Mineral Exploration using modern Airborne EM systems and ground follow-up with state of the art SQUID sensor

Case Study: Jacomynspan Ni-Cu deposit, South Africa

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Main objective

- This talk is intended to highlight the feasibility of using specifically electromagnetic (EM) methods in combination with airborne magnetic data set and geology in obtaining a model of the distribution of the well mineralized harzburgite pods hosted within the less conductive poorly mineralized Jacomynspan ultramafic sill.

Introduction

- This talk is based on geophysical work done on a well known Jacomynspan Ni-Cu deposit in RSA.
- Electromagnetic (EM) methods, frequency and time domain are used for a wide variety of purposes.
- Time-domain electromagnetic (TEM) methods – which are the subject of this presentation are increasingly being used for mineral exploration, saltwater intrusion, geotechnical applications and a variety of other physical planning purposes.
- Over the past decades, TEM systems have developed to provide early time measurements for improved near-surface resolution and late time measurements to increase the depth of penetration.
- To the geologist interested in geophysical exploration for base metals, it is helpful to understand some basic principles of EM theory because EM methods have been so successful in the discovery and delineation of these deposits.

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Geology

- The Jacomynspan Nickel-Copper (Ni-Cu) occurrence in the Northern Cape Province of South Africa is located 50km east of Kenhardt and 130km south of Upington the commercial center of the region.
- It is located within the Meso to Neo-Proterozoic Namaqua Tectonic Province which is part of the Kibaran-aged (1400 – 950Ma) orogenic event.
- the sill is predominantly composed of tremolite schist (metamorphosed pyroxenite) containing highly conductive lenticular bodies of harzburgite.
- the harzburgite generally hosts net-textured mineralization with up to 50% of mineralization by rock volume. Massive sulphide veins and stringers are occasionally present.

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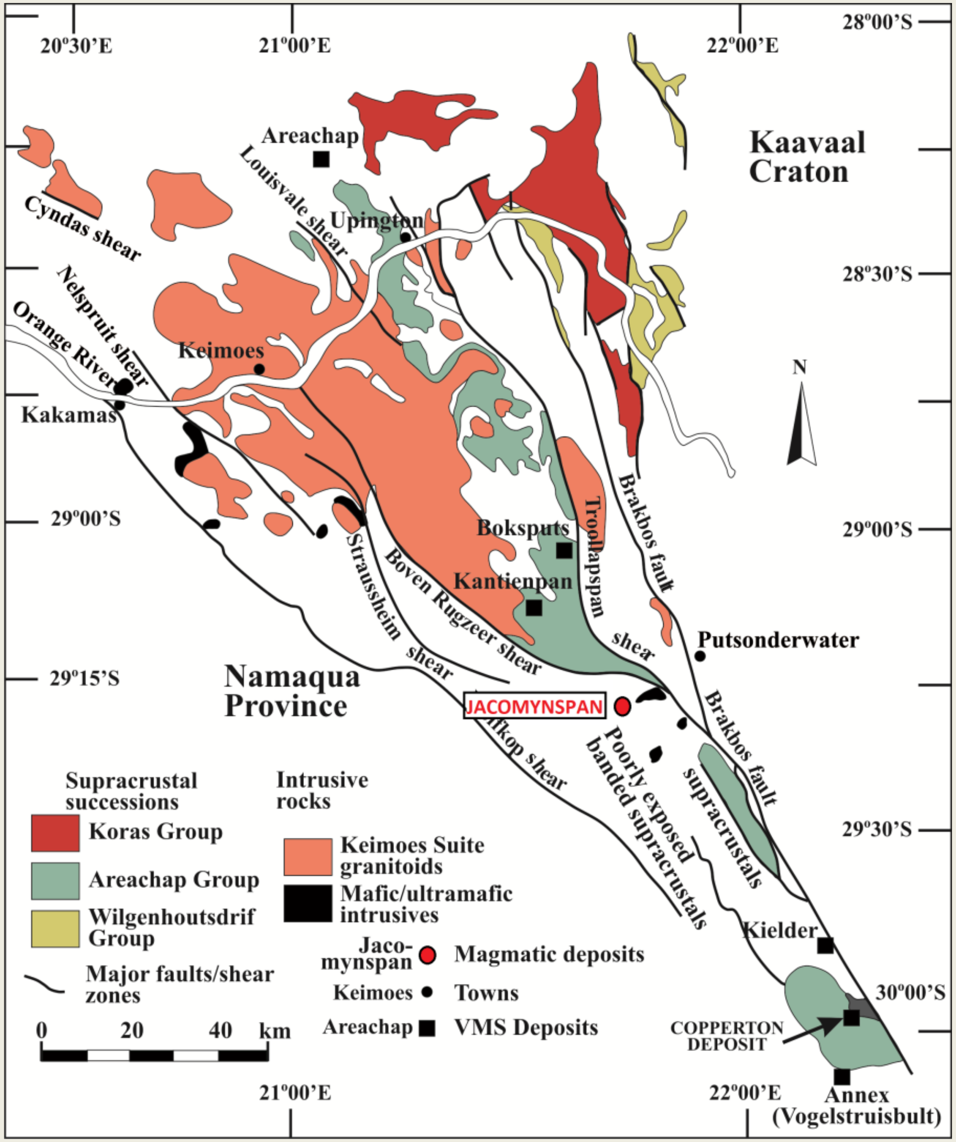
Simplified geological map showing the locality of the Jacomynspan Ni – Cu deposit in the Areachap Belt (Attridge,1986)



Cross section of the Jacomynspan mineralised Ultramafic sill

Electromagnetic Theory

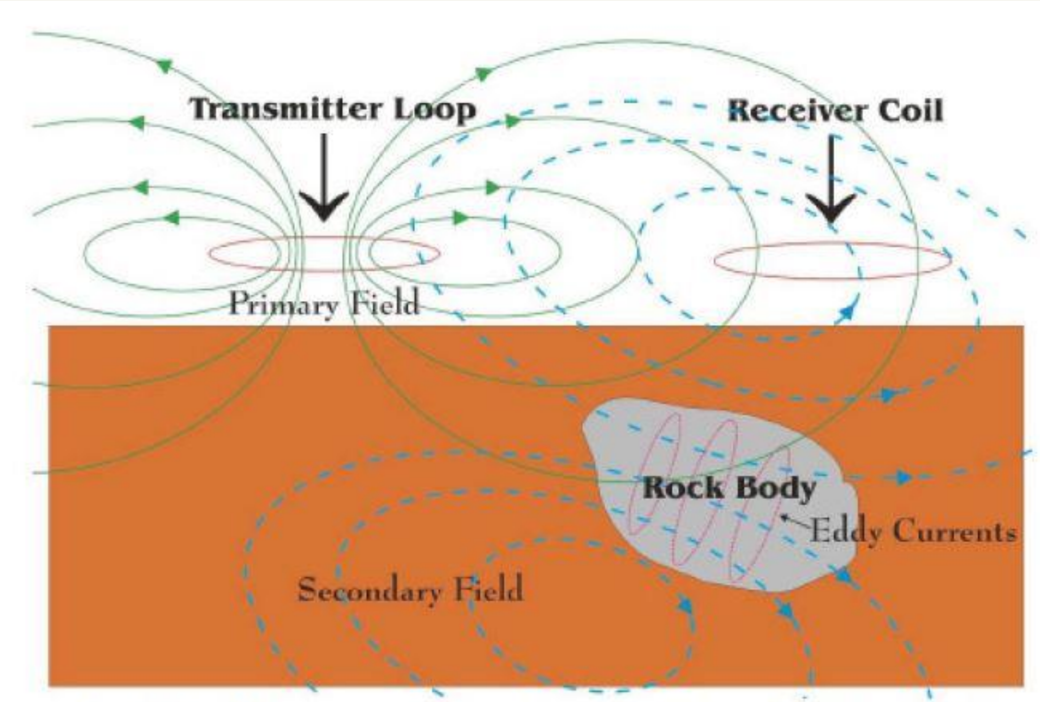
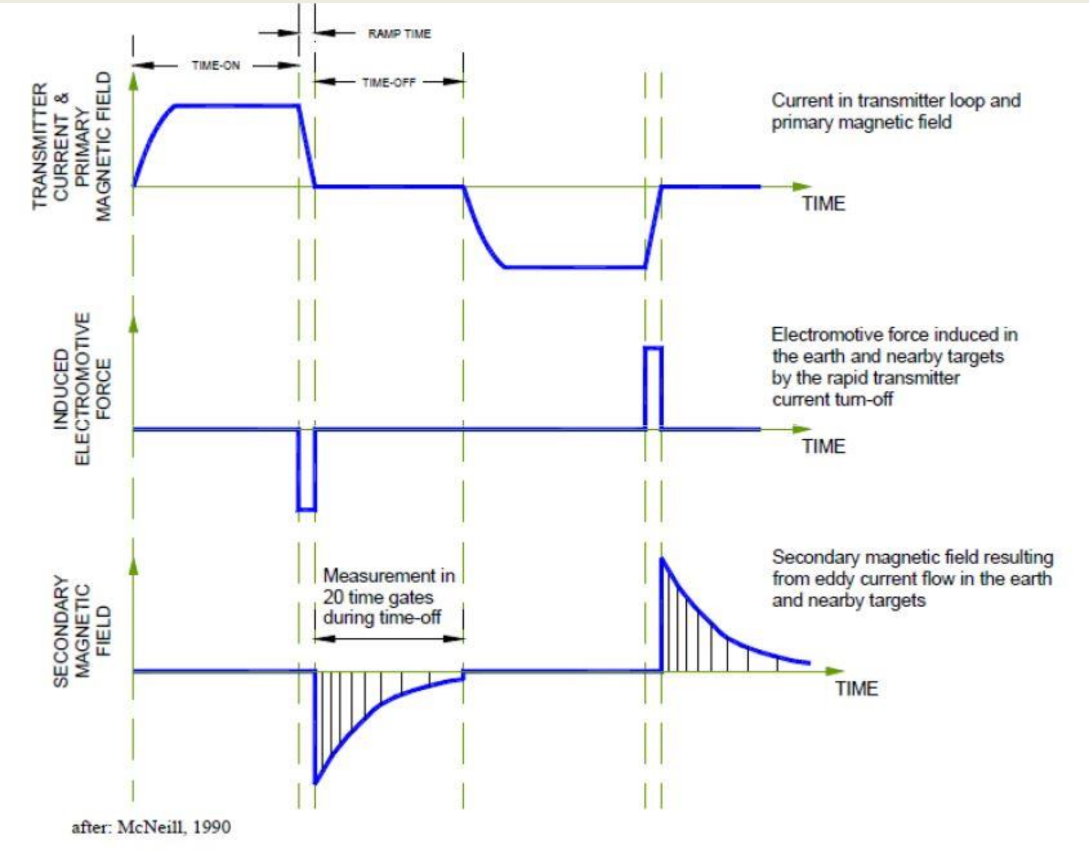


Figure 2 - Basic EM surveying system. The transmitter generates a primary field that induces eddy currents in the subsurface conductor resulting in a secondary field. (Modified from Grant and West 1988)

- In EM prospecting, a time-varying electromagnetic field called the ***primary field*** is generated by a transmitter.
- The primary field travels through resistive host rock by the process of ***induction*** and interacts with a conductor by generating eddy currents over the conductor's surface.
- The eddy currents in turn create a secondary magnetic field called the ***secondary field*** which travels back through the resistive host rock and is measured by the EM receiver.

- All EM methods measure and record this ***secondary field***.

Time Domain EM waveforms



- In time domain EM systems, the time variation of the current is a switch on, followed by a rapid switch off.
- In general, good conductors have secondary field responses which decay slowly after the switch off.

The B-field

- Geophysicists refer to the magnetic component of the electromagnetic field as the B-field and use a coil of wire known as an induction receiver to measure it.
- Induction receivers do not measure the **B**-field directly but instead measure the rate of change in the **B**-field as a function of time or *dB/dt*.
- The units of measurement of the **B**-field are nanoTeslas (nT) and for *d**B**/dt* nanoTeslas per second (nT/s).
- In order to measure *d**B**/dt* of the secondary field, the current in the transmitter must be changing.
- However with the introduction of the ***Fluxgate*** and ***SQUID*** magnetometers, we can now measure the **B**-field directly.
- The **Fluxgate** and **SQUID** are **B**-field (i.e. very fast sampling magnetometers) sensors that measures the time-integral of the impulse response which is called “step response”.
- This time integral is an important ‘filter’ which attenuates fast decays from weaker or unconfined conductors in preference to decays from strong conductors which are slow.

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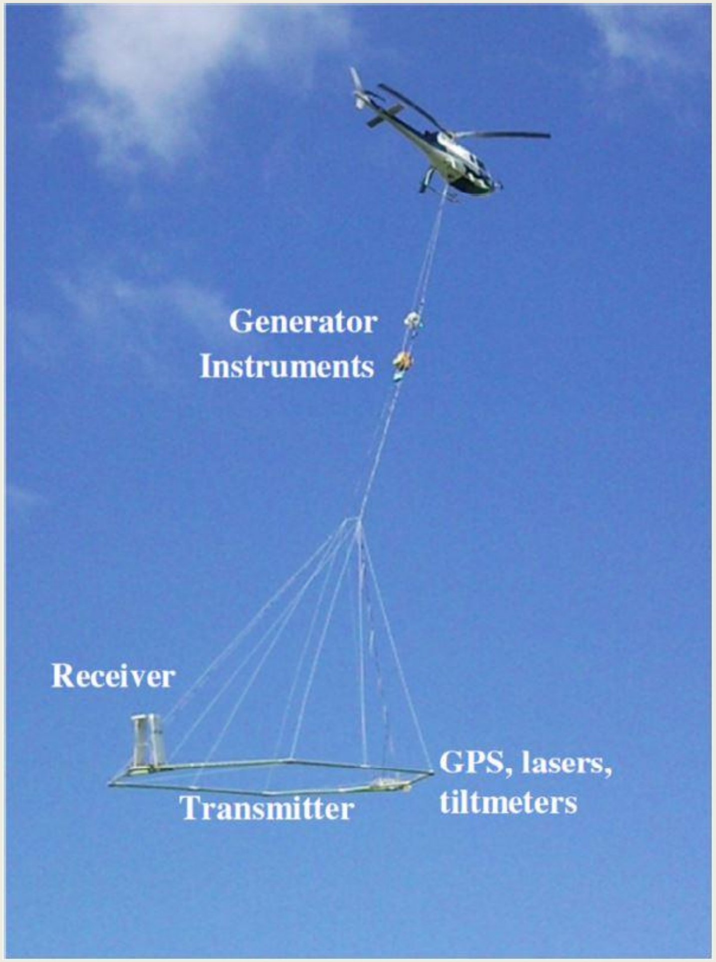
Airborne EM systems (AEM)

- AEM systems were developed in the 1950's (Fountain, 1998) and were substantially improved with the introduction of digital technology in the 1970's.
- Two basic configurations have emerged - the rigid transmitter-receiver systems mounted on helicopters and the large separation towed bird systems mounted on fixed-wing aircraft.
- To plan and operate more efficiently and effectively, exploration companies must take advantage of recently introduced innovative and advanced technology specifically engineered to quickly collect high quality data from which high value information can be extracted.
- There are a lot of airborne EM systems but we will take a look only at 3 systems which are mostly in current use i.e. SkyTEM, VTEM and SPECTREM.

SkyTEM system



SkyTEM system in operation

- SkyTEM is a time domain, helicopter borne electromagnetic system initially engineered for hydro-geophysical and environmental investigations.
- The system has a unique Dual Moment transmitter - a Low moment for shallow mapping and High Moment, with high current and low base frequency providing quality late-time data for deep imaging.
- The receiver coils measure both the vertical (**Z**) and horizontal in-line (**X**) components of the secondary voltage response. The X-component provides additional resolution of lateral conductivity contrast and steeply dipping conductors.

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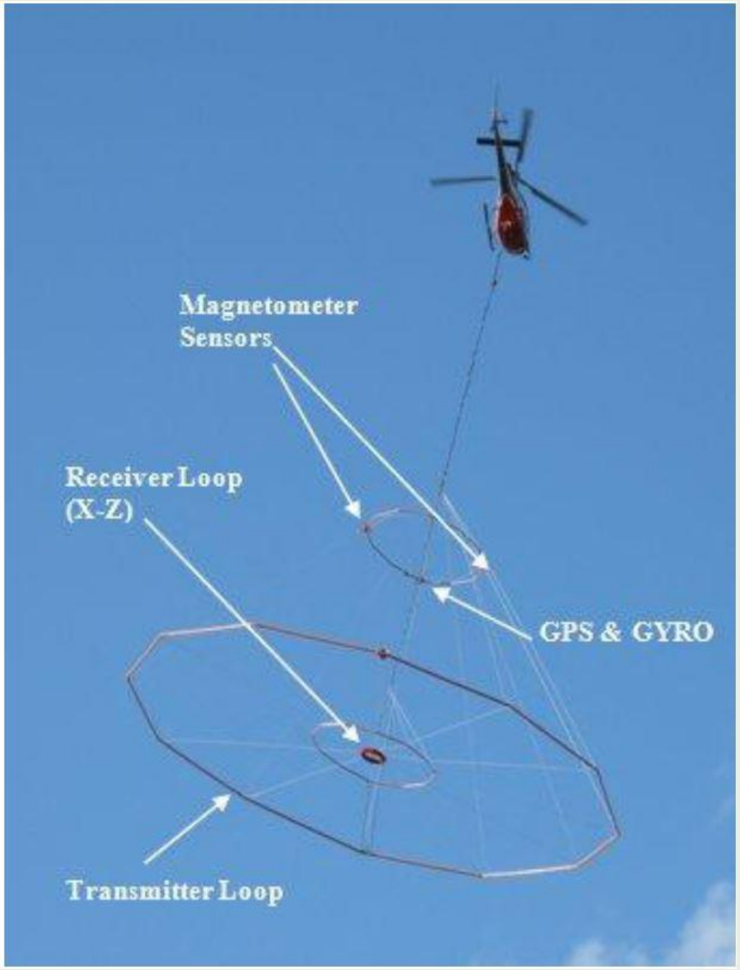
VTEM system



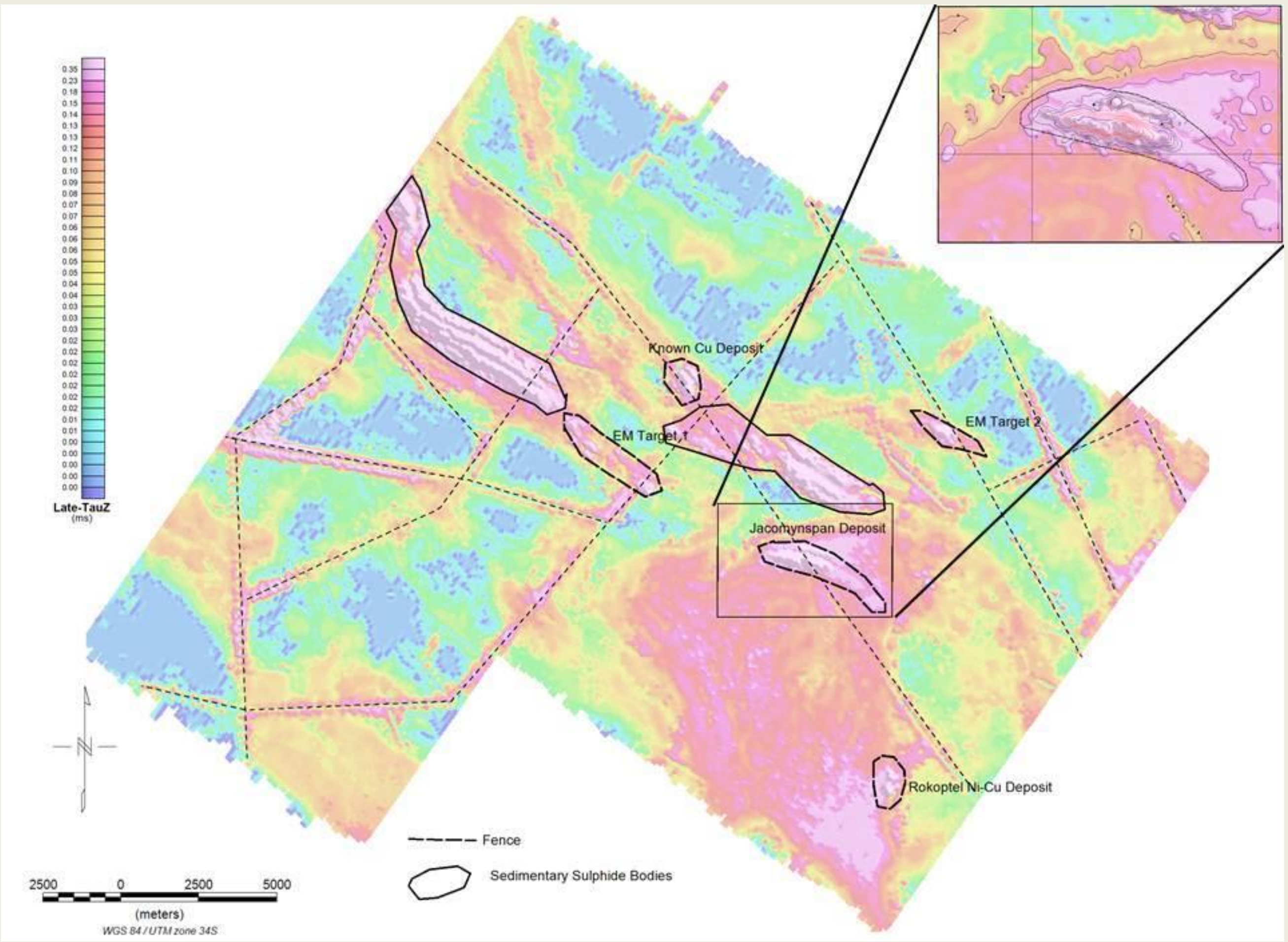
VTEM system in operation

- Versatile Time Domain Electromagnetic (VTEM) system has a coincident vertical dipole transmitter receiver configuration that provides a symmetric response.
- Has various dipole moments.
- Transmitter has bucking loop to reduce signal at receiver.
- The VTEM system has been used to explore for a wide variety of deposits styles in a diverse range of settings.

SPECTREM System

- SPECTREM is a fixed wing system housed in a BASLER DC3 PLATFORM that simultaneously takes electromagnetic, total field magnetic, radiometric and digital elevation measurements.
- Both the electromagnetic and magnetic sensors are towed behind the aircraft in “birds” while the radiometric crystals are installed inside the cabin.
- The system has a very high dipole moment.

Example of Spectrem data at Jacomynspan project



- Late time constant image from a Spectrem survey with interpretation
- Known and new targets are clearly mapped.

An example of SPECTREM data flown over a known Ni-Cu deposit in South Africa

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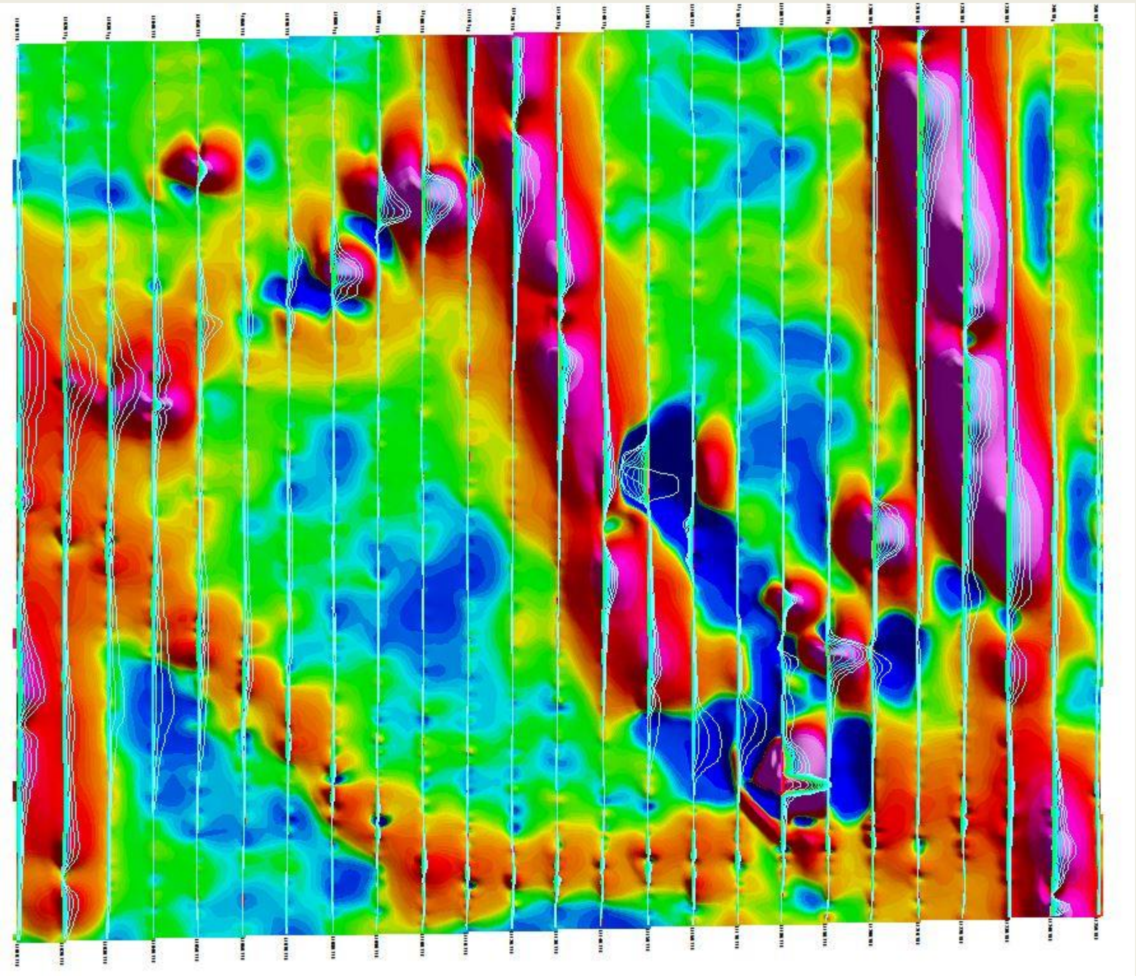
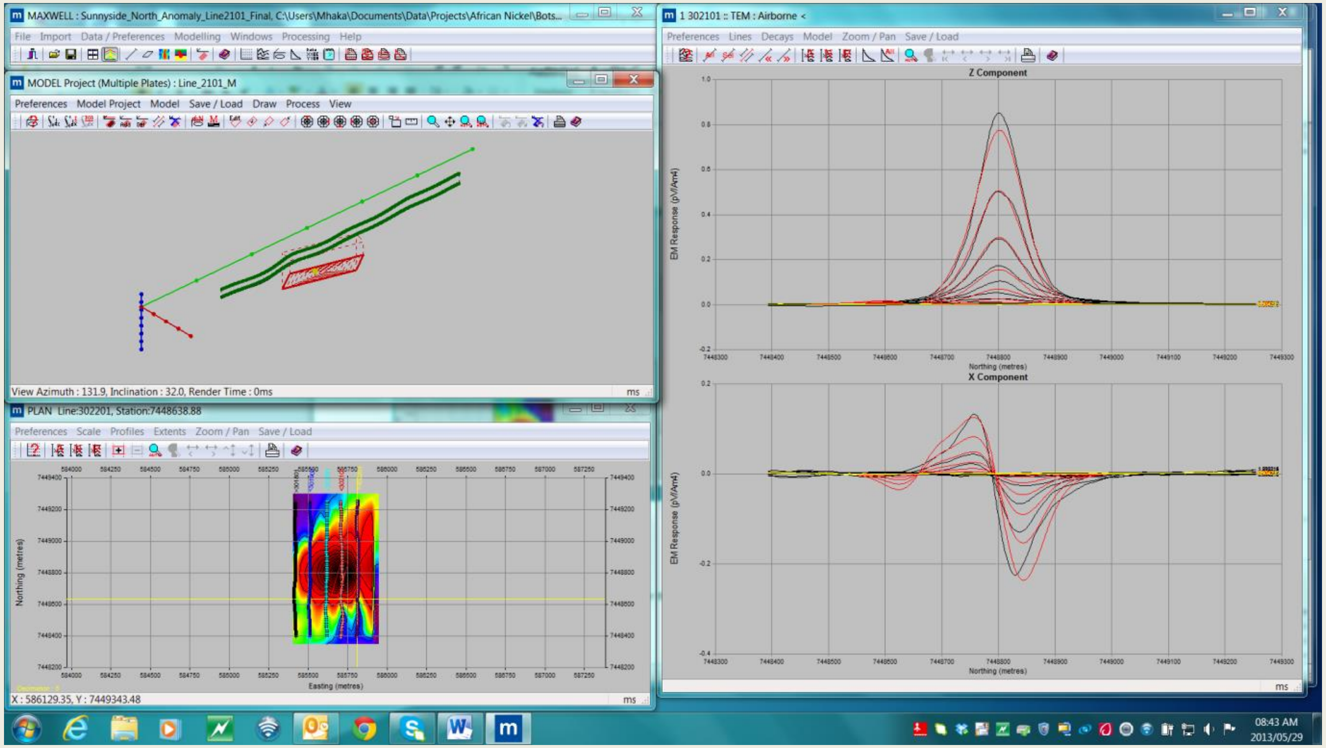
Target generation from VTEM Data



An example of VTEM data flown over an area in Botswana.

- VTEM data showing channel 20 gridded data and profiles from channel 14 to channel 34 in blue.
- Targets can easily be identified using both the gridded data and profiles.
- The selected targets can then be windowed out and imported into Maxwell software for modelling

Target generation from VTEM data using Maxwell software



One of the selected target modelled in Maxwell

- Selected targets can be windowed out and modelled in Maxwell software.
- This can then provide us with *priori* information for planning our ground follow-up.
- Some Geophysicist can try to cut costs by trying to drill directly from the VTEM data modelling but this is not advisable as targets can easily be missed.

Criteria for selecting best targets

- For all the modelled targets, good conductors are picked and parameterized in terms of conductance (conductivity-thickness product), conductor dip and depth below surface and magnetic association (*remember mag data is also collected simultaneously with the EM data*).
- The most reliable estimate is the conductance. Massive sulphides are always excellent conductors; net-textured sulphides are usually good conductors while disseminated sulphides typically have higher conductance values than their fresh weathered host rocks.
- Therefore conductance values obtained from the airborne EM modelling can be used as the criteria to select the best targets for ground follow-up

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Ground follow-up using SQUID Magnetometers

Filling up LT SQUID with liquid Helium

Filling up HT SQUID with liquid Nitrogen

- **SQUID** stands for Superconducting Quantum Interference Device.
- Currently there are 2 types of SQUIDs – the **LT SQUID** (low temperature) and the **HT SQUID** (high temperature).
- **LT SQUID** operates at a very low temperature of -269 degrees Celsius. It is made up of a cryostat which is filled with liquid helium.
- **HT SQUID** on the other hand operates at -169 degrees Celsius and is also made up of a cryostat which is filled with liquid nitrogen.
- We are going to look at the **HT SQUID** which is commercially available

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The HT SQUID

HT SQUID in operation

- **HT SQUID** is a very sensitive instrument which enables Transient Electromagnetic (TEM) measurements to be performed up to very late times.
- it is a **B**-field (i.e. a very fast sampling magnetometer) sensor that measures the time-integral of the impulse response which is called "step response".
- This time integral is an important 'filter' which attenuates fast decays from weaker or unconfined conductors in preference to decays from strong conductors which are slow.
- This makes it easier to discriminate a response from a good conductor in the presence of a weaker conductor such as a host, overburden or less conductive bedrock.

Squid system and high power Transmitter

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Positioning of the Fixed loop

- The position of the transmitter loop for the fixed loop mode is very critical since it must be positioned in such a way that there is maximum coupling with the target body.
- In order to come up with the best fixed loop position for maximum coupling with the target body and also to get a feel of the anticipated theoretical EM response, forward modelling is carried out using EMIT's Maxwell software.
- Forward modelling however assumes a *priori* knowledge of the position of the conductor and its dip. When possible dip and position of the conductor is unknown, it is essential to use more than one transmitter loop position to avoid a zero coupling situation.
- Since this will be ground follow-up, we can get some of the priori knowledge from the modelling airborne data as explained before.

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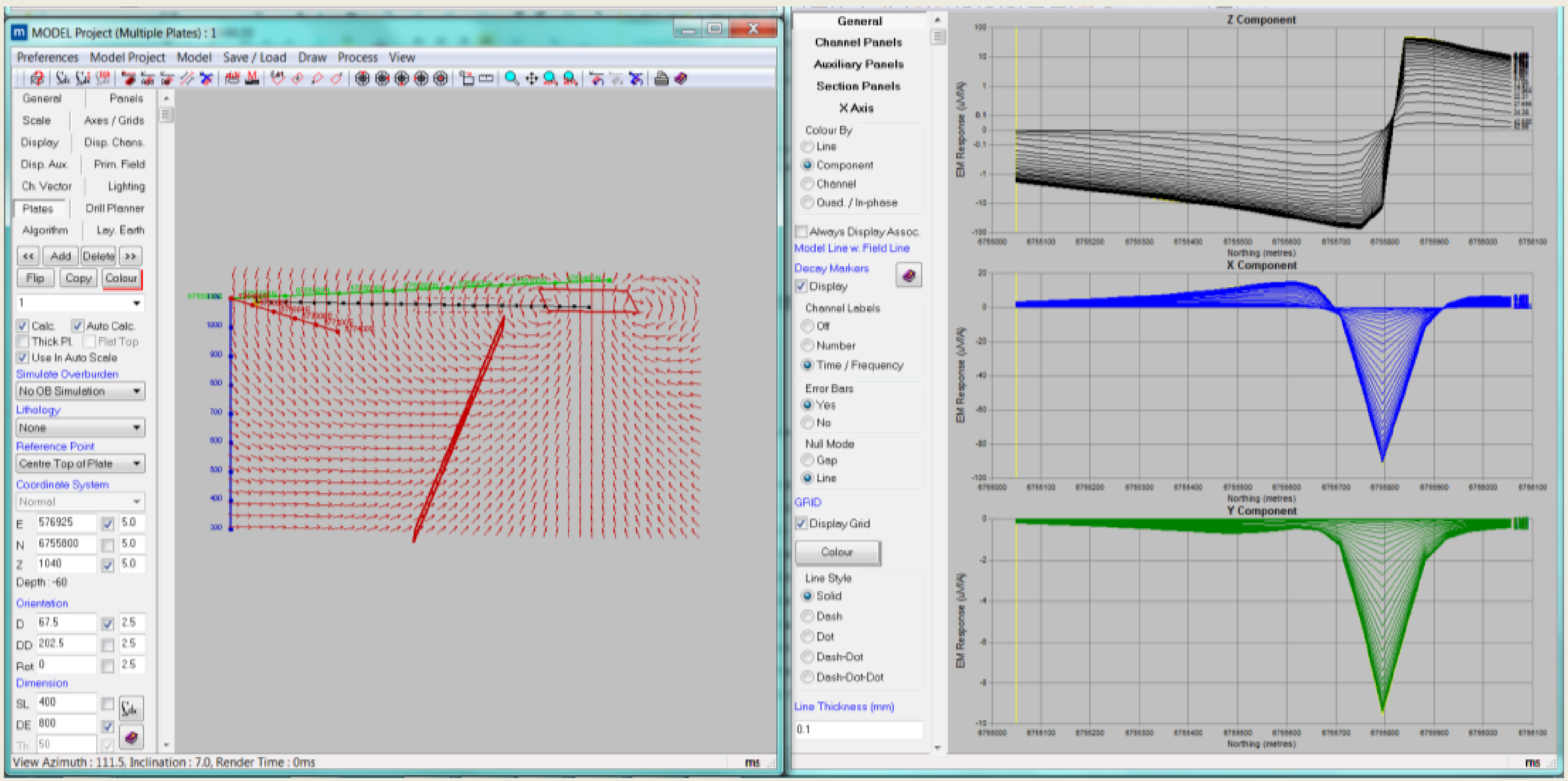
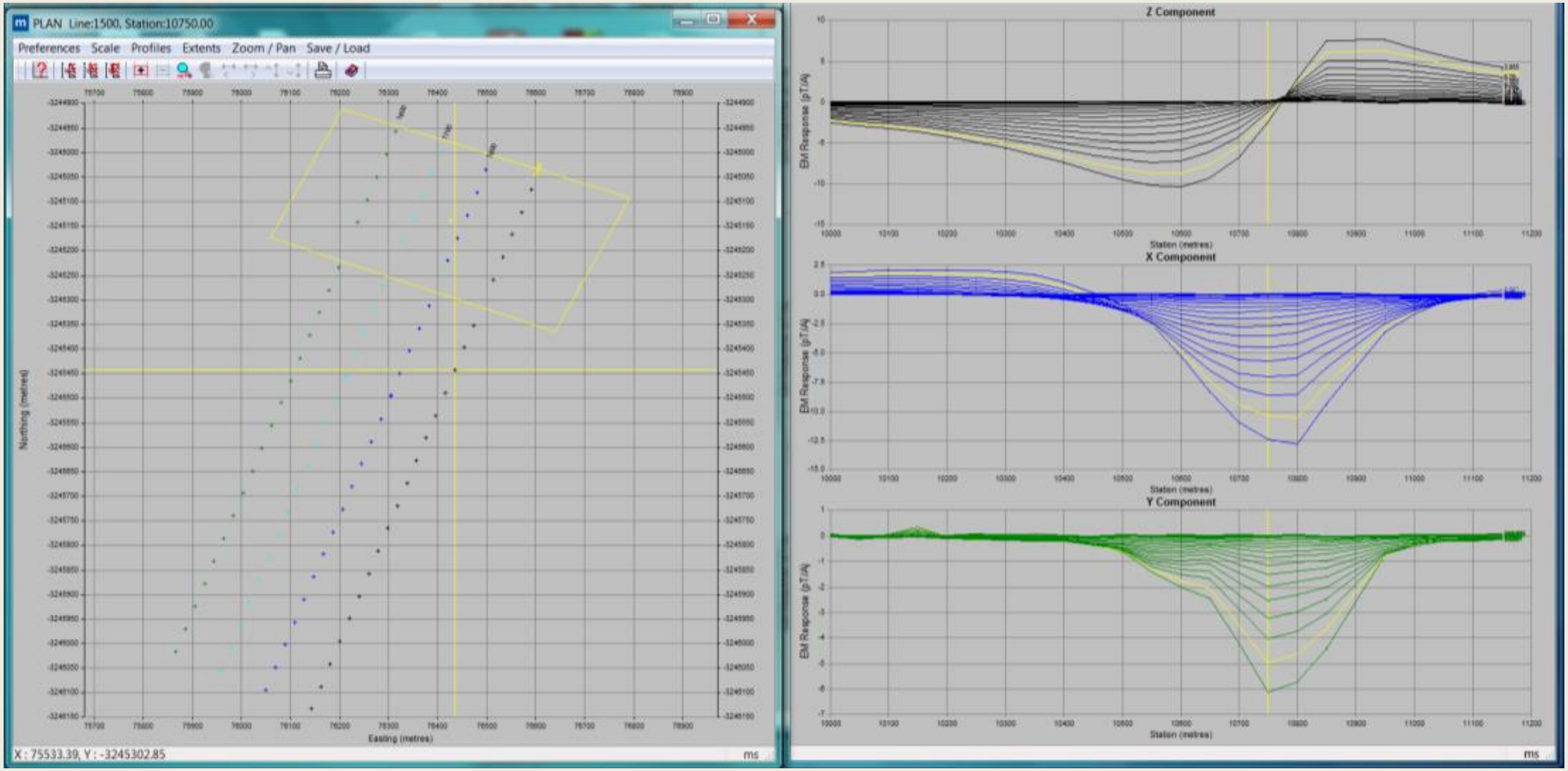
Forward modelling using Maxwell – Case Study



An example of Forward modelling results for a known Ni-Cu deposit in South Africa. The position of the fixed loop and the anticipated theoretical EM response can be determined from this modelling.

EM response curves for fixed loop



An example of fixed loop data for a single line for a known Ni-Cu deposit in South Africa after importation into Maxwell Software showing the EM response profiles for the three components Z, X, and Y to the right and the fixed loop position and surveyed lines to the left.

Interpretation of the response curves

- The **Z** component is anti-symmetrical across the plate with a zero crossover above the centre of the plate.

- The zero cross-over does not change position with time for a good conductor.

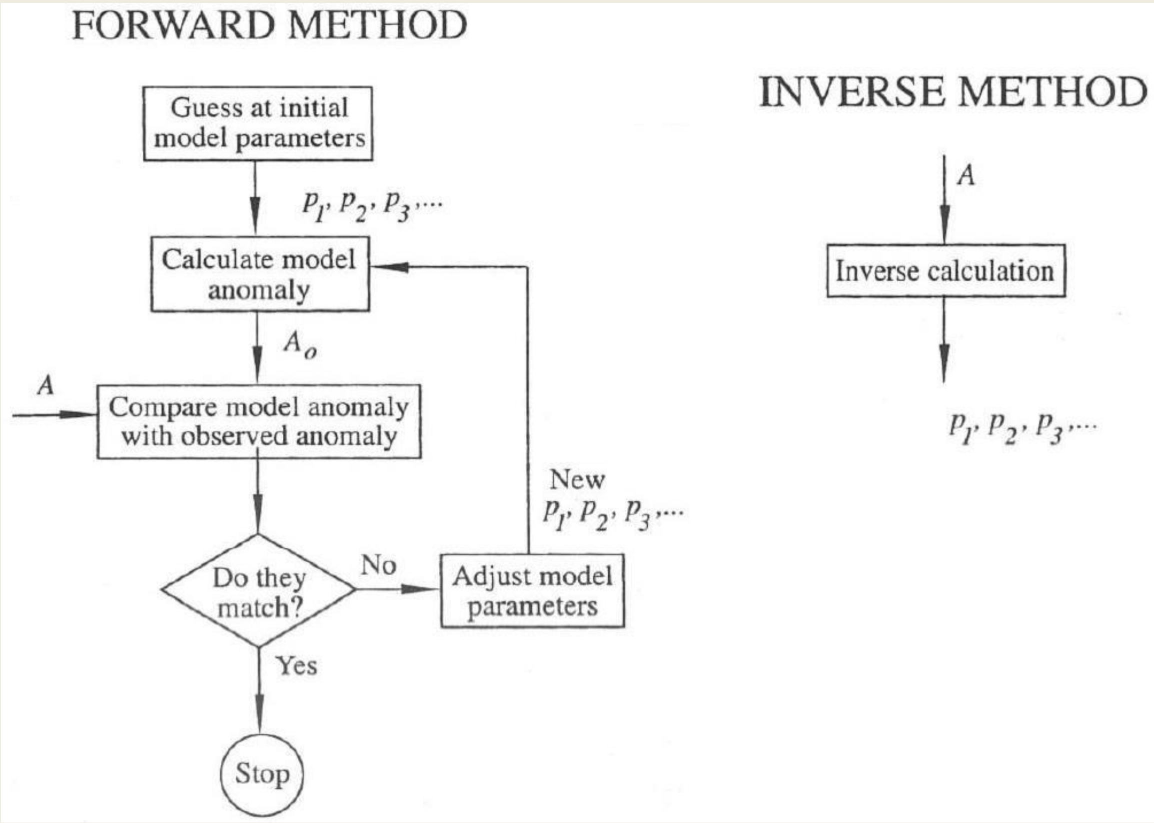
- The **X** component is symmetrical across the plate, with the peak amplitude above the centre of the plate.

- The position of this maximum does not change with time.

Geophysical inversion of data

- In exploration, geophysical inversion usually means producing an earth model which is in agreement with geophysical survey data, in a timely and cost effective manner.
- Geophysical inversion is a non-unique process meaning different models can produce the same response. For example, a broad dense body close to the surface creates a gravity response that is similar to a very dense compact body deeper in the earth.
- A *priori* information must be included in the inversion (e.g. smoothness, geology, drilling, geophysical data etc.) in order to constrain the process.
- Integrating other information improves reliability and greatly increases the acceptance of the inversion into the exploration process.
- From a practical perspective, these processes must be robust and easy to use.

Methods of modelling Geophysical data



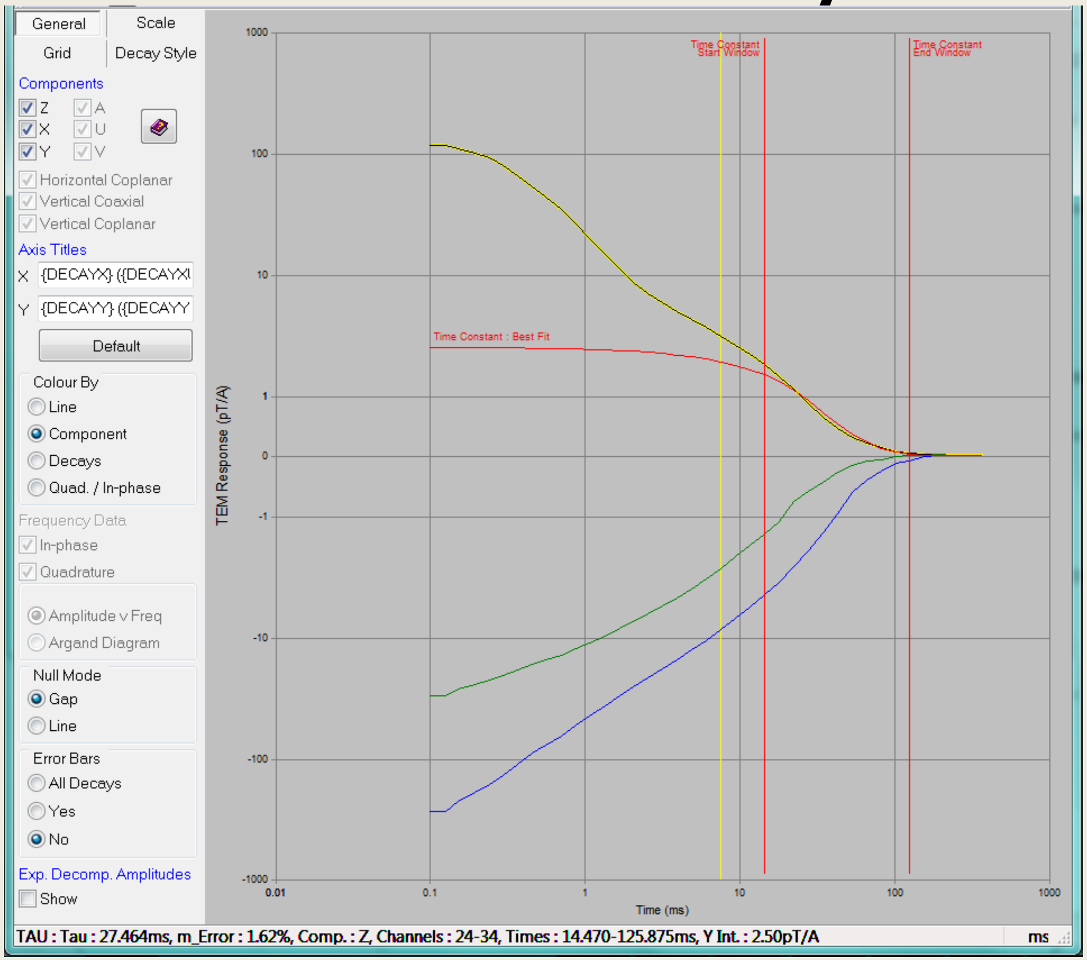
- The inverse problem is complementary to forward modelling. It helps determining what distribution of physical properties yields a measured field response best.
- It needs and allows the inclusion of a ‘starter model’ which is given by the forward model into which has been incorporated the *a priori* information on the source body.

Comparing the forward and inverse method. ***A*** *represents the measured anomaly, and* ***Ao*** *the calculated anomaly. Parameters* ***p1***, ***p2****,… are the source attributes (e.g. depth, thickness, density), (Blakely, 1995).*

Procedure for modelling in Maxwell

- Decay analysis is used to determine the best time channels to model and in this case from channel 24 to channel 34.
- The next step is to modify the plate parameters to represent the target based on the anomalous data taking into account the *a priori* information that is available from airborne data modelling.
- A forward model is then calculated while adjusting the conductance until there is a response and moving the plate until a reasonable fit is obtained for a single line.
- Continued necessary adjustments are made until the model response mimics the measured EM response as shown to the left window as shown below.
- The black traces show the measured EM response while the red traces depict the model response.
- Since the plate is considered to be thin, its thickness and conductivity are strongly correlated and cannot be determined separately and therefore their product, conductivity thickness or conductance, is used to characterize the electrical property of the thin conductor

Decay analysis



- there is a need to first determine the best time channels to model by making use of time constant decay analysis which can be performed in the Decay Window of the Maxwell software
- The time constant fit to the selected decay is shown by the asymptotic red line and the channels to be modelled are displayed in the Decay window status bar at the bottom.

An example of decay analysis window showing the Z component fit used to determine the best time channels to model. The Z component decay curve is shown in black(with yellow hue), the X component decay curve is in green while the Y component is in blue.

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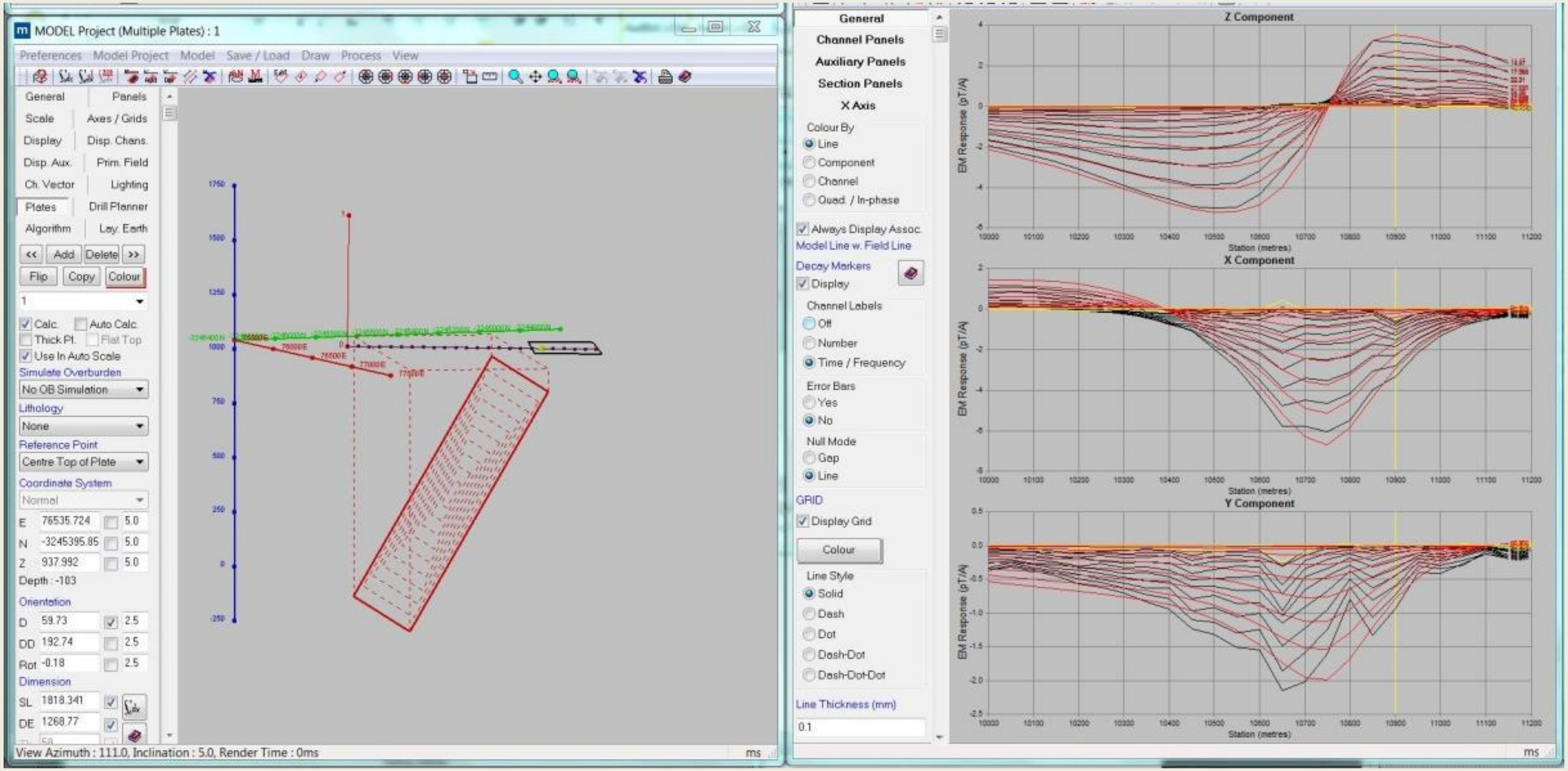
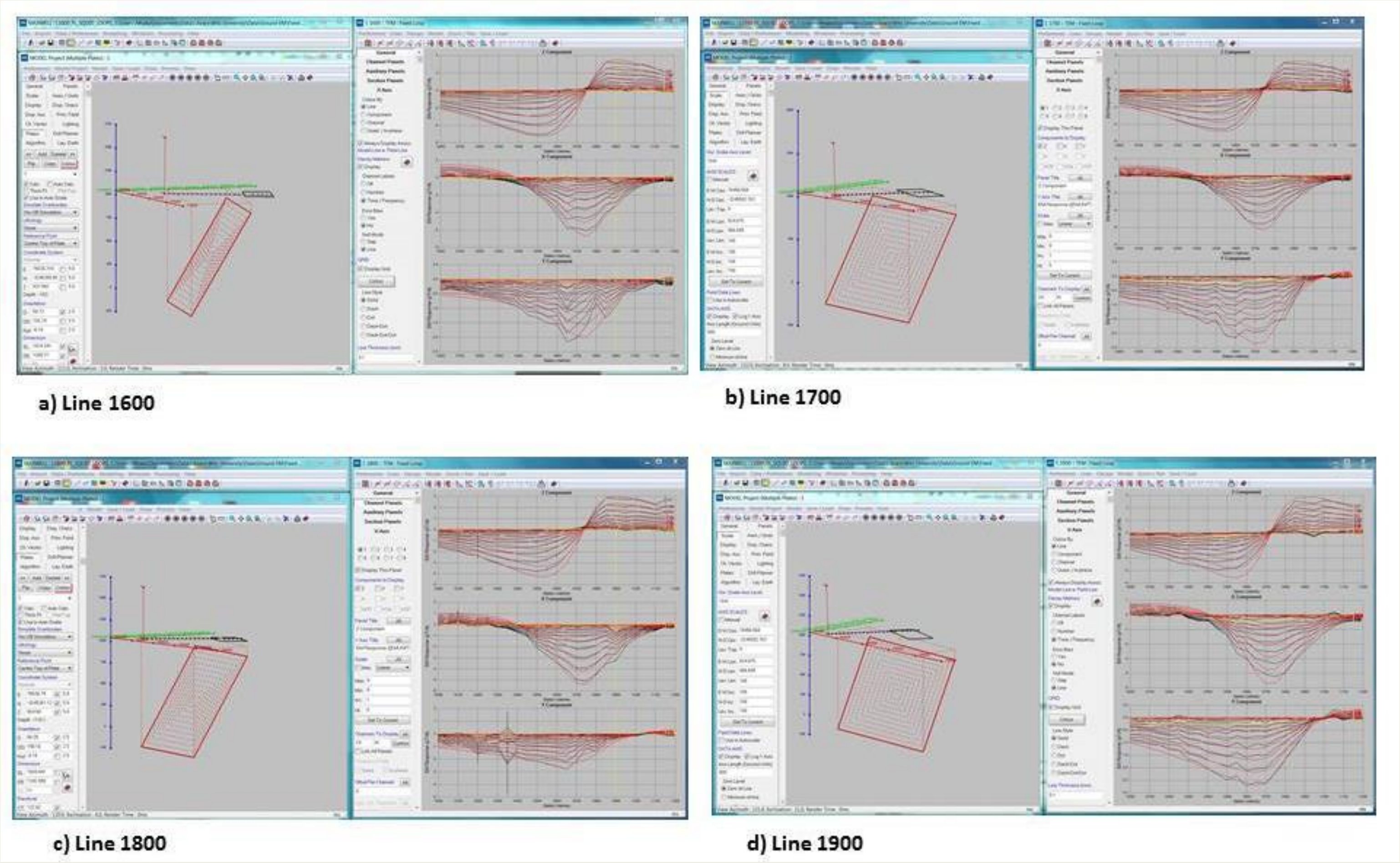
Modelling EM data in Maxwell



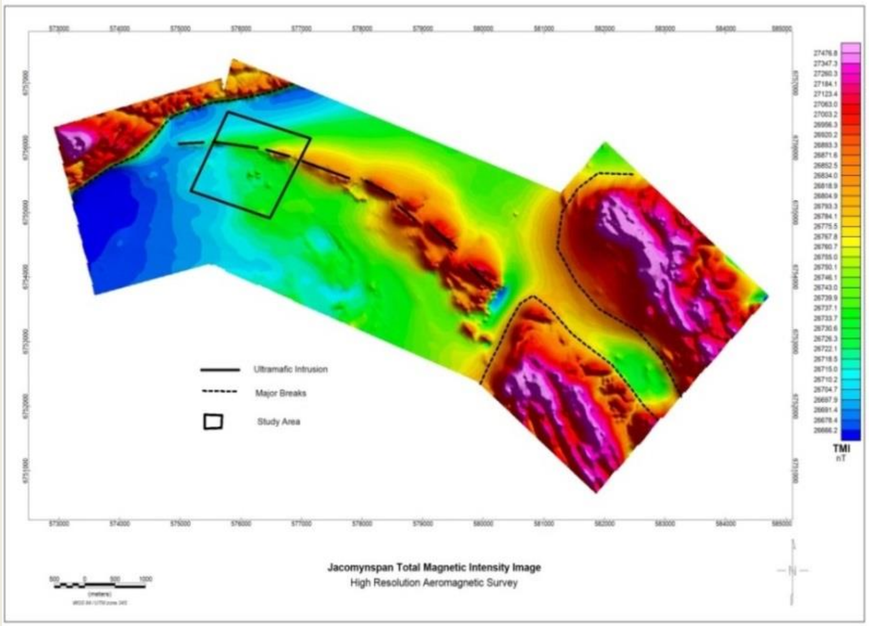
An example of modelling results for a single line at the known Ni-Cu deposit. The left widow shows the modelled EM plate steeply dipping to the south. The right window depicts the measured EM response traces in black and the modelled EM response in red for the three components Z, X and Y.

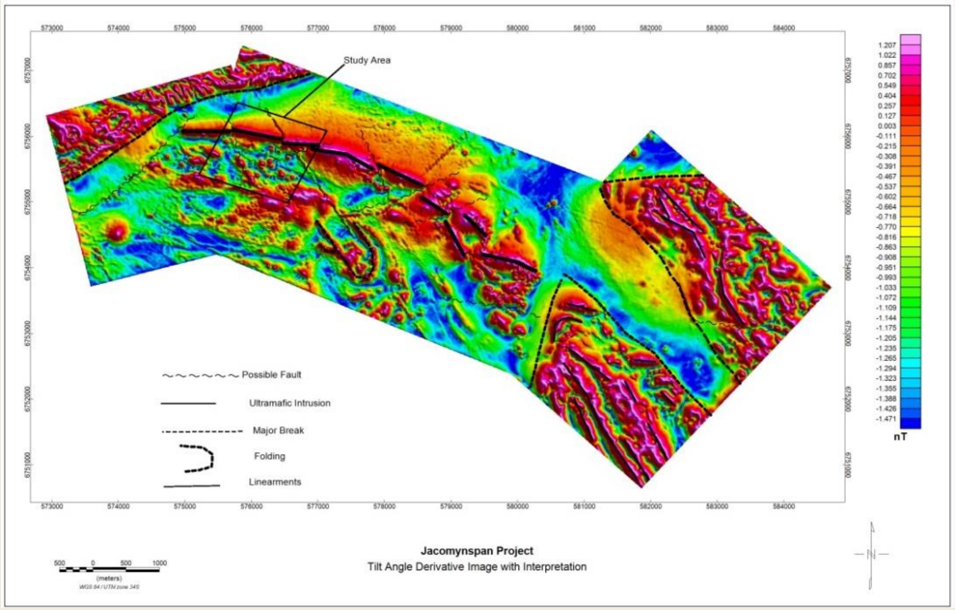
Modelling results of all the 4 lines



An example of the modelling results for the known Ni-Cu deposit

Xcalibur High Resolution Aeromagnetic data





Total Field Magnetic image **Tilt Angle Derivative image**

- A high resolution aeromagnetic survey was carried out by Xcalibur Airborne Geophysics covering the Jacomynspan project area.
- The east-west trending ultramafic rocks over the main target zone are clearly visible in both the TMI and the tilt angle derivative images.
- This information proved useful in terms of planning the ground EM techniques and providing information regarding structure and setting of the deposit.

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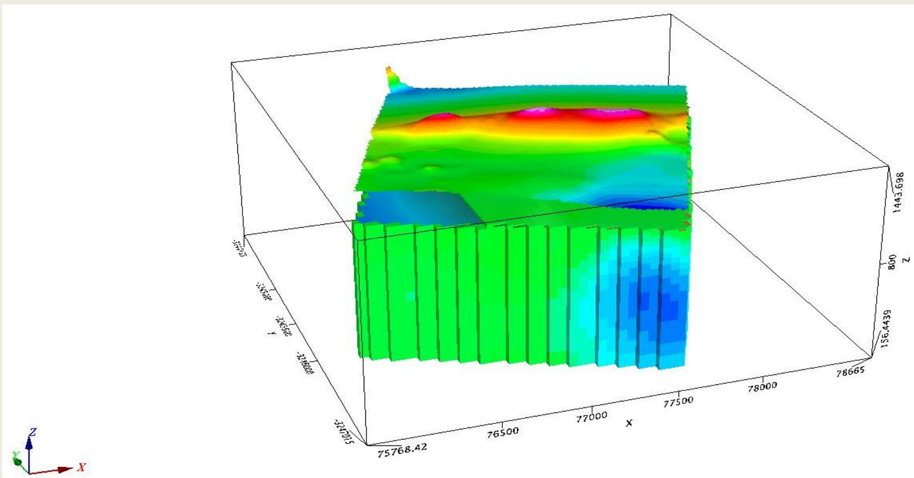
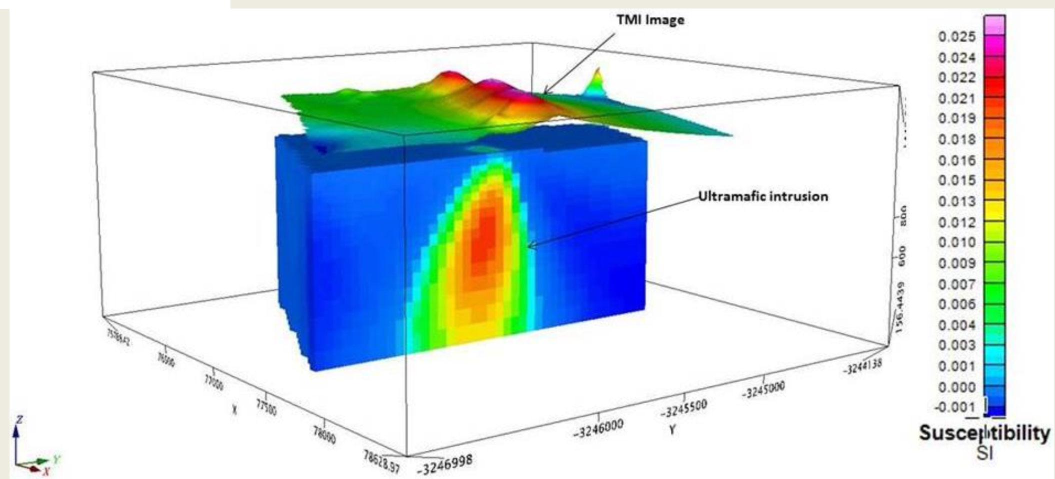
VOXI Modelling of the Aeromagnetic data



VOXI Earth Modelling is a Geosoft® geophysical inversion software service that generates 3D voxel models from airborne or ground gravity and magnetic data using cloud computing.

In VOXI modelling, the idea is to quantify the closeness between the predicted model response and the observed data using the data misfit equation.



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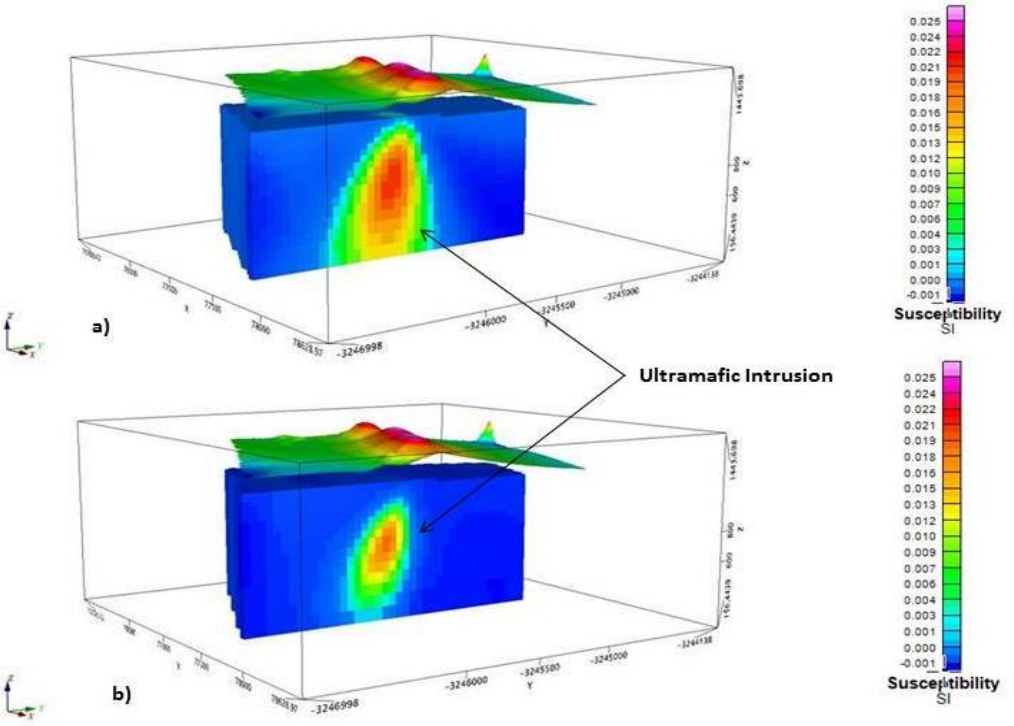
VOXI's Iterative reweighting Inversion (IRI)



- The IRI Focus constraint normalizes and sets the outcome of the previous inversion as the weight constraint for the next inversion. It allows the model to be refined in order to emphasize positive or negative anomalies.
- The IRI Focus results show a more compact and focused but deeper magnetic susceptibility distribution of the mineralised mafic to ultramafic intrusion compared to the smooth model inversion results.

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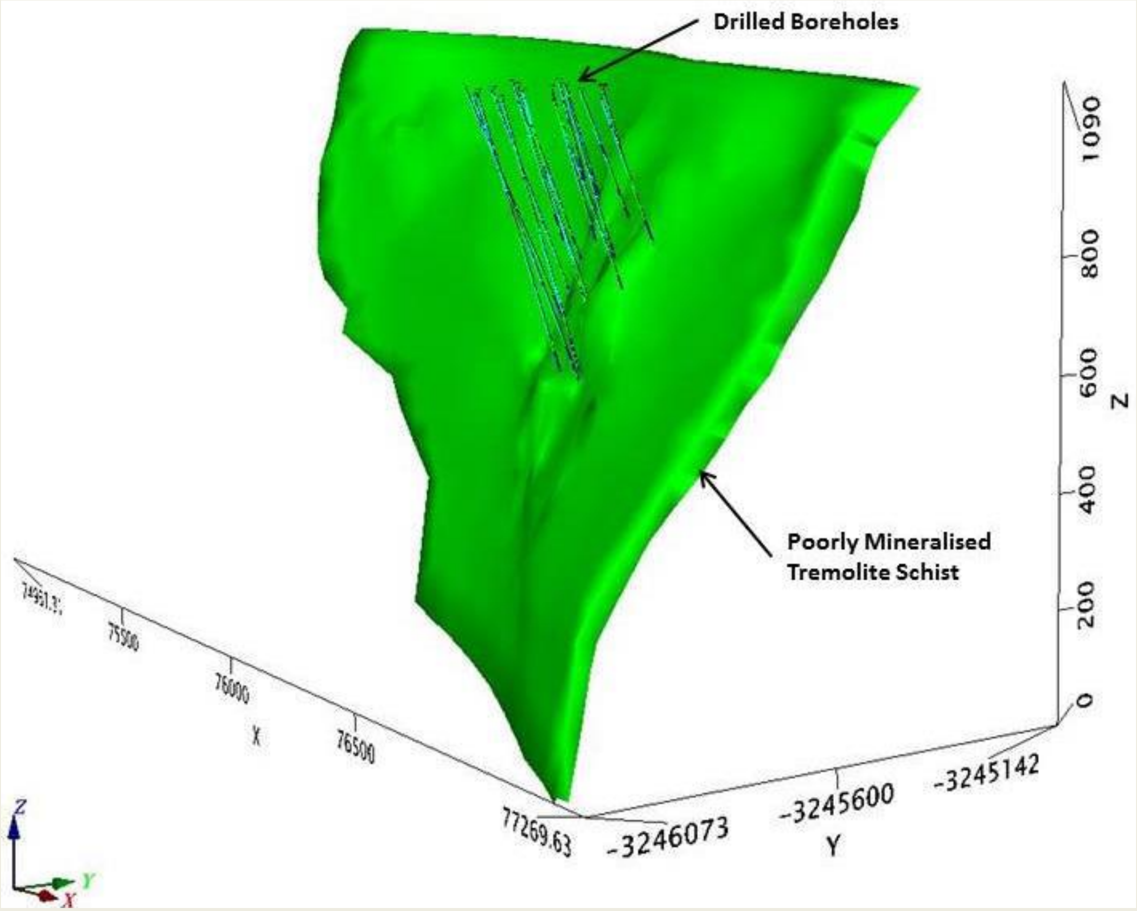
Data Integration with geology

- Drilling results have shown that the Ni-Cu mineralisation at this known Ni-Cu deposit is hosted within a steeply dipping tabular, differentiated, sill of mafic to ultramafic composition intruded into country rocks of the Namaqualand Metamorphic complex.

- Using the drilling results and that from historic drilling, the geology model of the poorly mineralised tremolite schist (metamorphosed pyroxenite) as well as the high-grade well mineralised net textured harzburgite was created in Micromine software.

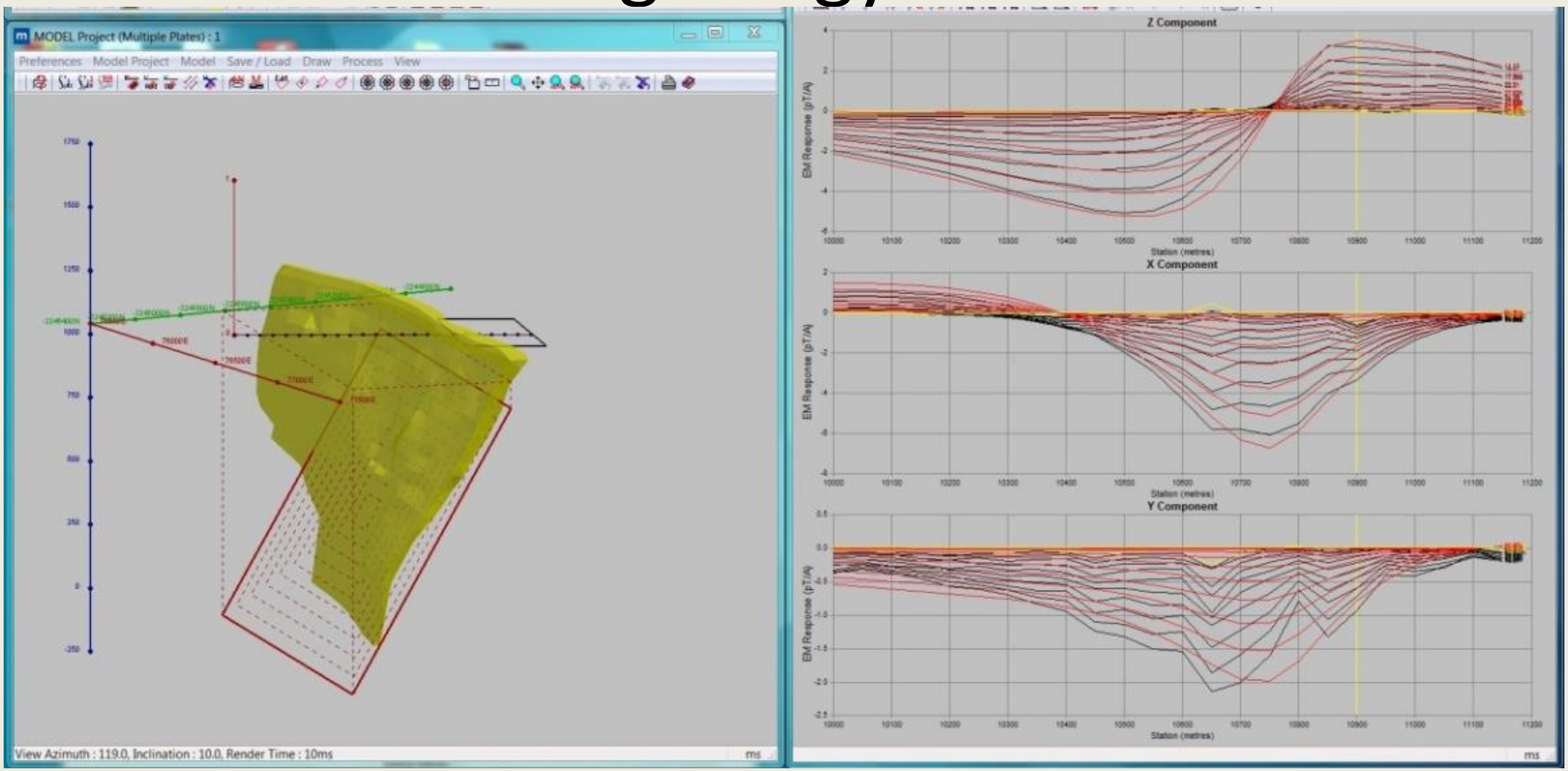
- The tremolite schist model was used as a 'starter model' for all the modelling carried out.

Micromine geology model of the intrusion



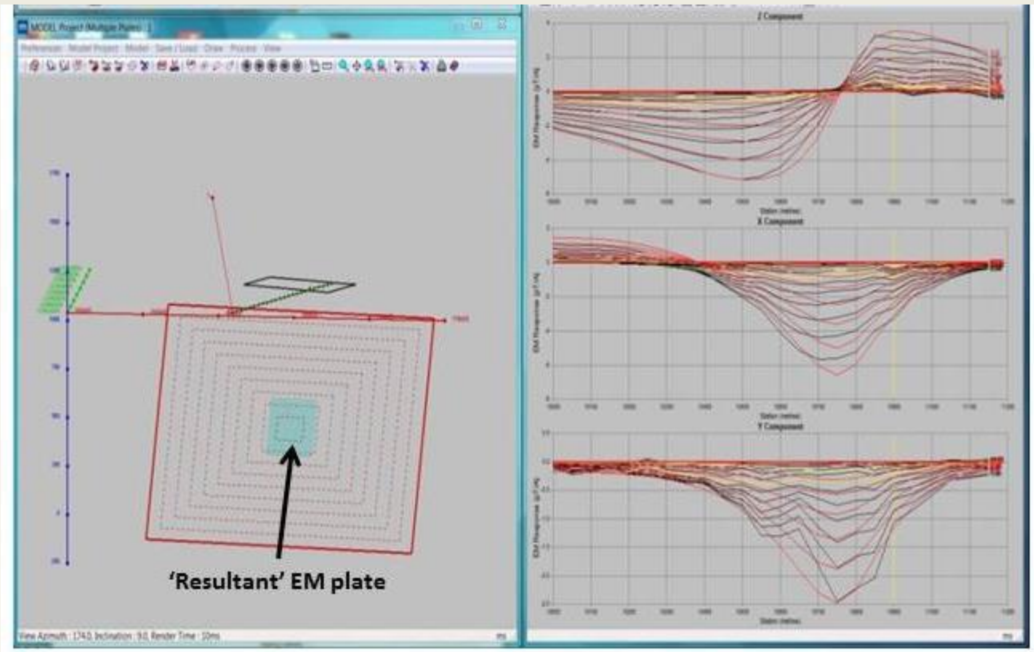
3D view of the Micromine model (in green) for known Ni-Cu deposit showing the mineralised ultramafic intrusion (tremolite schist) steeply dipping to the south and the drilled boreholes.

Integration of the modelled EM plates with the geology model



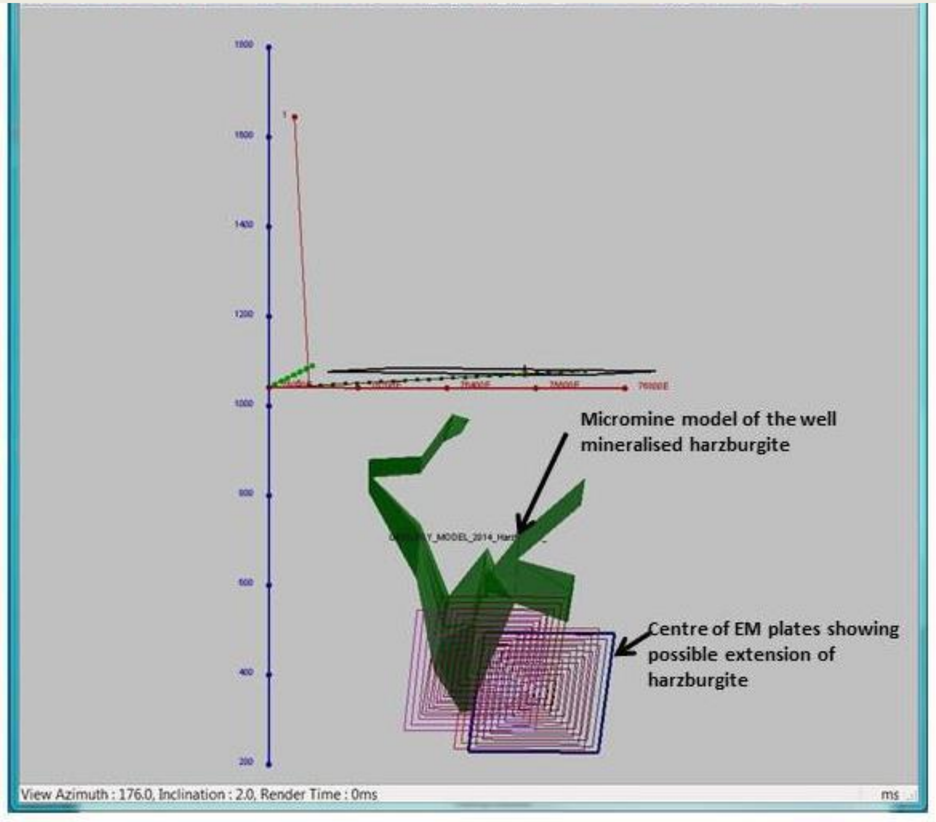
The modelled EM plate in red integrated with Micromine geology model of the mineralised ultramafic sill in yellow showing a direct correlation. The right window show the measured EM response profiles in black and the modelled EM response in red for the three components Z, X and Y.

Mapping the highly conductive net textured Harzburgite



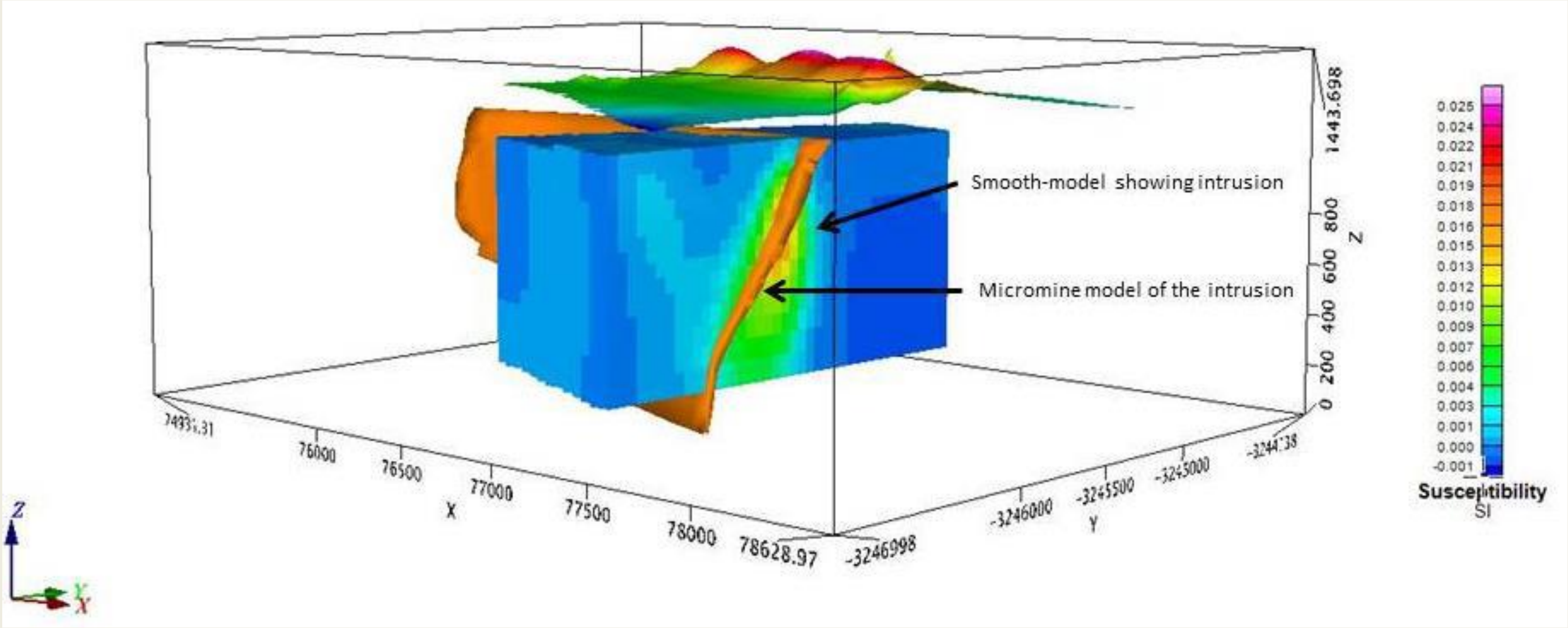
- An assumption was made that at late decay times the currents would be focused in the centre of the large EM plate giving an indication of the most conductive part of the intrusion.
- Since the net-textured well mineralised harzburgite is more conductive than the disseminated mineralised tremolite schist, the constructed centre of EM plates with conductivity thickness above 100 Siemens were interpreted as to give an indication of the location of the well mineralised harzburgite and massive sulphide stringers.

Integration of Micromine model of the harzburgite with ‘resultant’ EM plates



- Integrating in Maxwell software the DXF file of the Micromine geology model of the well mineralised harzburgite with the constructed ‘resultant’ EM plates.
- This gives an indication that the well mineralised harzburgite has been mapped and could be extending to the eastern side.

Integration of the Micromine geology model with geosoft Voxi magnetic model



Integrating the Voxi 3D smooth model inversion results with the Micromine model of the mineralised ultramafic sill (orange) shows there is a direct correlation.

Conclusion

- Time-domain electromagnetic (TEM) methods are increasingly being used for mineral exploration, all aspects of hydro geophysical mapping, saltwater intrusion, geotechnical applications and a variety of other physical planning purposes.
- For AEM systems, two basic configurations have emerged - the rigid transmitter-receiver systems mounted in helicopters and the large separation towed bird systems mounted on fixed-wing aircraft.
- AEM systems can quickly collect high quality data from which high value information can be extracted.
- Targets can easily be generated from AEM data using both the gridded data and profiles. The selected targets can then be windowed out and imported into Maxwell software for modelling in order to prioritise targets for ground follow-up.
- Currently there are 2 types of SQUIDs – the **LT SQUID** (low temperature) and the **HT SQUID** (high temperature). The HT SDUID is commercially available.
- The SQUID magnetometer is a **B**-field sensor that measures the time-integral of the impulse response which is called "step response".
- The aim of the geophysical inversion is to invert the measured EM data into knowledge about the spatial distribution of conductivity within the deposit, and to use that information in geological interpretation.

Possible application

- Deep seated Ni-Cu deposits e.g. Hunters' Road,Epoch, Shangani,Damba
- Ultramafic dykes and sills e.g. Umvimeela and East Dykes
- Archaean komattitic sill hosted chromite deposits e.g. Sebakwean, Shurugwi ultramafic complexes

For questions you can contact: **info.geopaceconsulting@gmail.com**

Thank you