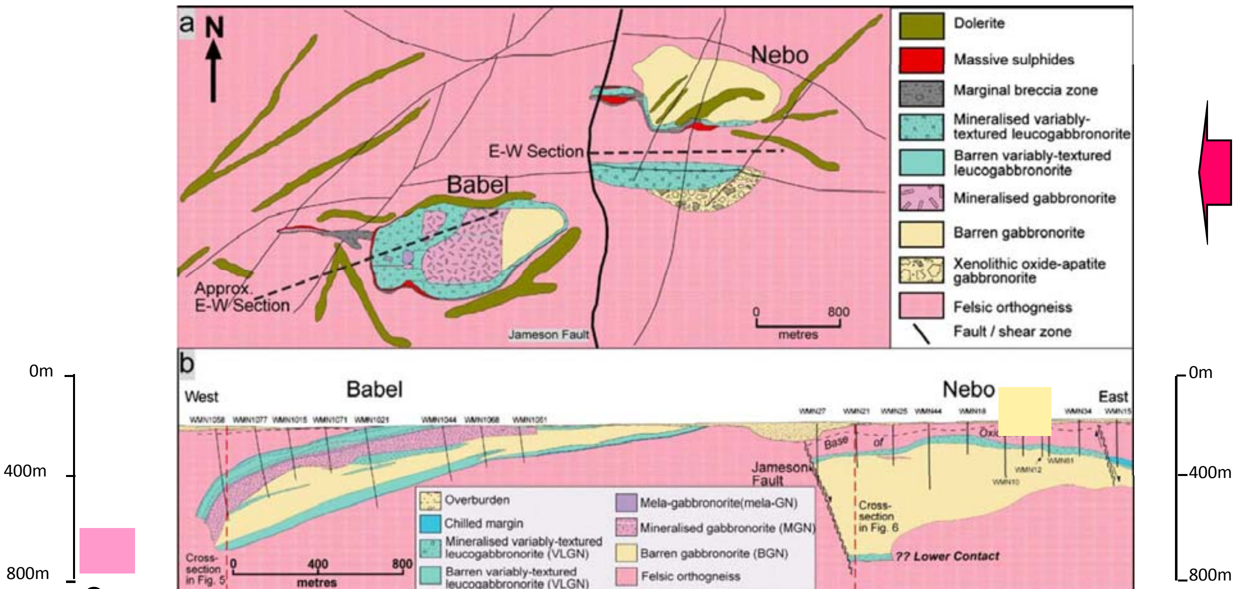


ZTEM and AirMt surveys (Oct-2010) consisted of 541 & 574km:

- 17 x 10km NS flight lines @ 400m spacing
- 31x 12km EW flight lines @ 200m spacing
- Tzx & Tzy Tippers (ZTEM) and AP (AirMt) - both In-phase & Quadrature
- 5-6 frequencies in 25-600Hz bandwidth
- Total field magnetics

(Results shown courtesy of BHP Billiton)

Nebo-Babel Geology



Nebo and Babel are hosted in 2 separate gabbro-norite intrusives in orthogneiss host-rocks (~ 5km x 1km x 0.5km)

Fault-offset along the north South Jameson Fault

Babel is larger but low grade disseminated, subcrops, plunges west, open at depth (base at 600m)

Nebo is smaller but has massive sulphide pods, buried, open at depth (base inferred at 600m)

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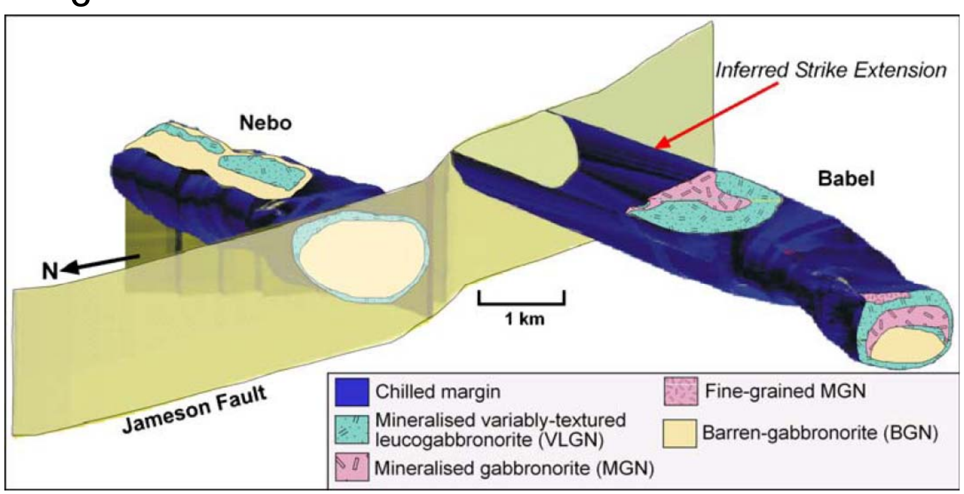
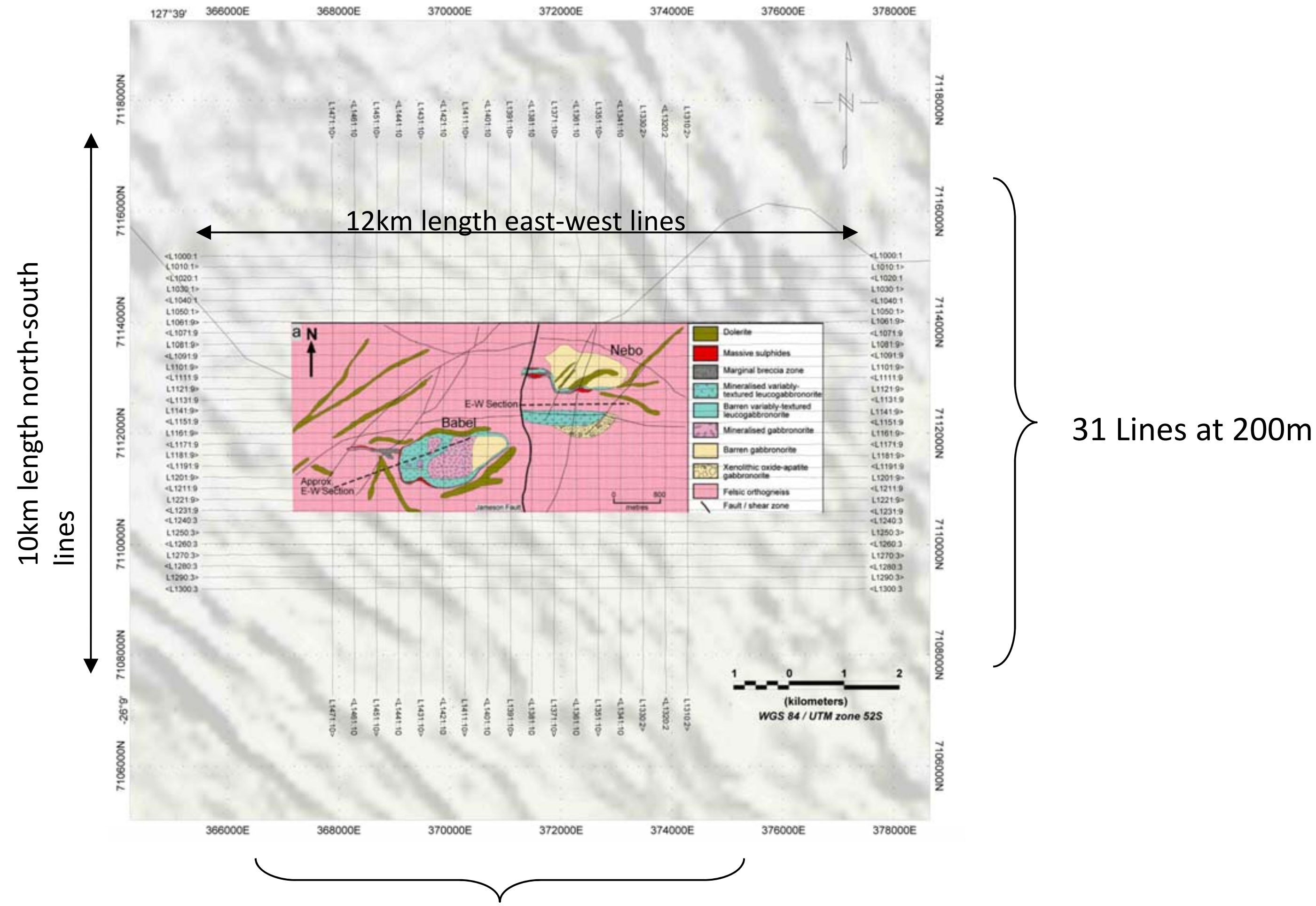


Nebo-Babel features strong magnetic, electromagnetic, and gravity anomalies highlight the massive and disseminated mineralization in the deposit

(after Seate, et al., 2007).

ZTEM Flight Path over Nebo-Babel Geology (modified after Seat et al., 2007)

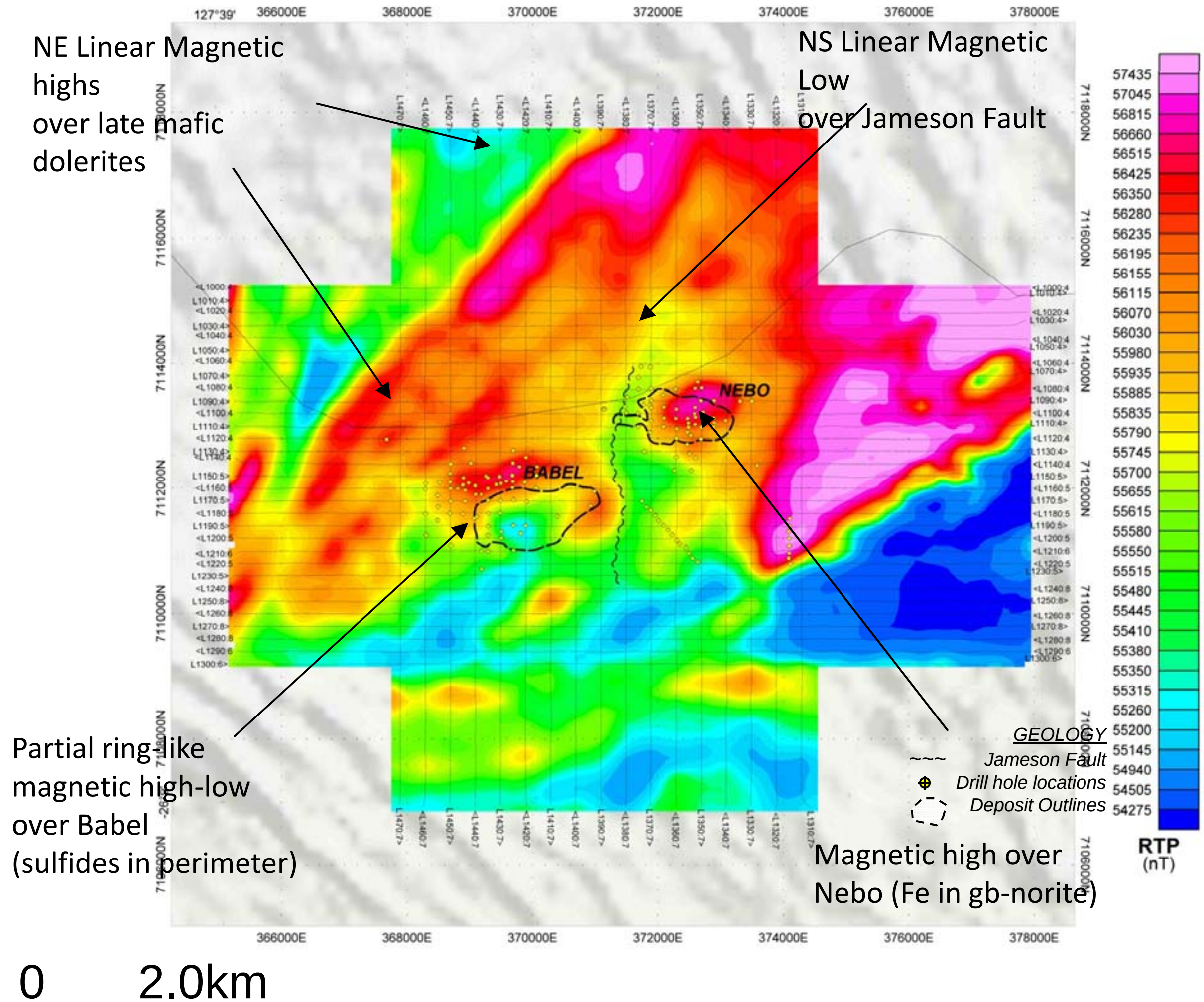
Nebo-Babel Survey



ZTEM and AirMt flown in both survey directions

Nebo-Babel Survey Data

Total Magnetic Intensity - Reduced to Pole (RTP)



Aeromagnetics highlight regional & local geology, structures

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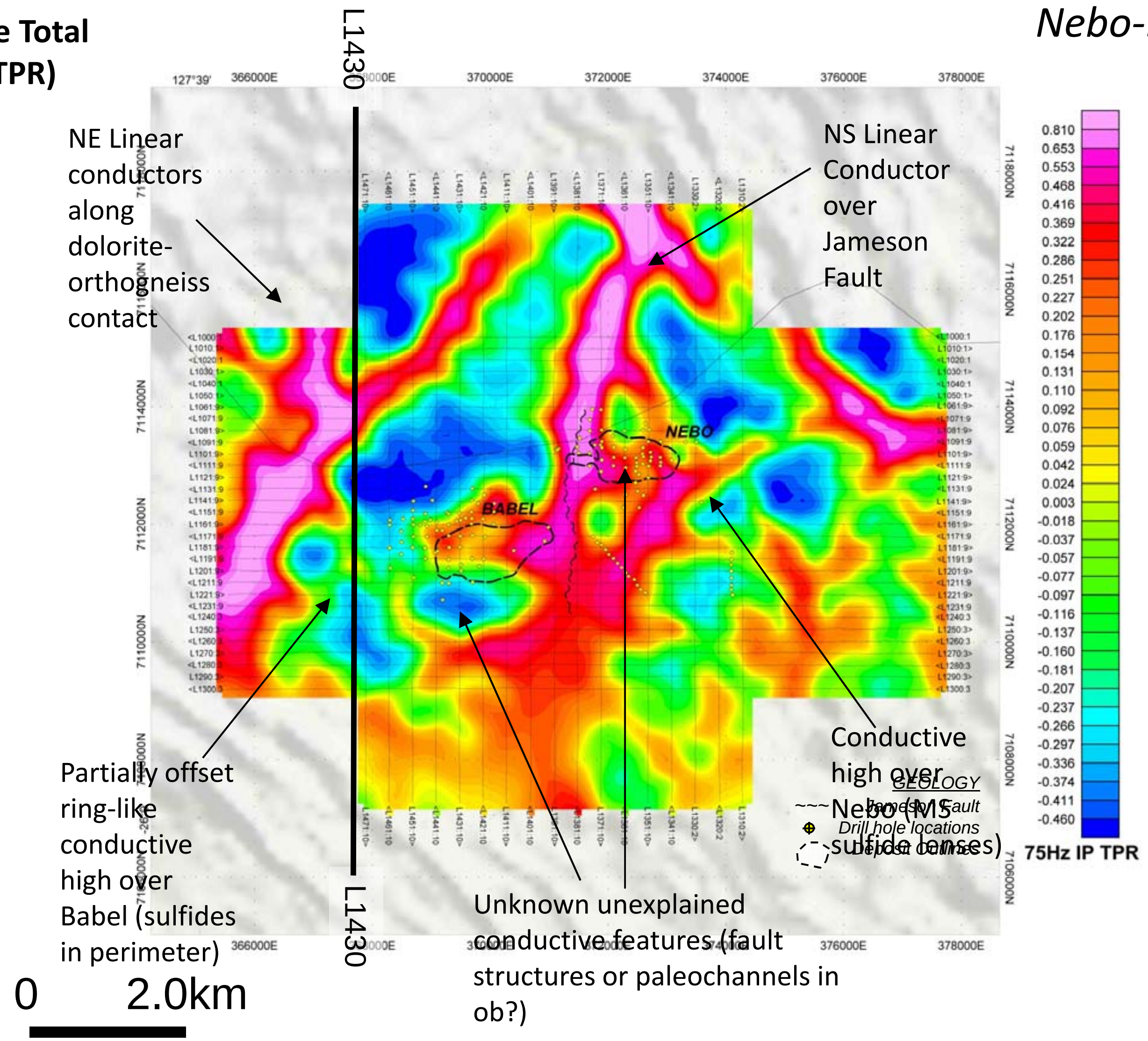
ZTEM 75Hz In-Phase Total Phase Rotation (IP TPR)

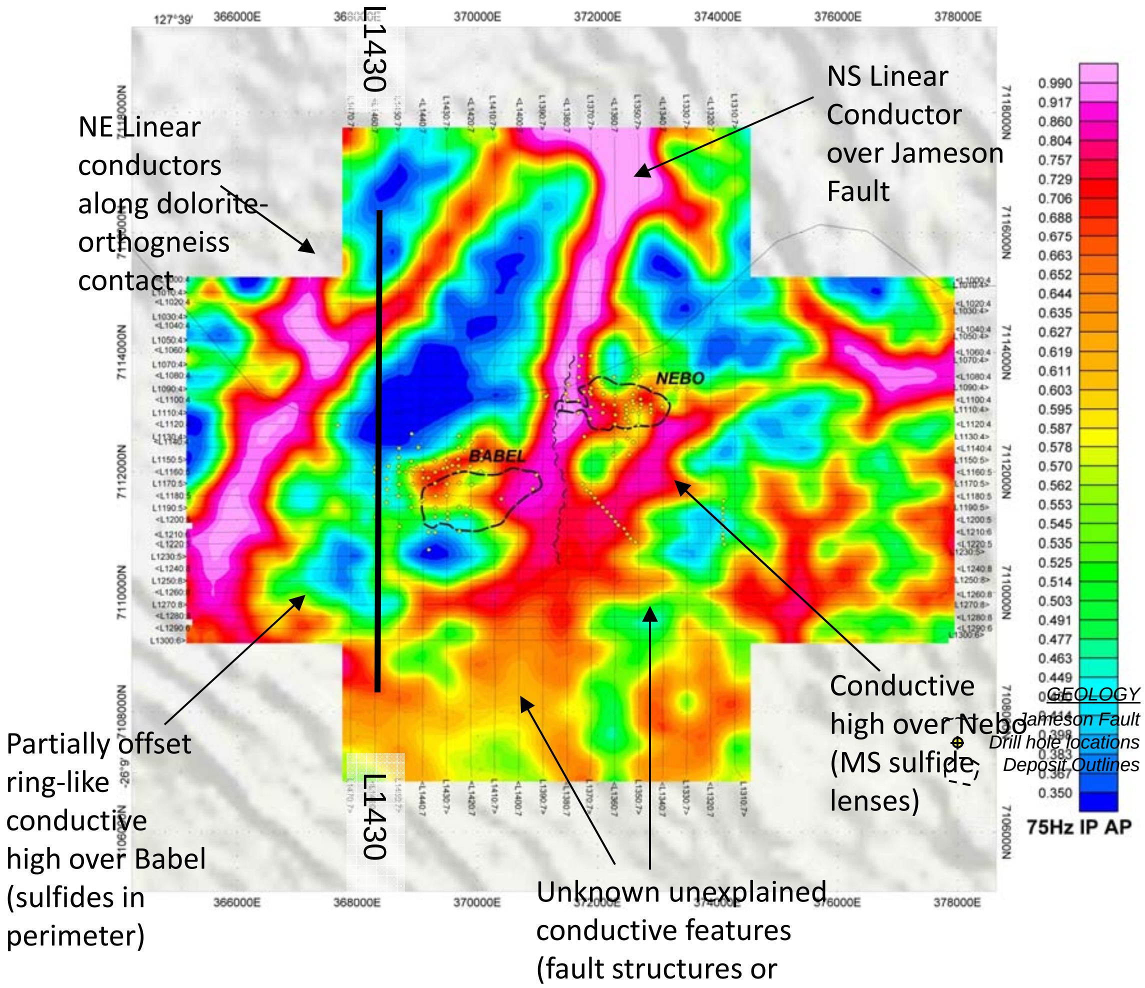
Nebo-Babel Survey Data



ZTEM TPR highlights Nebo-Babel, known Geology and Other features

AirMt 75Hz In-Phase Amplitude Parameter (IP AP)

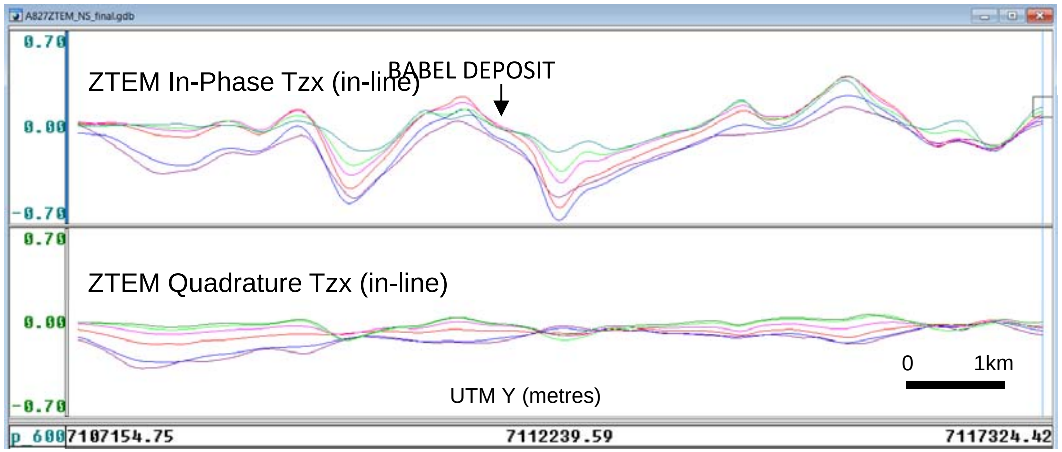
Nebo-Babel Survey Data



AirMt AP results closely resemble ZTEM – yet both independant

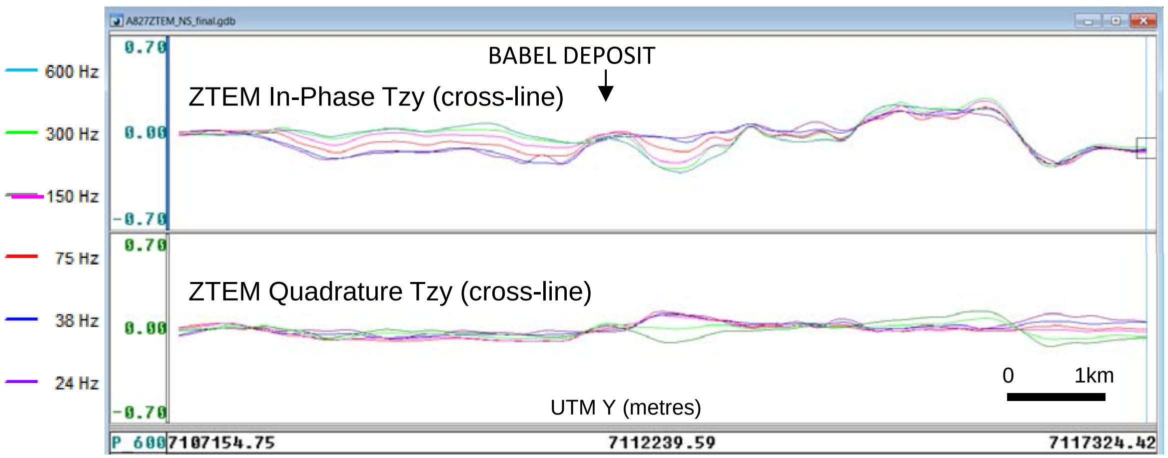
Nebo-Babel Data

L1430



ZTEM In-phase Tzx (in-line) displays well-defined normal cross-overs at all frequencies but building in amplitude from high to low - indicates partial buried conductive body.

The reversing Quadrature cross-overs at lower frequencies might indicate a lower conductivity at depth or limited vertical extent.



ZTEM Tzy (cross-line) results are weaker than Tzx (in-line) – might suggests that the responses are not strongly 3D along profile

(unlikely to be the case, given its short strike-length and presence/ influence of NS Jameson Fault)

BABEL DEPOSIT

BABEL DEPOSIT

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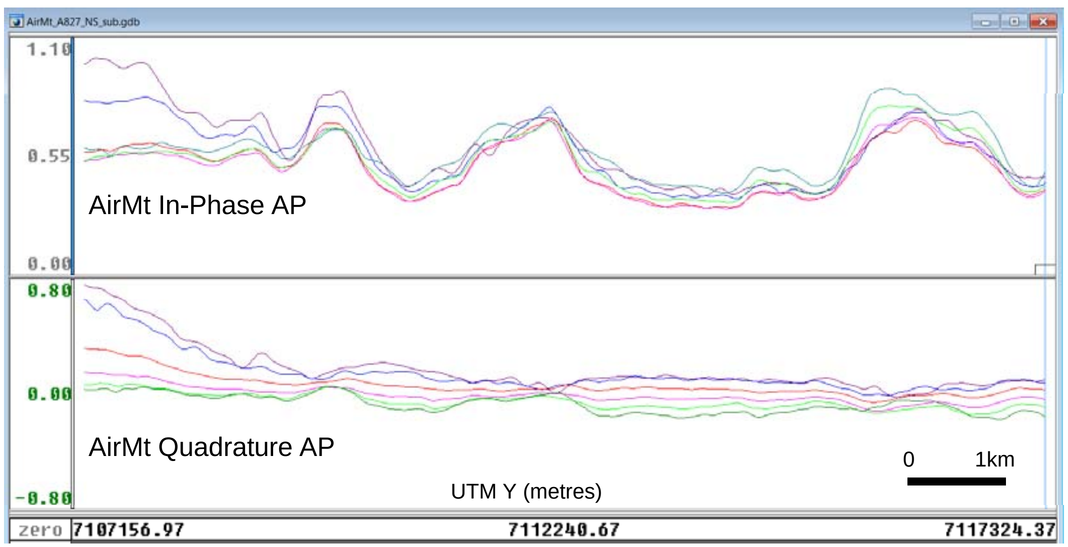
Cont…



AirMt In-phase displays well-defined positive peak response at all frequencies, building in amplitude from high to mid frequencies - indicates partial buried, depth-limited conductor

The flat to weak negative peak Quadrature response at lower frequencies might indicate lower conductivity at depth.

No indication of dimensionality in AirMt response.

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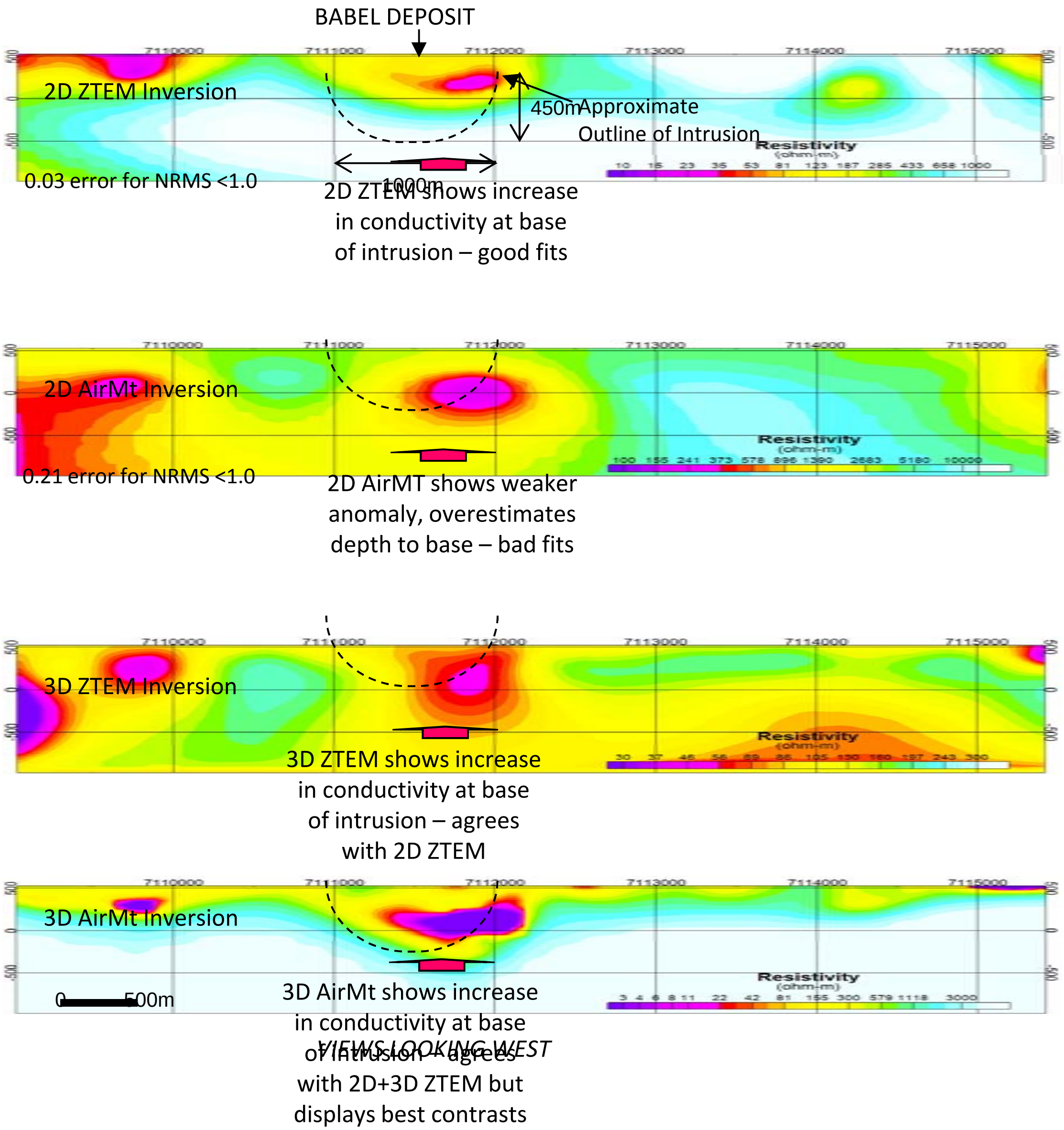
Nebo-Babel Inversions



Using Geotech Av2dtopo inversion code developed by P. Wannamaker (2009 & 2011) based on 2D finite-element code of de Lugao & Wannamaker (1996).

TechnoImaging 3D integral equation method of Hursán & Zhdanov (2002) and RRCG method of Zhdanov (2002)

Conclusions – Passive AEM Development

- It has now been more than 10 years since Geotech embarked on the development of airborne AFMAG technology:

    i. Lightweight, heli-slingable prototype in 2001

    ii. Fully damped, attitude-corrected receiver with modern A/D acquisition & DP processing in 2002

    iii. Larger air-coil with GPS attitude-sensors and fixed base-station ZTEM in 2006

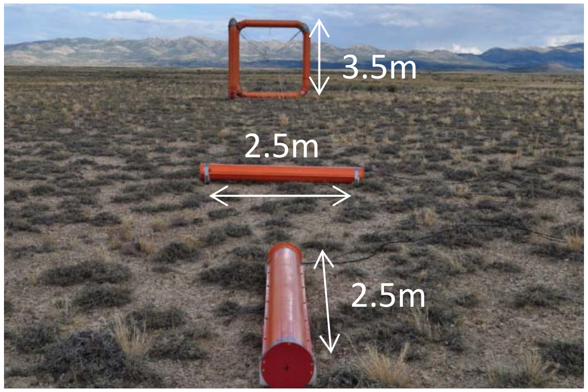
    iv. Multi-axis receiver and innovative AP parameter of AirMt system in 2009

    v. Aerodynamic, retractable sensor of FW-ZTEM in 2011

Conclusion – 10 years of AEM (continued)

What's new in 2012 for Geotech passive AEM:

i. Smaller, portable, low noise base-station ferrite-core sensors – possible multiple site deployment for on-site & remote monitoring.



New (foreground) vs old (background) ZTEM base-station sensors (Nevada 2011)


New portable ZTEM base-station sensors (Quebec 2011)

ii. Ground MT measurements on-site (Core Geophysics)
- will allow more accurate apriori model and more robust interpretation using 2D & 3D joint-inversion.

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Conclusion – 10 years of AEM (continued)

- What's in the future for Geotech passive AEM:

  i. Unlikely that lower frequencies (<25Hz) are obtainable from airborne sensors, because "airflow" noise dominates lower spectrum - noise increases by 100x.
  Longer averaging may only get a few more Hz of data.

  ii. But adding higher frequencies above 1kHz deadband is certainly possible – particularly if focus on high amplitude events instead of averaging.

  iii. Redesign of AirMt sensor – more aerodynamic, smaller, possible multi-component extraction (i.e., combined AirMt AP parameter & ZTEM tipper data from same sensor/measurement).

10 years of Passive AEM Development

THANK YOU

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