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Discovering and imaging mineral systems at all scales using natural-source electromagnetic methods

Alan Jones

Manotick GeoSolutions Ltd., Manotick, Ontario, K4M 1E3

Introduction

Meeting the technological demands of the future—especially achieving NetZero targets by 2050—requires discovering new mineral resources at an unprecedented pace. These must include not only critical minerals but also base metals such as copper, which remain essential yet are often underappreciated in energy transition discussions.

Copper poses a particularly urgent challenge. While current global production is approximately 20 million tonnes per year (Mt/year), projections for 2050 estimate demand will rise to between 35 and 50 Mt/year. This widening supply gap is worsened by the expected closure of nearly 200 major copper mines by 2035, declining ore grades in existing operations, and a limited pipeline of new projects forecast to add only 2 Mt/year.

With most easily accessible deposits already discovered, exploration must advance into deeper and more geologically complex terrains. To achieve this, exploration strategies must evolve.

A paradigm shift from deposit-scale targeting toward understanding entire mineral systems is now underway. This approach, based on the Mineral Systems concept of McCuaig and Hronsky (2014) and the Minerals Targeting framework of Begg (2015), focuses on mapping the broader lithospheric architecture controlling mineralization.

From a geophysical perspective, this involves a hierarchical exploration strategy. Deep-probing geophysics is used to image lithospheric-scale structures and identify potential fluid sources. Crustal-scale probing then delineates prospective "camp-scale" fluid reservoirs, followed by shallow-probing methods that target individual ore bodies at economically viable depths.

Natural-source electromagnetic (NSEM) methods—encompassing both ground-based and airborne techniques—can contribute significantly at all three spatial scales. This paper critically reviews the capabilities, strengths, and recent developments in NSEM methods within this mineral systems framework.

Methodology

NSEM techniques utilize naturally occurring electromagnetic fields, offering distinct logistical and economic advantages over controlled-source EM methods. While they remove the need to generate an artificial source, a key limitation is the inability to control source characteristics, which can affect data quality and resolution.

Ground-based methods

The primary ground-based NSEM technique is magnetotellurics (MT), which records the time-varying horizontal components of both the electric (Ex, Ey) and magnetic (Hx, Hy) fields at a common site. Ideally, the vertical magnetic field component (Hz) is also acquired to enhance data quality and dimensionality assessment.

MT spans three frequency bands, each suited to imaging different depth ranges:

1) **Low frequency magnetotellurics (LMT):** Targets lithospheric-scale structures using low frequencies (~0.1 Hz to <0.0001 Hz).

2) **Broadband magnetotellurics (BBMT):** Suitable for crustal-scale imaging (~400 Hz to 0.001 Hz).

3) **Audio-magnetotellurics (AMT):** Used for high-resolution, deposit-scale imaging (~10 kHz to ~8 Hz).

Hybrid MT approaches also exist. The telluric–magnetotelluric (T-MT) method, originally proposed by Hermance and Thayer (1975), combines electric field measurements (Ex, Ey) at multiple sites with magnetic field measurements (Hx, Hy) at fewer base stations. Garcia and Jones (2005) introduced a modified version to address the AMT deadband (5 kHz–800 Hz).

Nick Sheard's MIMDAS (Mount Isa Mines Data Acquisition System) adapts seismic profiling principles to EM acquisition, with in-line electric fields recorded continuously and off-line components measured every 2–4 dipoles. The magnetic field is recorded at a reference station. Quantec Geophysics commercialized this approach as Titan24, offering enhanced near-surface imaging.

Another established technique, Geomagnetic Depth Sounding (GDS), uses only the magnetic field components (Hx, Hy, Hz) and was widely applied in the 1960s–1970s for lithospheric-scale mapping. At the deposit scale, tipper analysis—the transfer function between Hz and (Hx, Hy)—is particularly effective for detecting lateral conductivity contrasts. A hybrid variant acquires only Hz across the survey area, with Hx and Hy measured at one or more base stations.

Airborne NSEM methods

In recent decades, several airborne NSEM systems have emerged, advancing the AFMAG concept developed in the 1950s (Ward, 1959). These systems offer rapid and cost-effective reconnaissance capabilities, especially at the deposit scale.

1) **ZTEM (Z-Axis Tipper Electromagnetic ststem):** Developed by Geotech Ltd. (Canada), ZTEM measures the vertical magnetic field (Hz) using an airborne horizontal coil. It operates at six

fixed frequencies (30–720 Hz), below the AMT deadband. Since its commercial debut in 2006 (Legault et al., 2012), ZTEM has been widely deployed. The Aerospace Information Research Institute (AIR) of the Chinese Academy of Sciences has recently developed a similar helicopter-borne system.

2) **MobileMT:** Developed by Expert Geophysics (Canada) in 2018 (Prikhodko et al., 2020), MobileMT measures all three magnetic field components (Hx, Hy, Hz) in a helicopter-towed bird. These are related to horizontal electric fields (Exb, Eyb) recorded at a ground base station. A major challenge is correcting for the bird's unknown orientation. The system operates from ~20 kHz to 30 Hz, avoiding the AMT deadband.

3) **QAMT:** Currently in final development by Dias Geophysical Ltd. (Canada), QAMT is a quantum-based airborne three-component magnetometer system. Its key innovation is full orientation tracking of the bird, enabling precise determination of the full 3×2 transfer function tensors between airborne magnetic field components and base station electric (Exb, Eyb) and magnetic (Hxb, Hyb) fields.

MT Results

A compelling demonstration of the Mineral Systems approach using MT is provided by the Olympic Dam deposit in Australia—type locality for iron oxide–copper–gold (IOCG) systems enriched in Cu–U–Au–rare earth elements. Two MT-derived crustal resistivity models illustrate this: the first from AusLAMP long-period MT data (33 stations at 5–10 km spacing; Heinson et al., 2006), and the second from follow-up BBMT surveys (110 stations at 1–2 km spacing; Heinson et al., 2018). In the high-resolution BBMT model, both the deep fluid reservoir and the vertical fluid pathways are clearly imaged.

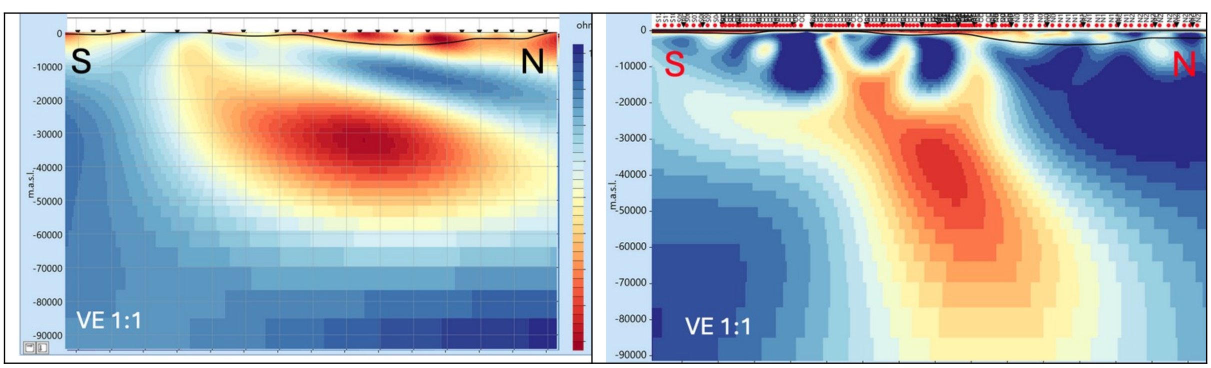

Figure 1: Resistivity models around Olympic Dam. Left: Original regional model. Right: Updated model including higher-spatial BBMT data.

Additional MT case studies will be presented at regional, camp and deposit scales.

EM Fields

In order to better understand the strengths and limitations of airborne NSEM methods, it is useful to consider the fields rather than responses. This is appropriate as all airborne methods map the spatial variation of one or more components of the magnetic field.

A simple model that can be examined is a 2-D fault, with 10 Wm (on the left) juxtaposed against 1,000 Wm (on the right). Fields were derived using the analytical expressions of Weaver et al. (1984, 1986). The plots in Figure 2 show the fields at 1 Hz for the TE mode and TM mode.

In the TE mode, the along-strike Ex electric field shows a 10x increase on the resistive side of the fault (which it must, as the resistivity contrast is 2 orders of magnitude), but poor localization of the fault. The across-strike Hy magnetic field exhibits a 65% anomaly and a 20% anomaly on the conductive side, but shows good fault localization.

In the TM mode, there is again an order of magnitude increase in across-strike Ey electric field, but the along-strike Hx magnetic field is uniform and has no response to the fault at all.

The responses than can be derived from MT, Tipper, MobileMT and ZTEM data are shown in Figure 3. The greatest sensitivity is in the MT TM mode due to the discontinuity in the across-strike electric field Ey from Ohm’s Law.

The ZTEM response is actually more sensitive than the local Tipper response, with higher amplitude and a very sharp peak at the fault.

Keep in mind that airborne NSEM methods have far higher spatial sampling than does ground based NSEM methods, by a factor of order 100x. This greater sampling can go some way to addressing the inherent weakness of magnetic-only methods given that most of the anomalous EM response is in the electric fields.

The fields of other bodies will also be examined.

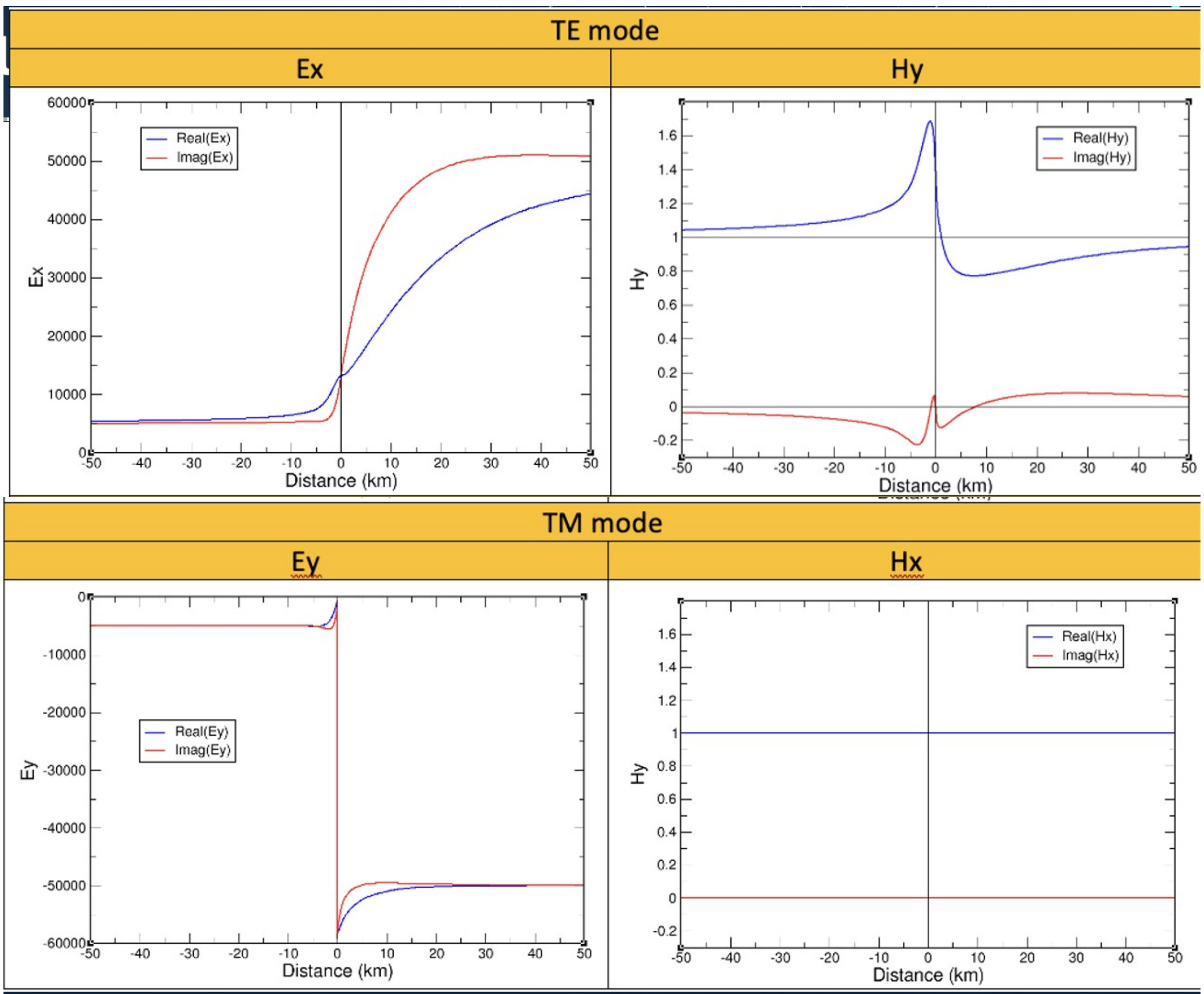

Figure 2: Electric and magnetic responses across a fault at 1 Hz. Top: TE mode. Bottom: TM mode.

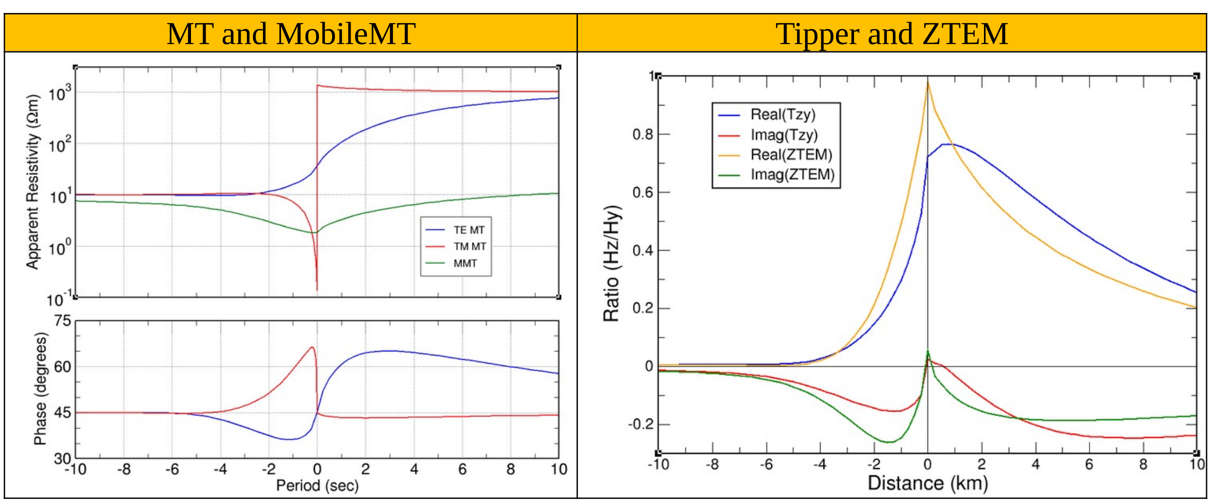

Figure 3: The responses than can be derived from MT, Tipper, MobileMT and ZTEM data

Continental scale MT Arrays: a framework for high-resolution volcanic, geothermal and mineral resource investigations

Adam Schultz[1,2], Brady Fry[3]

[1]Enthalpion Energy LLC, Philomath, OR; [2]National Geoelectromagnetic Facility, College of Earth, Ocean and Atmospheric Sciences,Oregon State University; [3]IoMT LLC, Portland, OR

From 2006 to 2024, the National Geoelectromagnetic Facility at Oregon State University operated a large, transportable array of long-period magnetotelluric instruments at locations spaced ∼70-km apart spanning the entire conterminous United States (CONUS). Operated under the support of the NSF EarthScope Program (2006-2018), NASA (2018-2020), and the USGS Geomagnetism Program (2020-2024), this effort - referred to collectively as "the USMTArray", sought high-quality MT timeseries, associated metadata, and derived impedance tensor and tipper/induction vector data over the period band 10 s-10,000 s. While the first such continental-scale MT array project to successfully complete, USMTArray has motivated other countries to engage in projects on this scale, including AusLAMP (Australia), SinoProbe II (China), Brazil MTArray (Brazil), all of which are underway, as well as the effort to launch a related effort in Canada under EON-ROSE. While USMTArray with its open, non-proprietary data set was motivated at its inception two decades ago by the need for fundamental studies of the formation and evolution of the North American Continent, the increasing need for critical minerals and renewable energy resources has at least in part stimulated the aforementioned Australia, Chinese, Brazilian and Canadian successor projects.

From an engineering viewpoint, the USMTArray project led to technological developments, including development of real-time telemetry using LTE and Starlink backhauls to a cloud-based MT data analysis system (the "IoMT Cloud"), a development that ultimately motivated the design and fabrication of a new generation of "DART (Distributed Architecture for Real-time Telematics)" MT/CSEM instruments now being released through IoMT LLC.

The release of USMTArray data through the IRIS/EarthScope.org data management system led to a profusion of 3-D models of the electrical structure of CONUS for studies of continental structure and evolution, and it provides information important to mitigating risk to the power grid from geomagnetically induced currents due to space weather. Such models are also useful to identify targets for higher-resolution studies. USMTArray data have been included as part of the regional background information used in such studies and long-period USMTArray data have also been included with wideband MT data for 3-D inversion in regional and more targeted studies.

In the present work, we very briefly summarize the key achievements of the USMTArray, and we present key findings from wideband MT projects that incorporated USMTArray data, including volcanic studies at the Yellowstone system and in the volcanic arc of southern Washington State, volcanic and geothermal studies in the near backarc of central Oregon, and geothermal surveys in the

Great Basin of Nevada. These and related studies have led to geothermal drilling projects, and they also set the stage for integrated, multi-scale mineral resource studies of central importance to the economies of North America.

The Yellowstone dataset provided an independent view of the distribution of crustal melt storage and the progression between basaltic and rhyolitic volcanism at Yellowstone. Long-period and wideband MT data revealed the accretionary history of the Cascade volcanic arc in southern Washington and the structural controls governing the location of Mount Saint Helens west of the main axis of the arc. Wideband MT and gravity data in combination with seismic tomographic models and well data constrained the composition of a sub-caldera magma body at Newberry volcano and identified new geothermal energy resources on the southern flank of the volcano that are now targets of confirmatory drilling. In Nevada we show how gas emission, ERT and MT complement each other in a geothermal investigation. These studies provide examples of how coordinated, multi-scale, and in some cases multi-physics approaches have developed and have benefited from open data models, joint inversion and thermodynamic modeling.

The Next Big Thing in MT is Time

Martin Gal, Nick Smith, Gerrit Olivier, Darren Burrows*

Fleet Space Technologies

Magnetotelluric (MT) data is a staple of many resource exploration projects with deep mineral systems expressions, or in areas under cover. The method was initially conceived in the 1950's with the following developments providing notable improvements:

- Analog to digital hardware
- GPS time-based synchronisation
- Remote referencing
- 3D inversion codes

An important barrier to increased use of the MT method is time – the time it takes for MT station installation and time it takes to process MT data. This increased time leads to increased costs which ultimately means spatially undersampled MT datasets.

We will discuss practical developments being made at Fleet Space technologies (Fleet) to address this issue in two ways:

- Hardware changes that limit or remove the need to bury instruments.
- Hardware and software changes that allow for live streaming of MT data for QC and automated preprocessing, as well as inversion code for rapid 3D models.

A case study showcasing point number two above will be shown for a copper exploration project in South Australia.

Volterra Short-Interval MT

Syd Visser*, Agustina Pesce, Dogukan Oskay, Kalen Martens

SJ Geophysics Ltd.

SJ Geophysics has designed a system that is used to collect and process AMT data in conjunction with an IP survey. Data can be taken between the short intervals of time when the IPTx is not transmitting.

We call this Volterra Short-Interval MT (SIMT) which will be described in this talk. The effectiveness of the techniques has been simulated using SimPEG and shows that a robust result is obtained. Results from a study to investigate signal/noise in overnight readings will also be presented.

The influence of base station structures on airborne magnetotellurics

Devin C. Cowan, Lindsey J. Heagy

UBC-GIF

Magnetotelluric methods are used to infer Earth's electrical conductivity structure from natural source electromagnetic (NSEM) field measurements. Airborne magnetotelluric (AirMT) systems have enabled the rapid collection of magnetotelluric data over large areas and/or areas with poor land access. The data collected by AirMT systems are harmonic transfer functions, which relate roving airborne magnetic field measurements to either electric or magnetic fields measured at a base station. AirMT data, therefore, depend on conductivity structures both within the survey region and at the base station.

Our presentation discusses the influence of 3D conductivity structure at the base station on the interpretation and inversion of AirMT data. Since the data collected during an AirMT survey is system-dependent, our analysis considers a variety of transfer function data types. Results from numerical forward simulation indicate that 3D conductivity structure at the base station can significantly scale the amplitudes of AirMT anomalies, while the influence on the phase and shape of AirMT anomalies is negligible. The influence of 3D conductivity structure at the base station is much higher when electric fields are measured at the base station. The inversion of various transfer function datasets for a remote base station showed consistency in recovering the margins of target structures within the survey region. Significant conductivity structure was also recovered at the base station that depended on the transfer function data being inverted. These base station structures exhibited varying influence on fitting the amplitudes of the inverted transfer function data, which can bias the recovered conductivity contrasts of target structures within the survey region.

Data Quality in Magnetotellurics: Controlling the Process

David Quirogo

DIAS Geophysical

The Magnetotelluric (MT) geophysical method measures natural electromagnetic field variations to image the electrical properties of the subsurface and is widely used in mineral exploration to map deep conductive/resistive structures. Ensuring consistent data quality from an uncontrolled source necessitates stringent control over the entire process, from field acquisition to final processing. Modern MT surveys follow careful and rigorous field procedures to leverage technology and software quality controls at all stages of acquisition as well as data processing for the computation of subsurface soundings and resistivity models. Advanced MT processing workflows should support the combined use of multiple data-derived and/or statistical quality features, such as: Coherence, Polarization Angles and Mahalanobis Distance, among others, to improve the signal-to-noise ratio through data weighting and noise rejection, together with robust regression algorithms. This is demonstrated through a comparative analysis between various industry/academic processing results. We discuss the future developments at both the hardware and software levels with a focus on integrated cloud storage, processing, and inversion services, as well as the advantages of a fully transparent MT processing ecosystem.

Transforming Mineral Discovery: The Power of Airborne Natural Field Electromagnetics

Alexander Prikhodko

Expert Geophysics Surveys Inc. (Newmarket, ON)

In 2018, a significant advancement in airborne electromagnetic (EM) passive (or natural field) methods was introduced to the geophysics market. The MobileMT system, which utilizes natural EM fields, has since proven to be an effective tool for mineral exploration across diverse geological and geoelectrical settings. Unlike systems relying on controlled primary field sources, MobileMT offers several advantages, including an exploration depth from near-surface to 1–2 km, or even deeper depending on environmental conductance. It detects resistivity across a broad spectrum—from highly resistive to strongly conductive materials—and is sensitive to boundaries in all directions.

Field applications, validated by drilling and in direct comparison with other airborne and ground methods, have consistently demonstrated these capabilities worldwide. Against time-domain airborne systems, MobileMT delivers superior depth penetration and sensitivity across a wider resistivity range, making it more reliable for detecting deep structures, subtle conductors, and providing comprehensive resistivity mapping. Compared with ZTEM, MobileMT benefits from a lower noise floor, a stationary electric-field reference, and broadband full-tensor H-field recording, which together yield higher signal fidelity and more stable, informative inversions. Relative to ground methods, MobileMT achieves comparable or better spatial resolution while offering much faster and more cost-effective regional coverage.

Proven results across epithermal and orogenic gold, IOCG, nickel, VMS, pegmatite, uranium, and porphyry projects demonstrate that MobileMT not only complements but often outperforms conventional airborne and ground EM approaches. Its versatility and depth capability have transformed airborne natural field EM from an experimental technique into a mainstream exploration tool, reshaping strategies for deep and concealed mineral discovery.

Magnetotelluric imaging of mineral systems and mineral deposits: Opportunities, challenges, and best practices

Ben Murphy

Moombarriga Geoscience

In this presentation, we will show several examples of MT imaging applied to various mineral deposit/system types. We will demonstrate the utility of MT in each type of system: imaging structure and stratigraphy in a sediment-hosted copper system, imaging the alteration footprint of a blind porphyry system, directly detecting mineralization in a CRD deposit obscured under conductive shale units, and directly detecting mineralization in a komatiite-hosted nickel deposit under cover. We will also discuss key considerations and best practices when acquiring MT data for mineral exploration applications, such as the value of acquiring MT tipper data alongside MT impedance data and the importance of either acquiring horizontal magnetic field data at every station or at least taking into account in the inversion where common sets of horizontal magnetometers were located during acquisition.

Geology-constrained ZTEM modelling at the Kutcho Property, British Columbia, Canada: From proof-of-concept to property-wide VMS targeting.

Thomas Campagne P.Geo, Scott Napier P.Geo, Chrissy Williston P.Geo

Mira Geoscience

In an effort to extend known VMS mineralization, and identify new targets, a ZTEM survey was flown over the Kutcho Property in northern British Columbia.

Initial efforts focused on a test area centered on the Kutcho Deposit to evaluate the ability of ZTEM inversion modelling to image known mineralization.

A 3D geology model was interpreted from geological mapping and interpretation of the geophysics, and the 3D model was used to constrain inversions. This methodology successfully highlighted and enhanced conductive features coincident with mineralization. The approach was then implemented over the full extent of the survey seeking to identify new prospective targets throughout the property.

Advanced Imaging of Mineral Resources at Jervois: Magnetic-image-guided 3D joint inversion of MT and Gravity

Friedemann Samrock[1], Randall Mackie[1], Atiqullah Amiri[2], Marianne Parsons[1], Carsten Scholl[1], Wolfgang Soyer[1], Stephen Hallinan[1], Keith Mayes[2]

[1]Viridien, [2]KGL Resources, Presenting Author

The Jervois Copper Project is a mining area located in the Northern Territory, Australia, approximately 280 kilometers northeast of Alice Springs. The project is operated by KGL Resources Limited (KGL). Known mineraliza on at Jervois is concentrated along a 12km long fold, with a distinctive "J" shape. Over the past decade, geophysical data have been collected across the project area, particularly over the southern extent of the J-fold structure including magnetics, gravity and magnetotellurics. Subsurface information is available from drillholes and includes downhole density and magnetic susceptibility, alteration domains, and wireframes of known mineralized zones.

We re-examined existing geophysical and geological data using modern multiphysics joint inversion codes to yield improved resolutions of target-related structure. As an initial step, we carried out standalone 3D inversions of the geophysical data without prior knowledge. This was followed by 3D joint inversion of gravity and magnetotelluric data using magnetic-image-guided structural constraints and density drillhole a priori information. The results demonstrate that our novel approach increases spatial coherency between recovered geophysical models and known locations of mineralized zones. The findings from this study are generally relevant for improved subsurface imaging and demonstrate the usefulness and validity of implementing structural and petrological a priori information to obtain high quality and reliable 3D models.

Joint inversion of MT tipper and impedance data with direct current data – A case study

Jeff Zurich

Computational Geosciences

A 3D-style pole-dipole and gradient DCIP survey was completed in 2019 at Ivanhoe Electric's Tintic project in central Utah, a historic mining district underlain by complex volcanic and intrusive geology. In 2024, the dataset was complemented by 50 magnetotelluric (MT) stations collected along three main lines and six infill sites, with both impedance and tipper responses recorded. Rigorous QA/QC protocols retained more usable DCIP data than standard practices, providing a stronger foundation for inversion. Both datasets were modelled using OcTree meshes, which balance accurate representation of small-scale features and topography with computational efficiency. The resulting joint inversions yielded a robust 3D geoelectrical framework that directly informed exploration targeting at Tintic.

Helicopter Natural Field Electromagnetic and Magnetic Results over the Valley Reduced Intrusion Related Gold System (RIRGS) Deposit, Rogue Plutonic Complex, Yukon.

Jean M. Legault*, Karl Kwan (Geotech Ltd.), Thomas Branson (Snowline Gold Corp.), and Brock Bolin (Bolin Geophysical Services LLC)

ABSTRACT

ZTEM helicopter electromagnetic and aeromagnetic surveys were flown for reduced intrusion related gold system (RIRGS) targets on the Rogue Project, located in the Tintina Gold Province, in east central Yukon. Survey results added to a regional ZTEM survey flown in 2008. Supported by 2D-3D EM and magnetic inversions, the results indicate that the Valley stock that hosts a known RIRGS gold deposit features low magnetic and high resistivity signatures, with surrounding annular resistivity lows and magnetic highs, due to more magnetic and conductive hornfelsed rocks, resulting from intrusion into sedimentary rocks of the Selwyn Basin, making it easily identifiable with the combination of ZTEM and magnetics. Similar signatures over other RIRGS prospects have assisted targeting other intrusion related mineralization nearby and regionally.

INTRODUCTION

In 2023 and 2024, helicopter-borne ZTEM (Z-axis tipper electromagnetic; Lo and Zang, 2008; Witherly, 2011) and aeromagnetic surveys were undertaken over Snowline Gold Corp.'s Rogue Project, located in the eastern Tintina Gold Province, approximately 215 km east Mayo, in east central Yukon (Figure 4). Rogue Project hosts the Valley RIRGS (reduced intrusion related gold system) deposit that hosts a 76 Mt, 4.05 Moz Indicated gold and 81 Mt, 3.26 Moz Inferred gold mineral resource (Burrell et al., 2024). The 2023-2024 survey results added higher resolution, 500 m spaced infill to a regional ZTEM survey data flown in 2008 that was later made public (Witherly, 2013; Carne, 2015).

Geology and Geophysics

The Rogue Project covers a 60x30 km cluster of intrusions, referred to as the Rogue Plutonic Complex, situated in eastern Tombstone Belt of the Tintina Gold Province, with the Valley deposit located in the center of the cluster. The Tintina Gold Province is a >2,000 x 500 km northwest belt of rocks that resulted from extensional tectonic magmatism, which deposited numerous gold deposits throughout Alaska and Yukon (Branson, 2025; Hart, 2007).

Reduced intrusion related gold systems (Hart, 2007) are related to the shallower parts of major batholiths, with a variety of mineralization styles. Generally, the shallow intrusive stocks area elongate-shaped and felsic in composition, with ilmenite as the mafic mineral instead of magnetite, resulting in reduced intrusions. Within the intrusive rocks, RIRGS commonly form sheeted quartz vein systems, with potassic to sericite-chlorite alteration, as well as disseminated and stringer to massive sulphide mineralization. (Branson, 2025; Burrell et al., 2024).

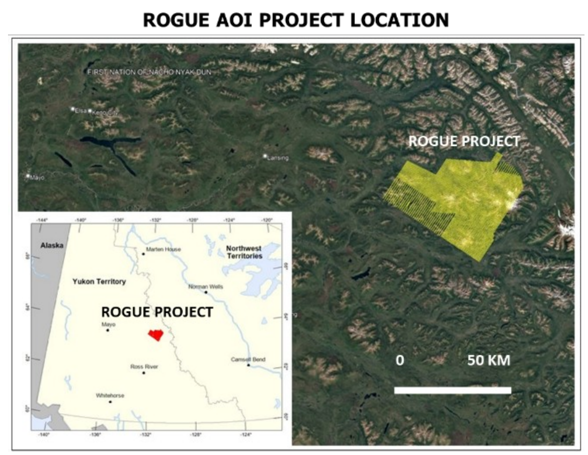

Figure 4: Rogue ZTEM project location and flight lines.

Why this is important in the context of ZTEM surveys is that, due to low magnetite, the intrusions generate a magnetic low surrounded by a magnetic high due to the presence of pyrrhotite in the contact hornfels, while the host rocks are resistive, with high conductivity aureoles in the hornfels. The combination of which can be used to more easily identify reduced intrusions in the ZTEM survey data, than only magnetic survey data (Branson, 2025).

The Rogue Project is primarily underlain by Neoproterozoic to Silurian age clastic sedimentary rocks of the Selwyn Basin, and sedimentary rocks of the Devonian to Mississippian Earn Group. These have been intruded by mid-Cretaceous Mayo and Tombstone plutonic suites. The Valley deposit is underlain by Elmer Creek and Steel formation argillite, shale and chert, which are in turn overlain by Devonian Portrait Lake sedimentary rocks. The stratigraphy has been tightly folded and is part of the Emerald Lake synclinorium. Two small granodiorite stocks intrude the Steel Formation at Valley and at the Reid target, 9 km east of Valley, while an unexposed intrusion is inferred based on geophysics and the intensity of hornfels alteration at the Gracie target, located 4 km east of Valley (Burrell et al., 2024).

Mineralization at Valley is hosted primarily within the western half of a 1-km-scale, polyphase granodiorite stock and to a lesser extent in surrounding hornfelsed sedimentary rocks. Multiple overprinting gold-bearing quartz vein arrays are present, and gold primarily occurs in its native form within the quartz veins and is strongly correlated with Bi and Te sulphides (Burrell et al., 2024).

METHOD

General Theory

The ZTEM airborne AFMAG (Ward, 1959) system measures the anomalous vertical secondary magnetic fields that are created by the interaction between naturally occurring, plane wave audio- frequency EM fields and electrical heterogeneities in the earth.

The vertical magnetic field is linearly related to the horizontal fields according to the following (Vozoff, 1972; Labson et al., 1985):

$$\mathbf{Hz} = \boldsymbol{Tzx}\mathbf{Hx} + \boldsymbol{Tzy}\mathbf{Hy}$$

where the magnetic field vector $\boldsymbol{T}$ = (Tzx, Tzx), known as the tipper, is complex and a function of frequency, but has rotationally invariant properties, such as its magnitude and direction, that are independent of the subsurface, the measurement direction and the field polarization (Labson et al., 1985).

AFMAG uses naturally occurring audio frequency magnetic fields from worldwide atmospheric thunderstorm activity as the source of the primary field signal and therefore requires no transmitter. The primary fields resemble those from VLF except that they are not man-made, are at lower frequency (tens & hundreds of Hz versus tens of kHz), are pseudo-random, rather than periodic, and are usually not as strongly directionally polarized. These EM fields used in AFMAG have the unique characteristic of being uniform, planar and horizontal, and also propagate vertically into the earth – to great depth, up to several km, as determined by the magnetotelluric (MT) skin depth (Vozoff, 1972):

$$\boldsymbol{\delta_S = 503 * \sqrt{(\rho / f)}}\ \textbf{metres}$$

which is the depth where the amplitudes of the EM fields are reduced to 1/e (37%) of their surface values and is directly proportional to the ratio of the bedrock resistivity to the frequency.

ZTEM is an airborne variant of the AFMAG technique where the vertical dipole axis air-core magnetic receiver towed by the helicopter is coupled with a fixed ground base station that measures the horizontal primary fields using similar dipole axis magnetic sensors (Thomson et al, 2007; Lo and Zang, 2008).

RESULTS AND DISCUSSION

Helicopter-borne geophysical surveys were carried out over the Rogue Project from July-August 2023 and June-July 2024, on behalf of Snowline Gold Corp. Principal geophysical sensors included a Z-Axis Tipper electromagnetic (ZTEM) system, and a caesium magnetometer. Two Geotech ZTEM base station sensors measured the orthogonal, horizontal X and Y components of the natural EM field. Data from the three coils are used to obtain the Tzx and Tzy Tipper in-phase and quadrature components at six frequencies in the 30 to 720 Hz band. These data, flown at 500 to 1,000 m line-spacing and totalling 2,543 line-km, were then merged with archival 2008 ZTEM data from the Yukon Geological Survey (Witherly, 2013) and subsequently windowed to a 50x60 km area of interest, centred on the Rogue Project.

ZTEM and Magnetic Survey Results

Figure 5 presents the Total Magnetic Intensity results over the Rogue AOI project, and the corresponding location of Valley deposit and other mineral occurrences (after Branson, 2025). The magnetic results highlight prominent circular-shaped, ring-like/annular magnetic high features that surround magnetic lows, particularly in the northern half of the block. These features are associated with felsic intrusions and surrounding hornfelsed sedimentary rocks. As shown, most of the gold occurrences occur in the annular magnetic highs, including Valley deposit (Figure 2).

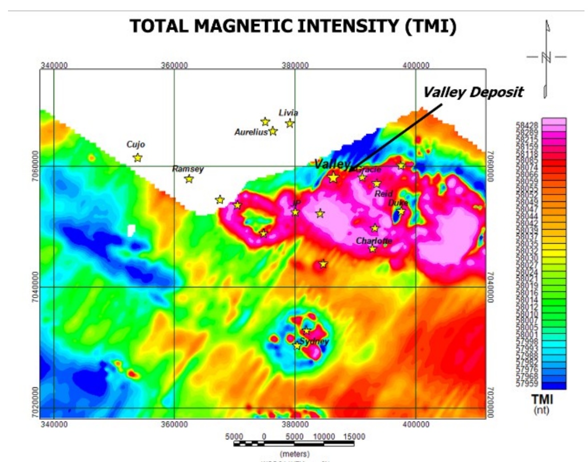

Figure 5: Rogue AOI project Total Magnetic Intensity (TMI), showing the Valley deposit location and other gold occurences/targets (stars).

Figure 6 presents the ZTEM tipper data, displayed as the Total Phase Rotation (TPR) at the 360 Hz frequency. The TPR image maps resistivity variations in plan, in addition to artefacts caused by topography (Sattel and Witherly, 2012).

The TPR image highlights the same pronounced ring-like pattern anomalies similar to those observed over intrusions and surrounding hornfels as shown in the magnetic results. However, in this case, the conductive anomalies are due to pyrrhotite in the hornfels. Arguably, the ZTEM anomalies map the intrusive-hornfels boundaries somewhat more clearly. As shown, most of the gold occurrences occur in the circular resistivity highs (blue), including Valley deposit

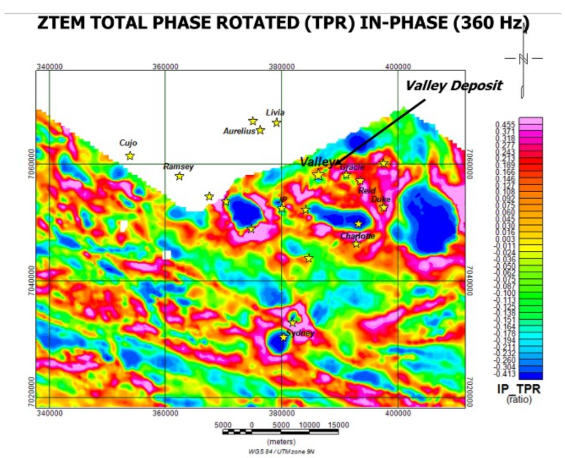

Figure 6: Rogue Project ZTEM In-phase TPR (total phase rotated) tipper data, showing the Valley deposit location and other gold occurences/targets (stars).

ZTEM and Magnetic Inversion Results

3D inversions were performed on the ZTEM data using the UBC-GIF MT3Dinv code (Holtham and Oldenburg, 2008) for converting the In-Phase and Quadrature ZTEM tipper data (30, 45, 90, 180, 360 ± 720 Hz) into equivalent resistivity vs. depth distributions. The 3D inversion utilized both in-line Tzx & cross-line Tzy data. A 300 ohm-m homogeneous half-space starting model was chosen based on the model-data misfit testing of a previous method of Holtham and Oldenburg (2010). Three-dimensional inversions were also performed on the aeromagnetic data using the VOXI MVI 3D inversion code (Ellis et al., 2012) that accounts for magnetic remanence.

Figure 7A presents the 3D ZTEM inversion result at -1000m depth. The resistivity-depth slice image closely resembles the previous TPR results (Figure 3) though arguably the edges of the resistive intrusions and conductive hornfelsed sedimentary rocks are sharper and much better defined. In particular, the small resistivity high associated with the Valley intrusion and the narrow conductive hornfels are both well resolved.

Figure 7b presents the corresponding 3D magnetization amplitude depth slice at -1000 m at the Rogue AOI project. As shown, the 3D MVI results map the magnetic portions of the Rogue Plutonic Complex, and all the known occurrences are shown to lie in in magnetic high features. Noticeably, however, the magnetic MVI results do a somewhat poorer job of resolving the key intrusion-hornfels contacts compared to the ZTEM results.

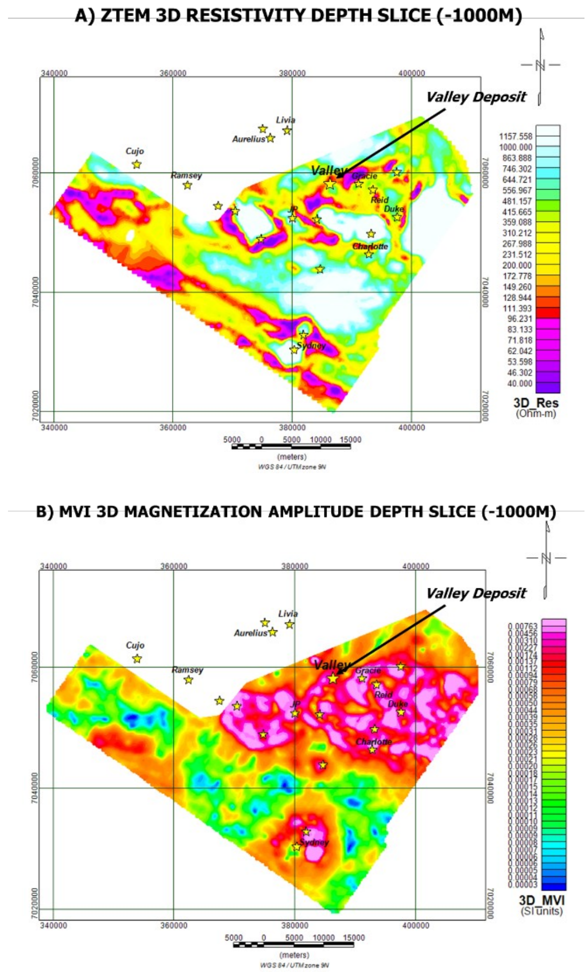

Figure 7: Rogue Project 3D inversions: A) ZTEM 3D resistivity depth slice at 1000 m depth, B) 3D MVI magnetization amplitude depth slice at 1000 m depth, showing Valley deposit location and other gold occurences/targets (stars).

CONCLUSION

ZTEM helicopter natural field electromagnetics and magnetics have been flown over the Rogue Project, including the world-class Valley RIRGS gold deposit. The results show that the combination of ZTEM and magnetics are useful tools to identify buried and exposed reduced intrusions associated with RIRGS gold mineralization.

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An Analysis of ZTEM and Titan MT data over the Kemess North Porphyry Copper-Gold Deposit, Toodoggone District, BC

Ken Witherly

Condor Consulting

The Kemess porphyry copper system is located in the Toodoggone District of northwestern BC. The Kemess North deposit was located in the mid-1960s by Kennco Exploration (Western), now Rio Tinto. The Kemess South was recognized in the early 1980s and was mined from 1998-2011. Kemess North has both near-surface and underground mineral potential and has been in pre-development for a number of years. A district scale IP survey was carried out in 1992 and in 2002 a DIGHEM HEM survey also covered the district. In 2006 and 2007, a Quantec Titan survey which included IP-DC resistivity and MT surveys was carried out and aided directly in the discovery of deeper zones of mineralization east of Kemess North. In 2014, a Geotech ZTEM AFMAG survey was carried out over the Kemess district which included the historic Kemess South Mine and the greater Kemess North zone of mineralization. The Kemess North system is a complex zone of disseminated and semi-massive to massive sulfides. The active and passive EM and IP-DC resistivity provide insights into this complex mineral system. The geophysical surveys over the Kemess district span over a quarter century and have made important contributions to defining alteration and mineralization of a major mineral deposit.