## Great Basin and Western Cordillera Mining Geophysics Symposium

**Saturday Morning, November 23rd 2013**

### Session A | Case Histories: Sediment-hosted Deposits

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<td>An assessment of airborne and ground geophysical data over a Carlin-Type gold prospect, Battle Mountain Nevada—<em>K. Witherly</em>, Condor Consulting</td>
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### Session B | Inversion and Application

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<td>Joint 3D inversion of airborne gravity gradiometry and magnetic data with Gramian constraints—<em>A. V. Gribenko</em>, <em>Y. Zhu</em>, <em>M. Endo</em>, and <em>M. S. Zhdanov</em>, TechnoloImaging and University of Utah</td>
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<td>3D inversion of natural source geophysical methods for mineral exploration in the Western Cordillera of North America with case history examples—<em>S. Napier</em>, Mira Geoscience</td>
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<td>Three-dimensional joint inversion of frequency domain and time domain airborne electromagnetic data—<em>L.H. Cox</em>, <em>D. A. Sunwall</em>, <em>M. Endo</em>, and <em>M. S. Zhdanov</em>, TechnoloImaging and University of Utah</td>
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<td>Multi-disciplinary airborne &amp; ground geophysical survey results for porphyry copper exploration in the Canadian Cordillera—J. Legault*, Geotech</td>
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<td>North Bisbee - A Case Study in Geophysical 3D Magnetic Modeling—C. O. Windels*, Consultant</td>
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**Session D | Case Histories: Epithermal Deposits**

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<td>High Resolution Aeromagnetic and Radiometric survey over the El Aguila and La Arista Epithermal Gold Deposits, Oaxaca State, Mexico —R. Ellis* and A. Smailbegovic*, EGC Inc. &amp; Teraelement Ltd.</td>
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<td>Hycroft Mine Geophysical Case History and Vortex Zone Discovery—J. L. Wright*, Wright Geophysics</td>
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An assessment of airborne and ground geophysical data over a Carlin-Type gold prospect, Battle Mountain Nevada—K. Witherly, Condor Consulting

Carlin-Type deposits represent a major class of gold deposit first defined at the type location in Nevada with the discovery of the Carlin deposit in 1960. Since then dozens of other similar deposits have been found and many exploited, making the NE corner of Nevada one of the most prolific gold districts in the world.

The petrophysical characteristics of these deposits are subtle as the primary deposit attributes; structures and lithology along with some alteration associated with ore emplacement are seldom unique and often overprinted by other similar events before, concurrent and post the primary ore forming events.

In the present study the results from three geophysical surveys; two airborne techniques ZTEM and HeliTEM and ground gravity are processed and assessed over a property that while near well-defined Carlin-Type deposits, is itself largely covered by young volcanic rocks which has made the assessment of the property challenging.

The geophysical results show good agreement with some previously recognized structural features derived from regional mapping and drilling. As well the surveys are providing information about what are considered significant structural features not previously recognized. Alteration could be a component of the observed responses but additional validation with drilling is required to fully assess the significance of these results.

Figure 1: Location map showing the Cortez Summit property and surrounding deposits/resources.
### A-2 A Review of Recent Geophysical Work on the Deposits of the North American Cordillera—R. S. Smith and K. Witherly, Laurentian University & Condor Consulting

Geophysical surveys have been used routinely in exploration for a variety of deposits in the North American Cordillera. In some cases blind deposits have been discovered directly on the basis of geophysical data. In other cases, the deposits are not always clearly evident in the geophysical data as the geophysical techniques are responding to alteration, structure and lithology. The link between these geological characteristics and the geophysics is the physical properties (e.g. resistivity, magnetic susceptibility, chargeability and radioactivity), so it important to have measurements of these properties so that the geophysics can be related to the geology. Typically these measurements are taken on samples on outcrop, on core samples or by using downhole logging tools. The geology can then be extrapolated away from areas where it is known (surface and drillholes) into unknown areas using geophysical data. The prime mechanism for doing this is by inverting geophysical data to give the physical properties unknown areas of the subsurface. When these inversions are unconstrained, the results are often geologically unrealistic and inconsistent with the known geology. Work at Mt. Milligan illustrates how using physical properties can be used with geological information, such as the surface and down-hole lithology and alteration, in order to provide more realistic inversions.

Nevertheless, unconstrained 3D inversions are used routinely in exploration programs and have played an important role in the discovery of prospects at Cinco de Mayo (Mexico) and Silver Queen (BC, Canada). The 3D inversions of airborne electromagnetic (EM) data are still somewhat experimental and have been tested on the Mt. Milligan deposit. Here the 3D EM inversions lead to an interpretation that was more realistic than the interpretation from the simpler and faster 1D inversions.

There are a number of cases where experimental geophysical systems (ZTEM, VTEM and hardrock seismic) have been tried on deposits in the Cordillera of North America. The efficacy of the methods results vary from location to location, but further use is warranted if there is a physical property contrast between the geological feature of interest and the background.

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Examples of multivariate statistical analyses of geology and physical properties data that are used to define prospective zones for mineral exploration have been published from the Canadian Shield. A simplified approach applied to data from Mt. Milligan gave insight into the geology and similar analyses might be of benefit elsewhere.
This study attempts to modify oil and gas industry seismic processing and interpretation techniques for use in Carlin-type Deposit (CTD) gold exploration. Magmatic and deformation overprints on the Nevada carbonate platform-slope setting present challenges in seismic interpretation when compared to conventional seismic data, which is commonly imaged in petroliferous basins with low deformation. Barrick Gold Corporation provided 2D seismic reflection data for this case study, which assesses the viability of certain seismic practices when applied to hardrock seismic data of NE Nevada. Initial seismic interpretations of the pre-stack depth migrated (PSDM) sections located first-order structures and enhanced the geological model. This study uses derivatives of the PSDM, called seismic attributes, in an attempt to improve interpretability. Seismic attributes, which are analogous to filtering on potential field data, can reveal structural and stratigraphic features that are not apparent in the conventional PSDM amplitude data. Attribute analysis leverages correlations made from a seismic response database of ~500 petrophysical drill core samples. These petrophysical measurements indicate that the ore-zone exhibits a porosity, acoustic impedance, decarbonitization relationship that is distinguishable from unaltered rock. This suggests the viability of attribute analysis for detection of CTD alteration. Energy and frequency based attributes best highlight the ore-zone, which is expressed as a chaotic zone of reduced amplitude within one 2D profile. Amplitude Versus Offset (AVO) analysis and modeling was attempted and suggests that rock-properties and contrasts associated with alteration are of sufficient magnitude to detect at the resolution of surface seismic data. Given the ability to directly correlate abundant wire-line logs (e.g., density and sonic) against pre-stack and post-stack seismic attributes, it may be possible to predict CTD alteration features in surface seismic data.
Geophysical inversion from exploration to resource evaluation—C. Martínez, J. Sun, and Y. Li, Colorado School of Mines

The past few decades have seen tremendous progress in the geophysical inversion. Applied 3D inversion of geophysical data is becoming a common practice in the mineral industry thanks to instrumentation and algorithmic advances. The ability to incorporate geologic and petrophysical information into geophysical inversion is likewise developing. Upon producing a reasonable 3D physical property model, the next logical step is to identify not only geologic structure, but also lithologic boundaries and alteration zones that are directly related to mineralization. The current state of geophysical inversion and utilization of the resulting models for understanding and characterizing geology is now at the forefront of research efforts.

From these endeavors, geophysical interpretation is no longer limited to exploration. Lithology and geology delineations based on geophysical models readily translate into added value and information for deposit feasibility studies and resource evaluation stages. The challenge for tomorrow’s geoscientist is the incorporation of such interpretations from geophysical observations into the evaluation of a mineral resource. In this presentation, we discuss the challenges facing integration and utilization of geophysical interpretations in resource evaluation and feasibility studies. Through an iron ore and a disseminated sulfide field example, we illustrate the potential that geophysical models hold in contributing to resource evaluation.
Joint 3D inversion of airborne gravity gradiometry and magnetic data with Gramian constraints—A. V. Gribenko, Y. Zhu, M. Endo, and M. S. Zhdanov, TechnoImaging and University of Utah

Zhdanov et al. (2012) introduced a new approach to joint inversion of geophysical data using Gramian constraints, which are based on the minimization of the determinant of a Gram matrix of a system of different model parameters or their attributes (i.e., a Gramian). This approach does not require an a priori knowledge about the types of relationships between the different model parameters, but instead determines the form of these relationships in the process of the inversion. In this paper we apply Gramian constraints for joint inversion of airborne gravity gradiometry and magnetic data. Note that, the Gramian constraints make it possible to consider both linear and nonlinear relationships between the different physical parameters of a geological model. We illustrate this fact by allowing for a quadratic relationship between density and susceptibility. The model study shows that if there is a nonlinear dependence between the model parameters, it can be defined by joint inversion with Gramian constraints. The case study includes joint inversion of the airborne gravity gradiometer (AGG) and magnetic data collected by Fugro Airborne Surveys in the area of McFaulds Lake located in northwestern Ontario approximately 50 km east of the town of Webequie (Balch et al., 2010). This project was collaboratively operated between the Ontario Geological Survey (OGS) and the Geological Survey of Canada (GSC).
B-3 3D inversion of natural source geophysical methods for mineral exploration in the Western Cordillera of North America with case history examples—S. Napier, Mira Geoscience

Mira Geoscience is recognized as one of the mineral industry leaders in the 3D modelling of all types of non-seismic geophysical data. This talk focusses on the application of 3D inversion modelling of natural source geophysical methods commonly used in mineral exploration. Gravity, magnetic and magnetotelluric data inversions are considered in case history examples which illustrate the advantages of 3D inversion modelling on geological interpretation and exploration success. Examples from the Western Cordillera include innovative gravity and magnetic modelling of the Nechako sedimentary basin in northwestern BC, magnetic and ZTEM modelling for copper-molybdenum porphyry deposits in central BC, and magnetotelluric modeling for Carlin style gold deposits in Nevada.
Three-dimensional joint inversion of frequency domain and time domain airborne electromagnetic data—L.H. Cox, D. A. Sunwall, M. Endo, and M. S. Zhdanov, TechnoImaging and University of Utah

Airborne electromagnetic (AEM) surveys can be flown relatively cheaply and rapidly, with sampling along line approximately every 3m. However, time domain AEM surveys often have poor resolution in the near surface, while frequency domain surveys are unable to penetrate conductive cover. In addition, each survey type may have its own systematic data biases. Combining frequency and time domain surveys provides the benefits of both methods: collecting high resolution data in both the near surface and at depth. In addition, the use of two independent data collection methods reduces biases in the final reconstructed geology.

We present a 3D inversion algorithm that jointly inverts frequency and time domain AEM data. The algorithm uses the moving sensitivity domain method, which makes it applicable to very large scale (1000s line km) surveys. The use of both data types significantly increases the resolution of the final images compared with each system individually. It also reduces the systematic bias from using a single survey. We demonstrate the effectiveness on joint inversion of RESOLVE frequency domain and SkyTEM time domain data along the Murray River, South Australia. The results show noticeable noise reduction and enhanced resolution than with either method below. New surveys can be flown with planning for joint inversion, or legacy data can be re-inverted with the technique.
### Session C | Case Histories: Porphyry Deposits

| C-1 | Geophysical Case History for Oquirrh Mountains, Utah - D. Hinks, Rio Tinto |

The use of physical property data has helped understand and interpret the geophysical responses in the Oquirrh Mountains in Utah. Understanding of the physical properties has also helped determine which geophysical techniques to use for further exploration. With the physical property knowledge and the known occurrence of the Bingham Mine within the exploration area, a large magnetotelluric survey was carried out over a four year period.

A magnetotelluric survey has the ability to map resistivity changes over a large volume of the earth. Porphyry systems cover a large area and require a large scale survey to map them adequately. The final 3D inverted magnetotelluric model confirmed the dip of the known quartz monzonite porphyry intrusion at Bingham, as well as identifying a previously unknown porphyry system.
Multi-disciplinary airborne & ground geophysical survey results for porphyry copper exploration in the Canadian Cordillera—J. Legault, Geotech

Porphyry copper deposits in Western Cordillera have been extensively studied with airborne and ground geophysics, but it’s only with the advent of 3D inversion, that these deposit responses be accurately compared based on derived physical properties.

For example the Mt-Milligan alkaline cu-mo porphyry in the Mackenzie region of central British-Columbia, Canada, where the geology is well known and the geophysics is available in the public domain making it an ideal inversion case-study example. As a result, it has been extensively studied since 1990’s, mainly by the UBC-GIF, with 1D-2D-3D inversions (Airborne HFEM, HTEM, AFMAG-EM, Aeromagnetics, Ground IP/Resistivity and Magnetics as well as gravity). However, the results have sometimes been contradictory – for example the borehole physical property, ground DC resistivity and airborne AFMAG have indicated that the deposit is resistive, where airborne TEM had initially suggested the opposite. More recent 3D TEM-AFMAG inversions have shed new light on the source of this discrepancy.

The Pebble calc-alkaline cu-mo porphyry is another example where widely different geophysical measurements have been presented (ie., Ground DC/IP, Airborne TEM, airborne AFMAG-EM, aeromagnetics, ground gravity, ground MT, drill hole data) with seemingly varied results. Yet a consistent resistivity model has been obtained as a result of 3D inversion of ground and airborne EM.

The Silver Queen cu-pb-zn-au-ag porphyry deposit case-study demonstrates successful application of reconnaissance airborne EM and ground methods that have lead to discovery thanks to 3D inversions. In this case-study example AFMAG-aeromagnetics were obtained over a deposit area that was originally surveyed with conventional ground IP/Resistivity. After analysis using 3D inversion, the AFMAG and Magnetica results were then successfully followed up by distributed array DC/IP-MT ground and the data integrated together using 3D inversion. This resulted in the newly discovery of Itsit cu-mo-au porphyry deposit in single field season.
North Bisbee - A Case Study in Geophysical 3D Magnetic Modeling—C. O. Windels, Consultant

The North Bisbee project is a porphyry copper exploration target located near Bisbee, Arizona and immediately north of the Lavender Pit and Cochise copper projects controlled by Freeport-McMoRan. Because the area is covered by 700 to 1000 meters of post mineral cover, initial target generation relied on 3D magnetic modeling in combination with district-scale geologic/structural relationships.

Various 3D magnetic models using University of British Columbia (UBC) - Mag3D, Geosoft -VOXI and FastMag3D are presented for both regional and detailed aeromagnetic data.
1. The UBC Mag3D inversion using the FastMag3D model as a reference model is compared to the UBC Mag3D default results.
2. The UBC Mag3D inversion using an interpreted pre-mineral rock model for the Cretaceous Bisbee Formation as reference model is compared to the UBC Mag3D default results.
3. The VOXI Iterative Reweighting Inversion (IRI) with defaults is compared to using the FastMag3D as a starting model and parameter reference model.

Magnetic features and an induced polarization anomaly at depths greater than 700 meters suggested potential of a porphyry target. Two holes were drilled to test the anomalies. Drill hole results are compared with the various 3D magnetic models.

Conclusion
• Initial interpretations of the Bisbee FastMag3D block model are supported by lithologies encountered in two drill holes combined with magnetic susceptibility measurements.
• The combination of FastMag3D with other 3D mag inversions provides a more useful model for exploration.
• IP/Resistivity methods using a 300 m dipole-dipole array, n-spacing 1-12 are sufficient to identify valid chargeability anomalies at depths in excess of 700 m. Drill results confirm the presence of sulfide mineralization as the cause of chargeability anomalies with anomalous Cu 10-700 ppm and Au 1-287 ppb.
The El Aguila and La Arista Au-Ag and base metal deposits are located approximately 120 km southeast of the capital city of Oaxaca, Mexico and operated by Don David Gold S.A.I.C. (DDG), a subsidiary of Gold Resource Corporation (NYSE MKT: GORO). Epithermal mineralization at El Aguila was mined by open pit and produced 345,000 tonnes at an average grade of 4.4 g/tonne Au and 43 g/tonne Ag. Mineralization consists of high grade structural feeders into a "manto" of silicified permeable Tertiary volcanic rocks consisting of volcanic breccia and tuff. Structurally controlled Au-Ag and base metal mineralization at La Arista consists of quartz veins and stockwork hosted in strongly silicified Tertiary rhyolite intrusive, breccia, andesite, and tuff. Within the same deposit Cretaceous carbonate and sandstone units below and or adjacent to the mineralized volcanic host are targets for base metal skarn mineralization in addition to the epithermal veins. From initial startup July 1, 2010 through June 30, 2013 the El Aguila-Arista Project has processed a total of 811,496 tonnes averaging 3.85 g/t gold and 290 g/t silver to recover 82,409 ounces of gold and 6,813,685 ounces of silver.

A "high resolution" airborne magnetic and radiometric survey was flown over the contiguous property holdings of DDG to identify structure, magnetite associated with possible skarn mineralization, and alteration associated with epithermal mineralization. The term "high resolution" implies certain survey specifications, equipment configuration, and sampling and processing criteria to get the best signal-to-noise data in the steep topography surveyed.

Interpretation of the magnetic data was done using standard digital image processing techniques and inversion modeling. The magnetic data helped to extend known mineralized structures and identify areas of potential magnetite destructive alteration and skarn mineralization. Magnetic vector inversion (R. G. Ellis, 2012) provided a better correlation of source location than other inversion approaches particularly where remanent magnetization is suspected to be a significant component to the total magnetization. (continued on next page)
Integrating the 3D model with geology has been helpful in targeting at the mine scale and provides better understanding of the regional geology.

Radiometric data was important to characterize the known mineralization and identify targets in the broader survey area. The radiometric detector consists of three main channels: uranium (U), thorium (Th) and potassium (K). These channels are traditionally combined in the analysis into various ratios to map the relative distribution and abundance of U-Th-K in the particular area. However, with the improvement in the overall design of recording instruments and available analysis software, now it is possible to use some of the additional statistical tools, namely the Principal Component (PC) transformation and Minimum Noise Fraction (MNF) to better investigate the relationship of the channels, their ratios or derivatives and outline the some correlative features with the other elements of data.

The Cahuilla project is a low-sulfidation, hot springs, gold-silver deposit located in northwest Imperial County, California. The system occurs within Pliocene-Pleistocene rocks and is located along the western margin of the Salton Trough, an area of active crustal extension associated with the northwest-trending San Andreas and San Jacinto fault systems. The mineralization is closely associated with the Truckhaven Fault, which places Jurassic plutonic rocks of the Peninsular Batholith against the Palms Springs Group, a sequence of fine- to coarse-grained clastic sediments and rhyolitic pyroclastic rocks. Mineralization consists of Au- and Ag-bearing chalcedonic veins and stockwork veinlets, within a large tabular envelope of disseminated mineralization hosted in sediments of the Palm Springs Group in the hanging wall of the Truckhaven Fault zone. Silicification is commonly associated with precious metals and occurs as open-space fracture and fault filling and replacement of fine-grained sedimentary rocks. Clay alteration occurs along the Truckhaven Fault zone and in its hanging wall, likely resulting from descending steam-heated meteoric water. To date, 383 holes have been drilled and a NI 43-101compliant indicated resource of 1.010 million ounces of gold and 11.855 million ounces of silver has been defined at a 0.008 oz Au per ton cutoff. Current exploration is primarily focused on the discovery of deeper high-grade vein or replacement zones with a secondary focus on the expansion of the near-surface resources.

Geophysical exploration programs conducted at Cahuilla include CSAMT, MT, IP/Resistivity, and gravity surveys.

The gravity data show a very strong gradient associated with the Truckhaven Fault and indicates that the presently-defined resource lies at the intersection of the Truckhaven Fault and a major northwest-striking fault zone. The CSAMT and MT surveys show the broad area of disseminated mineralization as a vertical wedge-shaped zone of high resistivity in the hanging wall of the Truckhaven Fault. This high-resistivity zone correlates with silicification that is spatially associated with the precious metal mineralization.

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Within the broad high-resistivity zone, coincident linear zones of higher resistivity and highs in the vertical derivative of the gravity are interpreted to reflect densification caused by increased silicification and/or veining associated with structural zones. Many of the highest grade gold-silver intercepts, to date, are within these areas of apparent densification. Linear resistivity lows and gravity lows correlate with zones of argillization along the Truckhaven Fault.

A moderate amplitude IP high is centered beneath and extends within a zone that contains many of the highest-grade intercepts within the presently-defined resource.
The Hycroft Mine is located 86 kilometers west of Winnemucca in Humboldt County, Nevada and operated by Allied Nevada Gold (ANV) Corporation (NYSE-AMES: ANV). Figure 1 shows the mine’s location relative to topographic and physiographic features.

Hycroft is a large, epithermal, low sulfidation, hot springs deposit. Gold and silver mineralization occurs as both disseminated and vein-controlled, with gold values ranging from detection to 8.8 ounces per ton (opt), and silver ranging from detection to 647.5 opt. Several styles of mineralization exist at the Hycroft deposit. An early silica sulfide flooding event deposited relatively low grade gold and silver mineralization, generally along bedding. This is cross cut by later, steeply dipping quartz alunite veins. Hypogene enrichment of gold and silver occurred at the base of the acid leach blanket. Late stage silver bearing
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veins are found in the Vortex zone and at depth in the Cut-5 area. Late to present super-gene oxidation along faults has liberated precious metals from sulfides and enriched gold and silver, generally along water table levels. The mine produced 136930 oz Au and 794097 oz Ag in 2012 (Wilson, 2012).

Between 1989 and 1995 CSAMT, seismic, airborne (AERODAT), induced polarization (IP) and ground magnetic surveys were completed over portions of the property. Loss of data and/or lack of location information marginalized much of this early work. Nevertheless, structural and alteration features were extracted from the airborne survey, specifically the resistivity and radiometrics. Two phases of gravity and IP surveys were completed from 2007 to 2011, resulting in a data resource of 2117 gravity stations and 107.3 line-km of IP coverage. The gravity data required customized processing to remove surficial responses produced by leach pads and dumps, while the IP data underwent rigorous quality control due to extreme electrical interference from mine operations. Considerable structural information was extracted from the gravity, as well as the basin geometry along the Black Rock Basin margin. The basin geometry guided planning for the two subsequent IP surveys. Numerous north-northeast trending, linear chargeability anomalies were defined by the IP survey. High resistivity correlation was noted with several of the anomalous zones. The most prominent anomaly, detected in the 2007 survey, was termed the “Vortex Zone” due to the magnitude and size of the IP response. Drill testing of the anomaly in 2008 resulted in discovery of the Vortex Gold Zone.

Moore (2013) notes the upper elevation at Vortex is hydrothermally clay (kaolinite) altered. Strong silicification to depths greater than 1,500 feet is due to veining and phreatic hydrothermal brecciation. At least four mineralizing events are present as evidenced by crosscutting vein and breccia relationships. The hydrothermal venting may have contributed to the eruption breccias overlying the Brimstone Zone. Propylitic and/or clay alteration extends outboard of the silification. The mineralization at Vortex is of both vein and disseminated type, with brecciated and altered rhyolite rocks and volcanic clastics acting as favorable hosts. In addition to gold mineralization, high grade silver has been encountered at Vortex; with values ranging from 10 to 647 opt. Oxide mineralization is present at a depth of approximately 500 feet below surface, with sulfide mineralization extending to 2,500 feet below surface. Mineralization thickness (true width) is 1,000 to 1,800 ft thick.

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Gold

Condor Consulting, Inc.

Contact Information
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Silver

Magee Geophysical Services LLC chris_magee@gravityandmag.com
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Great Basin & Western Cordillera Mining Geophysics Symposium

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Presentations welcome on mining and exploration geophysics case histories from the Great Basin & Western Cordillera and technological advancements

Who:
Geophysicists, Geophysical Service Providers, Geologists and Engineers are all welcome

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Presentations will be in the form of a POWERPOINT lasting 25 minutes, which will also be printed and bound for distribution to attendees.

Annotations and/or slide notes should be sufficient to inform readers using the bound presentation. Appropriate subjects include geophysical cases studies and recent technical advances, which should incorporate examples of field results. Discovery cases histories are particularly welcome.

Questions concerning the presentation format, content and submission procedure should be directed to:

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# GREAT BASIN & WESTERN CORDILLERA MINING GEOPHYSICS SYMPOSIUM PROGRAM

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<td>Geophysical inversion from exploration to resource evaluation — C. Martinez, J. Sun, and Y. Li*, Colorado School of Mines</td>
<td>B-1</td>
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<tr>
<td>11:00</td>
<td>Joint 3D inversion of airborne gravity gradiometry and magnetic data with Gramian constraints — A. V. Gribenko*, Y. Zhu, M. Endo, and M. S. Zhdanov, TechnoImaging and University of Utah</td>
<td>B-2</td>
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<tr>
<td>11:30</td>
<td>Magnetization Vector Inversion — Robert Ellis and Taronish Pithawala*, Geosoft Inc.</td>
<td>B-3</td>
</tr>
<tr>
<td>12:00</td>
<td>Three-dimensional joint inversion of frequency domain and time domain airborne electromagnetic data — L.H. Cox*, D. A. Sunwall, M. Endo, and M. S. Zhdanov, TechnoImaging and University of Utah</td>
<td>B-4</td>
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<tr>
<td>12:30</td>
<td>Lunch</td>
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### Session C | Case Histories: Porphyry Deposits

<table>
<thead>
<tr>
<th>Time</th>
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<tbody>
<tr>
<td>1:30</td>
<td>Geophysical Case History for Oquirrh Mountains, Utah — D. Hinks*, Rio Tinto</td>
<td>C-1</td>
</tr>
<tr>
<td>2:00</td>
<td>Multi-disciplinary airborne &amp; ground geophysical survey results for porphyry copper exploration in the Canadian Cordillera—J. Legault*, Geotech</td>
<td>C-2</td>
</tr>
<tr>
<td>2:30</td>
<td>North Bisbee - A Case Study in Geophysical 3D Magnetic Modeling—C. O. Windels*, Consultant</td>
<td>C-3</td>
</tr>
<tr>
<td>3:00</td>
<td>Coffee Break</td>
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### Session D | Case Histories: Epithermal Deposits

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<th>Time</th>
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<td>3:20</td>
<td>High Resolution Aeromagnetic and Radiometric survey over the El Aguila and La Arista Epithermal Gold Deposits, Oaxaca State, Mexico — R. Ellis* and A. Smailbegovic*, EGC Inc. &amp; Teraelement Ltd.</td>
<td>D-1</td>
</tr>
<tr>
<td>4:45</td>
<td>Hycroft Mine Geophysical Case History and Vortex Zone Discovery—J. L. Wright*, Wright Geophysics</td>
<td>D-3</td>
</tr>
<tr>
<td>5:15-6:30</td>
<td>Closing Statements and Refreshments</td>
<td></td>
</tr>
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</table>

*presenter
An assessment of airborne and ground geophysical data over a Carlin-Type gold prospect, Battle Mountain Nevada.

Great Basin and Western Cordillera Mining Geophysics Symposium

November 23, 2013
Elko, Nevada

Ken Witherly
Condor Consulting
Abstract

An Assessment of Airborne and Ground Geophysical Data over a Carlin-Type Gold Prospect, Battle Mountain, Nevada

Ken Witherly, Condor Consulting, Inc. Lakewood CO USA ken@condorconsult.com

Carlin-Type deposits represent a major class of gold deposit first defined at the type location in Nevada with the discovery of the Carlin deposit in 1960. Since then dozens of other similar deposits have been found and many exploited, making the NE corner of Nevada one of the most prolific gold districts in the world.

The petrophysical characteristics of these deposits are subtle as the primary deposit attributes; structures and lithology along with some alteration associated with ore emplacement are seldom unique and often overprinted by other similar events before, concurrent and post the primary ore forming events.

In the present study the results from three geophysical surveys; two airborne techniques ZTEM and HeliTEM and ground gravity are processed and assessed over a property that while near well-defined Carlin-Type deposits, is itself largely covered by young volcanic rocks which has made the assessment of the property challenging.

The geophysical results show good agreement with some previously recognized structural features derived from regional mapping and drilling. As well the surveys are providing information about what are considered significant structural features not previously recognized. Alteration could be a component of the observed responses but additional validation with drilling is required to fully assess the significance of these results.
Carlin Deposits – Exploration
Carlin Deposits – Section across shelf thrusting

- Deep water sediments
- 'Upper Plate'
- Roberts Mtn Thrust
- Limestones
- 'Lower Plate'
- Oceanic crust
- Mantle
- Archean crust

A Jackson-2012
Carlin Deposits – Section across shelf collapse

Oceanic crust

Mantle

Partial melting

Limestones

Archean crust

A Jackson-2012
Carlin Deposits - Mineralization

- Later fluids had neutral pH, 120-250°C
- Fluids filled porosity with quartz and pyrite.

- Gold introduced during one brief pulse towards the end of the event at ~40Ma and deposited as very fine grains in arsenic-rich pyrite (and other arsenic minerals).
Carlin Deposits – Mineralization

- Mineralization occurs as veins in original old faults and disseminated in favorable porous carbonate beds - ‘Christmas tree’ effect
Carlin Deposits - Genetic Model

- Displaced Leakage Anomalies
- Extensional Reactivation of RMT
- Post-mineral Detachment Fault That Roots Into Thrust Fault
- Folds In Plate Arc by Inversion
- Pre-Antler Normal Fault
- Pinning Of Deformation By Stock
- Accommodation Faults Along Margin Of Mesozoic Intrusion And Contact Aureole
- Metamorphic Contact Aureole

~1 km
Carlin Deposits – Exploration

Exploration targeting:

• In Carlin or Cortez ‘corridors’
• Within 500m of long-lived, inverted, crustal scale faults
• Often, but not always, within 1km vertically below the Roberts Mountain Thrust
• Within 1km of Eocene (~42Ma) intrusions
• In fault-related hanging-wall anticline (+/- carbon)
• In dirty carbonate host rock with de-calcification (gravity low)
Carlin Deposits – Exploration

• Several phases of exploration:
  – Early exploration focused on outcropping lower plate carbonate rocks with oxide ore.
  – Deeper sulfide portions of known deposits.
  – Areas under shallow upper plate gravels cover.
  – Now turning to blind deposits under deep gravels or upper plate rocks.
  – Future discoveries likely to be:
    • deep in Lower Plate rocks
    • covered by barren Upper Plate rocks
    • in valleys, covered by 100s or 1000s of feet of gravel.
The Model

Geophysical Criteria

Mapping structure; thrusts & older deep penetrating structures being most important
- Magnetics
- Gravity
- EM
- Seismic

Mapping de-silicified rocks (generally limestone)
- Gravity

Mapping silicification & sulfides
- CSAMT-IP-resistivity
Coretz Hills geology

Note: The geology color schemes have not been rationalized.
Geology

EXPLANATION

- **Tb**: Basaltic Andesite
- **Td**: Diorite dikes
- **Tg**: Gravels undivided
- **Tgp**: Paleozoic clast gravels
- **Tr**: Rhyolite
- **Trt**: Rhyolite intrusive
- **Ji**: Quartz monzonite
- **RMA**: Roberts Mountains Allochthon (includes some Dne)
- **Dhc**: Horse Canyon Formation
- **Dw**: Wentian Formation

Scale 1 : 12500

Gold reported in drill hole

deposit
CS Airborne Geophysics
CS Airborne Geophysics

Figure 13: Geometry of the HELITEM System
CS Exploration Assessment

Profile 1: Line L109230 (View [1/3])

Profile 2: Line L109230 (View [2/3])

Profile 3: Line L109230 (View [3/3])

Profile 4: Line L109230 (View [4/3])

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Conclusions

• Ground and airborne geophysical surveys reveal a pattern of structure and lithologies on the property that point to a complex geological history

• The gravity and ZTEM results appear to be mapping complimentary aspects of the geology

• The magnetic results indicate structure and magmatic events that are likely not primary to the formation of a Carlin-style deposit

• The HeliTEM provided good shallow mapping capability
Acknowledgments

Carlin Gold-Robert Thomas
Barrick Exploration-Jared Townsend
Sprott Global-Andrew Jackson
A Review of Recent Geophysical Work on the Deposits of the North American Cordillera

Richard Smith, Laurentian University
Ken Witherly, Condor Consulting
Abstract

A Review of Recent Geophysical Work on the Deposits of the North American Cordillera

Richard S. Smith, Laurentian University, 935 Ramsey Lake Road, Sudbury, Ontario, Canada, P3E 2C6. RSSmith@laurentian.ca

Ken Witherly, Condor Consulting, 2201 Kipling Street Lakewood, CO, United States, 80215 ken@condorconsult.com

Geophysical surveys have been used routinely in exploration for a variety of deposits in the North American Cordillera. In some cases blind deposits have been discovered directly on the basis of geophysical data. In other cases, the deposits are not always clearly evident in the geophysical data as the geophysical techniques are responding to alteration, structure and lithology. The link between these geological characteristics and the geophysics is the physical properties (e.g. resistivity, magnetic susceptibility, chargeability and radioactivity), so it important to have measurements of these properties so that the geophysics can be related to the geology. Typically these measurements are taken on samples on outcrop, on core samples or by using downhole logging tools. The geology can then be extrapolated away from areas where it is known (surface and drillholes) into unknown areas using geophysical data. The prime mechanism for doing this is by inverting geophysical data to give the physical properties unknown areas of the subsurface. When these inversions are unconstrained, the results are often geologically unrealistic and inconsistent with the known geology. Work at Mt. Milligan illustrates how using physical properties can be used with geological information, such as the surface and down-hole lithology and alteration, in order to provide more realistic inversions.

Nevertheless, unconstrained 3D inversions are used routinely in exploration programs and have played an important role in the discovery of prospects at Cinco de Mayo (Mexico) and Silver Queen (BC, Canada). The 3D inversions of airborne electromagnetic (EM) data are still somewhat experimental and have been tested on the Mt. Milligan deposit. Here the 3D EM inversions lead to an interpretation that was more realistic than the interpretation from the simpler and faster 1D inversions.

There are a number of cases where experimental geophysical systems (ZTEM, VTEM and hardrock seismic) have been tried on deposits in the Cordillera of North America. The efficacy of the methods results vary from location to location, but further use is warranted if there is a physical property contrast between the geological feature of interest and the background.

Examples of multivariate statistical analyses of geology and physical properties data that are used to define prospective zones for mineral exploration have been published from the Canadian Shield. A simplified approach applied to data from Mt. Milligan gave insight into the geology and similar analyses might be of benefit elsewhere.
Talk outline

• Geophysical discoveries
• New technology
  — 3D IP, hardrock seismic
  — ZTEM, use of 3D inversions
• Physical properties measurements for constrained inversion, geological mapping
• Multivariate statistical analysis
• IP effects in EM data
Maria Deposit discovery

• Cananea district of Sonora, Mexico
• Disseminated Cu-Mo deposit, called M1
• Exploration for richer zones unsuccessful with IP/resistivity and HLEM
• UTEM survey discovered a flat-lying high-grade zone buried at depth
  – 1.6 MT of 6% Cu, 0.36% Mo, and 31 g/t Ag, with a higher-grade zone of 0.75 MT at 10.6% Cu, 0.26% Mo, and 54 g/t Ag
The UTEM channel 4 Z-component response. Elevated responses are shown in red. The outline of the Maria deposit is shown as a black line. (Figure from Visser and Lajoie, 2012.)
Geophysics at Silver Queen

- New Nadina Exploration project
- Discovery of buried body
- Airborne geophysics helped define the target area
- Ground geophysics defined the drill target
Silver Queen is a project area south of Houston BC
Itsit Cu-Mo-Au porphyry.
Geophysics drove the exploration.
Regional aeromagnetic and ZTEM
Subsequent Titan resistivity IP and MT surveys identified a drilling target at depth.

ZTEM model showing the 500 ohm-m isosurface (blue) and the 12.5 ohm-m isosurface (brown).
The arrow labelled 1 points to a zone interpreted to be an intrusion.
The small purple zone labelled “Silver Queen vein” is nearby known outcropping mineralization.
The dashed yellow lines mark a structure interpreted from this data and the magnetic data.
The dotted red ellipse is an interpreted dilational.
Within the ellipse is a moderately conductive zone, possibly brecciated.

(Kowalczyk and Van Kooten, 2012.)
IP anomaly (black outline) was used to define the drill target.

Drilling discovered the Itsit deposit.

This slide shows a comparison of the ZTEM 3D inversions (left) with the MT inversions (2D). The ZTEM only shows a conductive zone at 500 m depth, but the MT shows it from 500 m to 1300 m depth.

The ZTEM covers a larger area; the MT is higher spatial resolution and higher frequency resolution and broader bandwidth.
Airborne EM (VTEM) image of an area on the north rim of the Grand Canyon containing breccia pipes prospective for uranium mineralization. Grump and Ollie were known pipes; A-1 and A-20 were mineralized pipes discovered by the survey and A-18 and A-21 are also believed to be mineralized. (Figure courtesy of Quaterra Resources Inc.)
Geophysics at Cinco de Mayo, Mexico

- MAG Silver project
- Carbonate replacement Ag-Pb-Zn deposits associated with sills and dikes
- Completely covered, so geophysics necessary
- Jose Manto
  - aeromagnetic
  - Airborne EM
  - Ground EM, gravity and IP/resistivity
- Pozo Seco
  - VTEM and ZTEM
- 3D UBC inversions used extensively for Mag, IP, resistivity and ZTEM (1D for VTEM).
  (Robertson and Megaw, 2009; Robertson, 2011)
A perspective view to the north-west showing the geophysical results. In the foreground is a VTEM section; the yellow are iso-surfaces of the ZTEM 90 Hz in-phase data after Karous-Hjelt tilt-angle filter. (Figure from Robertson, 2011.)
New geophysical tools and technologies

- 3D IP/resistivity
- Hardrock seismic
- ZTEM
- 3D inversions
3D IP/resistivity is an exciting new tool. Dense data coverage and data redundancy provide high resolution images. This example from Hidden Hill shows its potential. More details would be allow a closer analysis. There was a recent presentation of an example from Africa at the ASEG (Whiting, 2013).
Rain district, Carlin (Au)

Gold deposits related to structures (folds). Fold axes are fault related.

Good understanding for structure required to understand deposits. Seismic reveals structure.

Left is inferred structure prior to Seismic

Essman (2010)
Post seismic
Thrast faults recognized.
Stratigraphy not down thrown to right of Rain fault

Figure 15. b. Cross section shown in Figure 15. a. with updated geologic interpretation of the Rain fault and the controls on mineralization. Drill hole RAN-1765 specifically targeted the untested mudstone/carbonate contact (high amplitude reflector) and its intersection with a low angle thrust zone interpreted from geophysical data.

Essman (2010)
Comparison of conductivity images from Mt. Milligan derived from the ZTEM survey in the 0-50 m depth range (top) and the 400-500 m depth range (bottom). The left image shows the ZTEM only; the right image has the VTEM conductivity at the same depth as an inset because the VTEM survey covers a much smaller area. The known mineralization is outlined in black and shows on the VTEM data as a resistive (blue) feature. The red feature to the east is the conductive cover. Tick labels are every 2 km. (Figure from Sattel et al., 2010).
Why Invert in 3D?

Resistive MBX stock
Conductive sediments

1D Inversion

3D Inversion
A shallow conductivity slice at Mt. Milligan derived from 3D inversion of a 1.8 by 1.8 km subset of the VTEM survey. The left overlay is the geology; the right overlay is the 420 ohm-m contour of the model derived from the resistivity data. (Figure from Yang and Oldenburg, 2012.)
Magnetic Susc. measurements

- **Mt. Milligan** — mineralization associated with potassic alteration, magnetite and high susc.
- **Endako** — mineralization associated with quartz-sericite, destroyed magnetite, low susc. But low susc also barren kaolinite alteration
- **Huckleberry** — no significant change in susc. from host to mineralization. *(Mitchinson, Enkin, Bissig)*

Magnetic signature reflects the magnetic nature of the unaltered rock and the degree to which alteration has created or destroyed magnetite. Understanding these issues is critical when interpreting magnetic data.
Improving Inversion Models with Physical Property Constraints

Physical property information, along with geological knowledge of the mineral deposit setting, can be used to improve geophysical inversion model results. When suspected or known values are used as reference values, tying down different points or zones within the model, the values of the remaining model cells are likely to be more accurately calculated, leading to higher confidence in the model.

The Mount Milligan QUEST-West magnetic data set was inverted first without constraints. The data was then inverted using surface and downhole susceptibility measurements, and downhole geology as constraints.

Mitchinson and Bissig (2010)
Mitchinson and Bissig (2010)

Zoom of part of the previous slide showing more detail on the constrained inversion.
Multivariate statistical analysis of physical property data

Phillips et al., 2009 (Geoscience BC report)

Magnetic data
Gravity data
EM data for the five blocks (NT, A, B, C, D) of QUEST survey.

Each inverted using 3D, 3D and 1D models respectively
Simple physical properties classification into low, Medium high for mag susc and density, giving nine classes (blue box) and nine colours (legend). The map is the surficial classification.
Pebble is a large Cu-Mo-Au porphyry deposit in SW Alaska. Porphyry systems in the district are associated with magnetic highs (Anderson et al., 2013). However, the deposit itself is not magnetic. IP/resistivity, Spectrem (airborne EM) and ZTEM used for exploration. Chargeable zones around Pebble west (pyrite rich alteration). Spectrem similar to resistivity, but faster. ZTEM looks deeper than Spectrem. ZTEM data has been used as a test of EM inversions.
TOP  2D inversion section from the ZTEM data over Pebble. The copper zones are marked in grey. (Figure from Paré et al., 2012b.)

BOTTOM: 3D inversion section from ZTEM data over Pebble. The copper zone is marked in grey. Note the deeper zone to the east that corresponds to the Far East zone east of the ZG1 Fault. (Figure from Paré et al., 2012b.)
El Arco

- **El Arco Cu-Au Porphyry**
- Baja California, Mexico
- IP/resistivity successful
- EM shows IP effects
- Chargeability can map mineral concentration

(Flores and Peralta-Ortega, 2009)
Kratzer and Macnae (2012) also looked at the EM data and estimated the chargeability.
There is a negative transient near the MBX stock at Mt Milligan. These occur where the ground is chargeable and conductive (generally in the near surface). Note a second location to the right of the MBX stock where this nearly happens. Chargeability in the EM bandwidth (30-10 000 Hz) can be identified with TEM methods.
Here is some IP and resistivity data over Silver bell, inverted using a 3D algorithm for conductivity, chargeability, time constant and cole-cole power (c).
This is the CSAMT resistivity map for the depth slice 400 feet below surface. Note the 800 m long magenta line joining conductive features in the WNW direction at the Nth Silver Bell location.
This is the CSAMT resistivity map for the depth slice 600 feet below surface. Note the 800 m long magenta line joining conductive features in the WNW direction at the Nth Silver Bell location.
This is one line of GEOTEM x-component data collected over North Silver Bell. Each profile has a y-axis zero that is shifted up vertically, with earlier channels being shifted the most. It is not readily apparent in this format, but there are negative transients in this data. The red curve shows the chargeability (or polarizability) estimated from this data using a crude method.
This is the resistivity map estimated from the on-time GEOTEM data. There is a conductive formation to the west that appears to be dipping to the west. Otherwise, it is generally more than 100 ohm m.
Note the location of the ENE trend shown as a magenta line on the image. This is the location of Nth Silver Bell.
This is the polarizability or chargeability estimates from the GEOTEM data. Note the circular halo around Nth Silver Bell!
Conclusions

- Geophysics is being used successfully in a variety of ways in the Cordillera of North America.
- New tools are being developed and tested.
- Physical properties are useful for constraining 3D inversion and inferring geology.
- Multivariate statistical analyses on physical properties derived from surveys can reveal geological information.
- Keep your eyes and minds open to IP effects in EM data as a way to map alteration or mineralization in porphyry systems.
Acknowledgements

Peter Kowalczyk,
New Nadina Exploration [www.nadina.com],
Jean Legault, Geotech
Ken Robertson,
Pascal Pare, Anglo American,
Syd Visser & Casey Vandenberg of SJ Geophysics Ltd
Daniel Sattel, EMISolutions
Quaterra Resources Inc
Hardrock Seismic Attribute Analysis and AVO modeling for Carlin-type Deposit Exploration

Kyle T. Gray
Jared Townsend
John Louie

Great Basin and Western Cordillera Mining Geophysics Symposium
11/23/2013

1 University of Nevada, Reno Seismological Laboratory
2 Barrick Gold Exploration Inc.

BARRICK
The Nevada Seismological Laboratory
Abstract

Hardrock Seismic Attribute Analysis and AVO modeling for Carlin-type Deposit Exploration

Kyle T. Gray¹, Jared Townsend², John Louie¹
1-University of Nevada, Reno / 2-Barrick Mining Corp.

This study attempts to modify oil and gas industry seismic processing and interpretation techniques for use in Carlin-type Deposit (CTD) gold exploration. Magmatic and deformation overprints on the Nevada carbonate platform-slope setting present challenges in seismic interpretation when compared to conventional seismic data, which is commonly imaged in petroliferous basins with low deformation. Barrick Gold Corporation provided 2D seismic reflection data for this case study, which assesses the viability of certain seismic practices when applied to hardrock seismic data of NE Nevada. Initial seismic interpretations of the pre-stack depth migrated (PSDM) sections located first-order structures and enhanced the geological model. This study uses derivatives of the PSDM, called seismic attributes, in an attempt to improve interpretability. Seismic attributes, which are analogous to filtering on potential field data, can reveal structural and stratigraphic features that are not apparent in the conventional PSDM amplitude data. Attribute analysis leverages correlations made from a seismic response database of ~500 petrophysical drill core samples. These petrophysical measurements indicate that the ore-zone exhibits a porosity, acoustic impedance, decarbonitization relationship that is distinguishable from unaltered rock. This suggests the viability of attribute analysis for detection of CTD alteration. Energy and frequency based attributes best highlight the ore-zone, which is expressed as a chaotic zone of reduced amplitude within one 2D profile. Amplitude Versus Offset (AVO) analysis and modeling was attempted and suggests that rock-properties and contrasts associated with alteration are of sufficient magnitude to detect at the resolution of surface seismic data. Given the ability to directly correlate abundant wireline logs (e.g., density and sonic) against pre-stack and post-stack seismic attributes, it may be possible to predict CTD alteration features in surface seismic data.
Overview

- Both petroleum and mineral exploration attempt to locate zones of increased porosity.
- This study focuses on adoption of oil and gas methodologies for CTD exploration.
  - Seismic attributes, AVO analysis, Inversion
- We cannot get all of the benefits of seismic data without abundant down-hole logs.
Seismic Interpretation Methods

1. Conventional interpretation
   - Manual picking of horizons and faults

2. Seismic attributes
   - Analogous to filtering of potential fields data

3. Forward modeling
   - Synthetic data from down-hole logs

4. Inversion
   - Incorporation of down-hole logs to invert seismic data into elastic properties

- Methods exist to enhance certain seismic signatures (i.e., basic attribute analysis) but also to predict rock properties based on wire-line logs (i.e., inversion).
- All of these methods are routinely used in oil and gas exploration & development programs.
- Low S/N data can inhibit successful implementation of inversion and many seismic attributes.
- Knowing the limitations of your data is an important step. However, we will show that potential exists for advanced seismic analysis in the CTD-hardrock setting if abundant down-hole logs are present.
Hardrock Seismic

• Challenges
  - Structural complexity
  - Crystalline environment
  - Heterogeneous regolith
  - Ground relief
  - High ambient noise

• Benefits
  - Depth
  - Resolution
  - Images low-angle geometries e.g. thrusts
  - Results can image the subsurface better than fences of drilling

• Mining industry has been reluctant to use the seismic method due to these challenges (that are not an issue in petroliferous basins).
  • Benefits outweigh challenges.
• Necessary tool since shallow mineral reserves are being depleted.
• Better resolution at depth compared to traditional geophysics mining methods.
Seismic in Mining

- Previous seismic data for mining exploration is largely collected in the Proterozoic setting
  - No carbonates
  - No extant porosity
  - No direct analogies to petroleum industry

(Harrison and Urosevic, 2012)

- Previous studies largely focus on VMS deposits and Au-bearing reefs.
- In hardrock seismic the overall elastic properties of rocks is controlled by mineralogy whereas in oil and gas the properties of sedimentary rocks are primarily controlled by porosity, the minerals themselves are of secondary importance
  - <1% porosity in metamorphic/greenstone rock.
  - CTD seismic response is controlled by porosity.
Seismic in Carlin Type Deposits

paleo-stratigraphic setting: carbonate platform-slope

http://www.beg.utexas.edu/Imod/JOL-C013/cm03-stepC1.htm
Several to 100's of miles

(Cook and Corboy, 2004)

(Jansen et al., 2011)
Both petroleum and CTD exploration attempt to better understand diagenetic environments and overprinting geologic processes that increase porosity and permeability of the carbonate host rock.

Harry Cook has done much work on defining the paleo-stratigraphic framework of Nevada and discusses stratigraphic traps in detail (Cook and Corboy, 2004).

- Exploration targets include 3rd order lowstands (sea level regressions) that produce large-scale debris flows in the slope setting and subaerial exposure with associated karsting in the platform setting.

- These are also exploration targets in oil and gas industry so these features are fairly well understood in terms of seismic signatures.

- There is a significant deformational overprint on the Paleozoic platform-slope environment Nevada so were are still considered to be within the realm of hardrock seismic due to this increased structural complexity along with multiple episodes of plutonism/volcanism in the Tertiary.

  - Eocene magmatism and dikes cuts carbonate units in places
  - Northern Nevada Rift produced seismically attenuative basalts

- Regardless, the CTD setting is very different from previous hardrock seismic locations, even if the original platform-slope geometry is highly deformed, we still have a unique opportunity to adopt oil and gas methodologies because: 1) CTD are young and porosity still exists, and 2) they are hosted in carbonates

  - Brecciation should still have a similar appearance to the debris flow seismic facies as defined by Jansen et al., 2011.
In-house Petrophysics

- Decarbonatization = decreased seismic parameters and increased porosity.
- Sample bias in drill-core petrophysics towards less altered rock.

Acoustic Impedance vs. Porosity
(Limestone Host Subset)

- Acoustic impedance vs porosity crossplot allows separation of two trends: primary and secondary porosity. The black trend corresponds to no decarbonitization (i.e., unaltered rock) whereas the red lines show strongly decarbonitized rock.
  - The red line represents secondary porosity whereas the black line represents unaltered porosity
- Petrophysics tells us that inversion may work.
- Down-hole data suggests that the separation between these trends is far greater. This is due to a sample bias in the drill-core towards less altered samples; we cannot sample the most heavily altered rock via drill-core.
This (in conjunction with drill-core data) has significant implications for the feasibility of inversion and rock property prediction, which is why we decided to move beyond simple attribute analysis.
**Pseudo down-hole log**

- Drill core sampled at high resolution
- Cannot sample heavily altered rock
- Stresses importance of down-hole logging

- I sampled drill core last summer to try and replicate down-hole logs.
  - Goal was 10 ft. sample spacing.
  - Arrows point to sparsely sampled zones that correspond to heavy decarbonitization.
  - If this were a down-hole log we could have sampled these zones in-situ.
- This case study will focus on definition of the decarbonatized zone, which utilized physically significant attributes and AVO analysis (as opposed to geometrically significant attributes, which are used for structure).
- 2D line over an unnamed deposit, covered by 1500 ft. of Tertiary volcanics/gravels
- Ore-zone is defined by decarbonitization for the purposes of seismic analysis since we are interested in the associated porosity increase
  - gold assay on the left side of the drill track and decal on the right side of the drill track.
- Decarbonitized zone is within seismic resolution since the thickness of alteration is greater than a seismic wavelength.
We can derive a secondary quantity from a magnetic dataset such as: total horizontal derivative, tilt derivative, analytic signal, etc. Similarly, we can derive many different secondary quantities from seismic data, which are called seismic attributes.

There are many seismic attributes that are used to delineate structures (e.g., coherency), which are called geometric attributes. For the purposes of this study, we want to look at rock properties so we were interested in attributes thought to respond to changes in acoustic or elastic properties, which are termed physical attributes.
- All the attributes shown in the previous slide were calculated from post stack data. After my brief introduction to pre-stack data, my goal is that you will understand how much information is lost in the stacking process.
- Distance between the source and receiver controls the angle of incidence.
- Analyzing reflection coefficients at different angles of incidence can provide information about rock properties.
**Amplitude Versus Offset (AVO) Model**

- Far offset anomaly at base of decarbonatization

**Gradient plot for base of decarbonatization**

- Synthetic AVO model using P-wave and S-wave velocity from the VSP hole and Gardner's empirical density calculation.
- Convolved with a statistical wavelet extracted from the PSDM
- Red line on pre-stack data shows location of gradient cross-plot
- Convolution with a higher resolution wavelet produces effects within ore-zone.
Now we look for the far offset anomaly in the surface seismic common image gathers (CIG).
Far offset anomaly at the base of the ore zone and, to a much lesser extent, within the ore zone.
- Variable, but interesting.
- Indicative of changes in Poisson's ratio associated with ore-zone (or base of ore-zone?).
- AVO effects are very complex in CTD setting since fracture/breccia orientation plays a critical role in response
  - yet another argument for more down-hole logs
Inversion

- Pre-stack inversion using **ONE** down-hole log

- Full pre-stack inversion (aka elastic inversion) using Hampson-Russell software (HRS9)
- I show density since the units are more relatable/intuitive than velocity or acoustic impedance
- These are promising results considering we only used one VSP hole
  - Note the reduction of density in the eastern portion of the ore-zone
- Results warrant further studies in CTD setting using more downhole logs
  - Typical oil and gas exploration program would use 10+ wells for inversion in a small 3D dataset for reservoir characterization
- Inversion should be performed on a case-by-case basis; the carbonate section must be imaged appropriately.
Learnings from this research

- Decarbonatization can produce seismic reflections.

- Seismic attributes from CTDs can reveal alteration features.

- Inversion shows promise, even with only one down-hole log in the case study.
Recommendations

- More down-hole geophysical logs are required to gain all the benefits of seismic data.

- With abundant down-hole logs, more accurate inversion may enhance geological parameters from seismic and better refine drill targets.
References & Acknowledgements

- I would like to extend my gratitude to Barrick Gold Exploration Inc. for sponsoring this research and my graduate studies.

- REFERENCES:
Geophysical inversion from exploration to resource evaluation

Cericia Martinez
Jiajia Sun
Yaoguo Li

Center for Gravity, Electrical & Magnetic Studies (CGEM)

Department of Geophysics - Colorado School of Mines

Great Basin and Western Cordillera Mining Geophysics Symposium
November 2013
Abstract

Geophysical Inversion from Exploration to Resource Evaluation

Cericia Martinez, Jiajia Sun, and Yaoguo Li
Center for Gravity, Electrical, and Magnetic Studies Colorado School of Mines, Golden, CO

The past few decades have seen tremendous progress in the geophysical inversion. Applied 3D inversion of geophysical data is becoming a common practice in the mineral industry thanks to instrumentation and algorithmic advances. The ability to incorporate geologic and petrophysical information into geophysical inversion is likewise developing. Upon producing a reasonable 3D physical property model, the next logical step is to identify not only geologic structure, but also lithologic boundaries and alteration zones that are directly related to mineralization. The current state of geophysical inversion and utilization of the resulting models for understanding and characterizing geology is now at the forefront of research efforts.

From these endeavors, geophysical interpretation is no longer limited to exploration. Lithology and geology delineations based on geophysical models readily translate into added value and information for deposit feasibility studies and resource evaluation stages. The challenge for tomorrow’s geoscientist is the incorporation of such interpretations from geophysical observations into the evaluation of a mineral resource. In this presentation, we discuss the challenges facing integration and utilization of geophysical interpretations in resource evaluation and feasibility studies. Through an iron ore and a disseminated sulfide field example, we illustrate the potential that geophysical models hold in contributing to resource evaluation.
Outline

- Exploration geophysics vs. resource evaluation
- Resource Estimation
- Potential role of geophysical inversion
- Integration methods
Exploration Geophysics

- **Detection**
  - Suitable physical property contrast
  - Identify associated optimal techniques

- **Delineation**
  - Structure controls
    - Potential field maps (faulting, lineaments, etc.)
    - Reflection seismic or borehole techniques (bedding, faults, etc.)
  - Physical property changes
    - Wireline logging
    - 3D inversion
    - Seismic attributes
Resource Evaluation

- **Quality & Quantity**
  - Geologic character
    - Mineralization zone
    - Alteration zone
  - Volume estimates
  - Metal concentration

- **Distribution**
  - Structural and orientation information
  - Spatial continuity
Resource Evaluation

• Quality & Quantity
  – Geologic character
    – Mineralization zone
    – Alteration zone
  – Volume estimates
  – Metal concentration

• Distribution
  – Structural and orientation information
  – Spatial continuity

Exploration stage begins to identify these characteristics
Geophysical Inversion

- Joint inversion of $v_p/v_s$ with known petrophysical relation
  - Ability to model and invert for more complex phenomena
- Improved quality and reliability of geophysical models
Resource Evaluation

• Quality & Quantity
  – Geologic character
    – Mineralization zone
    – Alteration zone
  – Volume estimates
  – Metal concentration

• Distribution
  – Structural and orientation information
  – Spatial continuity

Challenge: Geophysical survey design and inversion focus on detection and delineation
Resource Evaluation

- Wireline logging
  - Resistivity
  - Conductivity
  - Gamma ray
  - Neutron-gamma
  - Sonic
  - Density

- Cross-hole
  - Radar and radio imaging
  - Seismic tomography

(Cochrane et al., 1998; McGaughey and Vallee, 1998; Davis et al., 2001; Mutton, 2000)
Resource Classification

- Factors contributing to economic resource evaluation
  - Social considerations
  - Political climate
  - Environmental implications
  - Geologic evidence
  - Mining costs
  - Etc.
Guidelines for classification

“A resource is an in situ (i.e., on surface or underground) mineral occurrence quantified on the basis of geologic data and a geologic cutoff grade only.”

-Sinclair and Blackwell (2002)

From Sinclair and Blackwell (2002)
Resource Estimation

• **Grade-tonnage curves**
  – Estimates of grade distribution

• **Model for resource estimation**
  – Based only on direct measures of grade
  – Product of intense drilling and sampling program
  – Legal concerns compel drilling confirmation

**Challenge:** Legality of ancillary information included in reserve estimation
Resource Assessment

• Indirect measure or proxy for grade
  – Quantitative description of resource quality

• Resource quality
  – Physical properties
  – Geologic or lithologic characteristics

• Geophysical Inversion
  – Continuous spatial information
Geophysical Inversion

• Current practice: Invert single geophysical data set

• Iterative or cooperative G&G modeling
  – Incorporation of geological constraints into geophysical inversion
  – Qualitative observations of recovered model incorporated into deposit model via geologist
  – Verify adjusted model agrees with both geophysical and geological information

• Quantitative geophysical information may be lost if physical property models are not carried through the deposit modeling process
Geophysical Inversion

- Inversion of multiple geophysical data
  - Potential for lithologic characterizations

- Joint inversion of multiple geophysical data with petrophysical constraints
  - Potential for geology differentiation
  - Utilize known geologic and petrophysical constraints
Geophysical Inversion

• Inversion of multiple geophysical data
  – Potential for lithologic characterization

• Joint inversion of multiple geophysical data with petrophysical constraints
  – Potential for geology differentiation
  – Utilize known geologic and petrophysical constraints

Challenge: Validation/link of true petrophysical properties and recovered models
Physical Property Considerations

- IP inversion from NEWDAS

![Measurements of chargeability over time](image_url)
Mining Symmetries

- **Goal:** Estimation of spatial grade distribution
  - Mine it or leave it?

- **SMU:** Selective Mining Unit
  - Volume of rock classified as ore or waste for mining purposes

- Geophysical models tend to represent discrete volumes

**Challenge:** Integration of inversion into mining workflow
Resource Assessment

- Bulk volume estimates
- Cokriging
  - Block
  - Indicator
- Conditional simulation
Resource Estimation

- **Local Estimation**
  - Could be 10s of meter
  - Resolution requirements depend on geophysical survey design

- **Global Estimation**
  - Geophysical models are estimates of bulk physical property distribution
  - Use 3D physical property, lithologic, or geologic models as supplementary information
Quantitative Integration

• **Kriging**
  – Rely on assay data
  – Estimation of grade
    – Spatial dependence of samples

• **Cokriging**
  – Rely on assay data & secondary variable
  – Estimation of grade
    • Spatial dependence of samples, secondary, and inter-spatial dependencies

• **Provide variance estimates**
Cokriging

• Estimation of a single variable
  – Utilization of additional spatial variable(s)
  – Estimation in 2D or 3D

• Strong spatial relationship
  – Cokriging introduces cross-spatial dependence

• Need covariance structure
  – Use cross-variogram

• Significant modeling efforts for semi- and cross-variograms
Synthetic Example

Zn Samples

$\Delta \rho$ from inversion of GG

Zn Kriging Estimates

Zn Cokriging Estimates

True Zn
Summary

• **Bridge the gap**
  – Link true physical properties to those recovered from geophysical inversion
  – Methods for direct incorporation of 3D geophysical models in geologic and mining workflows

• **Case histories**
  – Focus is on successful detection, delineation, or imaging
  – Few discuss quantitative integration for resource assessment

• **Guidelines and common practices**
  – Geophysical survey design focuses on detection, not resource evaluation
  – Legal definitions (will domino once the above is )
Acknowledgements

- Gravity and Magnetics Research Consortium (GMRC) funding support
- Richard Krahenbuhl and Murray Hitzman for providing Beltana geologic model and helpful discussion!
2013 GMRC Sponsors
Gramian constraints in the joint inversion of airborne gravity gradiometry and magnetic data

Yue Zhu$^1$, Alex Gribenko$^{1,2}$, Martin Cuma$^{1,2}$, Masashi Endo$^2$, and Michael S. Zhdanov$^{1,2}$

1 - Consortium for Electromagnetic Modeling and Inversion, University of Utah
2 - TechnolImaging

11/10/2013
Outline

• Introduction
• Principles of joint inversion using Gramian constraints
• Model study: joint inversion of synthetic gravity gradiometry and magnetic data
  • Model 1: linear relationship between the density and susceptibility
  • Model 2: quadratic relationship between the density and susceptibility
• Case study in the area of the McFaulds Lake, Ontario
• Conclusions
Introduction

- Efforts have been continuously made to jointly invert different physical properties (Jegen et al., 2009; Moorkamp et al., 2011)
- Several techniques used before include direct coupling and cross-gradient approaches
- Zhdanov et al. (2012) introduced a new approach to joint inversion using Gramian constraints
- Gramian constraints represent generalization of the previous joint inversion approaches

In the paper by Zhdanov et al. (2012), the authors introduced a new approach to joint inversion of geophysical data using Gramian constraints, which are based on the minimization of the determinant of a Gram matrix of a system of different model parameters or their attributes (i.e., a Gramian). This approach does not require an a priori knowledge about the types of relationships between the different model parameters, but instead determines the form of these relationships in the process of the inversion.
... Introduction

- We implemented Gramian constraints in our joint inversion algorithm
- In the synthetic model studies, we consider both the linear and nonlinear relationships between different physical properties
- The case study includes joint inversion of the airborne gravity gradiometer (AGG) and magnetic data collected by Fugro Airborne Surveys in the McFaulds Lake area in northern Ontario
- EMVision® was used for the joint inversion of airborne gravity gradiometry (AGG) and magnetic data

In this paper we apply Gramian constraints for joint inversion of airborne gravity gradiometry and magnetic data. Note that, the Gramian constraints make it possible to consider both linear and nonlinear relationships between the different physical parameters of a geological model. We illustrate this fact by allowing for a quadratic relationship between density and susceptibility. The model study shows that if there is a nonlinear dependence between the model parameters, it can be defined by joint inversion with Gramian constraints. The case study includes joint inversion of the airborne gravity gradiometer (AGG) and magnetic data collected by Fugro Airborne Surveys in the area of McFaulds Lake located in northwestern Ontario approximately 50 km east of the town of Webequie (Balch et al., 2010). This project was collaboratively operated between the Ontario Geological Survey (OGS) and the Geological Survey of Canada (GSC).
• TechnolImaging's advanced software package; based on proprietary technical solutions and can be used for modeling, imaging, and inversion of different geophysical survey data, including airborne, marine, land, and borehole data:
  — 3D forward modeling based on the integral equation (IE) method with multiple inhomogeneous domains ensures high stability and accuracy of the results
  — The moving sensitivity domain approach provides unique capability of 3D inversion of the large-scale geophysical surveys to models with the fine-grid discretization
  — The joint 3D inversion with Gramian constraint delivers an integrated geophysical model based on multimodal geophysical data
  — 3D inversion with focusing regularization provides images of the geological targets with sharp and focused boundaries
  — Parallelized and optimized for the in-house powerful TechnolImaging's PC cluster
Principles of joint inversion using Gramian constraints
Parametric functional incorporating Gramian constraints

\[ p^\alpha(\tilde{m}^{(1)}, \tilde{m}^{(2)}, \ldots, \tilde{m}^{(n-1)}, \tilde{m}^{(n)}) = \sum_{i=1}^{n} \left\| A^{(i)} (\bar{m}^{(i)} - \bar{d}^{(i)}) \right\|_D^2 + \alpha c_1 \sum_{i=1}^{n} S_{MN,MS,MGS}^{(i)} + \alpha c_2 G(\tilde{m}^{(1)}, \tilde{m}^{(2)}, \ldots, \tilde{m}^{(n-1)}, \tilde{m}^{(n)}) \]

where the Gramian constraint is the determinant of an N by N matrix as follows

\[ G(\tilde{m}^{(1)}, \tilde{m}^{(2)}, \ldots, \tilde{m}^{(n-1)}, \tilde{m}^{(n)}) = \begin{vmatrix}
(\tilde{m}^{(1)}, \tilde{m}^{(1)}) & \cdots & (\tilde{m}^{(1)}, \tilde{m}^{(n)}) \\
\vdots & \ddots & \vdots \\
(\tilde{m}^{(n)}, \tilde{m}^{(1)}) & \cdots & (\tilde{m}^{(n)}, \tilde{m}^{(n)})
\end{vmatrix} \]

For a regularized solution of the inverse problem, we introduce a parametric functional with the Gramian stabilizers, where \(A^{(i)}\) are the weighted predicted data, \(d^{(i)}\) are different observed data sets (which may have different physical natures and/or parameters), and \(m^{(i)}\) are the unknown sets of model parameters. \(\alpha\) is the regularization parameter, and \(c_1\) and \(c_2\) are the weighting coefficients determining the weights of the different stabilizers in the parametric functional. The terms \(S_{MN}\), \(S_{MS}\) and \(S_{MGS}\) are the stabilizing functionals, based on minimum norm, minimum support, and minimum gradient support constraints, respectively. The Gramian of a system of model parameters \(m^{(i)}\) is introduced as a determinant, of the Gram matrix of a set of functions \(m^{(i)}\). It is shown in Zhdanov et al., (2012) that the Gramian provides a measure of correlation between the different model parameters or their attributes. By imposing the additional requirement of the minimum of the Gramian in regularized inversion, we obtain multimodal inverse solutions with enhanced correlations between the different model parameters or their attributes.
Three types of Gramian constraints

- Element \((i,j)\) in the \(N\) by \(N\) matrix

\[
\begin{align*}
(\tilde{m}^{(i)}, \tilde{m}^{(j)}) & \quad (\nabla \tilde{m}^{(i)}, \nabla \tilde{m}^{(j)}) & \quad (T(\tilde{m}^{(i)}), T(\tilde{m}^{(j)})) \\
G(\tilde{m}^{(1)}, \ldots, \tilde{m}^{(n)}) & \quad G_{\nabla}(\tilde{m}^{(1)}, \ldots, \tilde{m}^{(n)}) & \quad G_{T}(\tilde{m}^{(1)}, \ldots, \tilde{m}^{(n)})
\end{align*}
\]

Most generalized type!

The first type of Gramian, provides a measure of correlation between model parameters, and favors solutions with direct correlation of different physical properties. In many applications, it is necessary to invert jointly the data, which are produced by unrelated physical phenomena. In this case, one cannot use any correlation between different model parameters, but instead should consider a possibility of some structural (geometrical) similarities between the different physical models. This is realized by second type of Gramian based on introduction of the Gramian space of model parameter gradients. The third type of Gramian constraint makes it possible to consider different properties (attributes) of the model parameters in the fusion of multimodal inversions. We can use, for example, second derivatives of the model parameters, absolute values of the gradients and/or second derivatives of the model parameters, any other transforms of the model parameters including non-linear relationships of model parameters.
Nonlinear relationship

- Consider a polynomial relationship between the density and susceptibility

\[ \chi = c_0 \Delta \rho + c_1 \Delta \rho^2 + \cdots + c_{n-1} \Delta \rho^n \]

\((i+1)^{th}\) order contains \(i^{th}\) order, with \(c_i = 0\)

- The Gramian constraint \( G(\tilde{m}^{(1)}, \ldots, \tilde{m}^{(n)}) \) with these model parameters:

\[
m^{(1)} = \Delta \rho, \ m^{(2)} = \Delta \rho^2, \ldots, \ m^{(n)} = \Delta \rho^n, \ m^{(n+1)} = \chi
\]

Auxiliary model parameters

The Gramian could be used to enhance the nonlinear relationships between different model parameters as well. For example, in a case of joint inversion of the gravity and magnetic data, we consider two different model parameters: anomalous density, and magnetic susceptibility. In this case, the minimization of the Gramian will result in enforcing the polynomial relationship between magnetic susceptibility and anomalous density. It is important to note that we do not need to know the specific values of the coefficients \(c_i\) of this relationship in order to apply the joint inversion.
Incorporation of Gramian constraint (stabilizer) in the inversion algorithm

- Consider the conjugate gradient method
- Modify the gradient direction of the parametric functional by adding steepest ascent direction of the Gramian stabilizer to the gradient direction of the misfit and standard stabilizer(s).

The solution of the minimization problem for the parametric functional with the Gramian stabilizers can be achieved by using the re-weighted conjugate gradient method, as discussed in Zhdanov et al., (2012).
Model study
Model 1: forward modeling parameters

- Linear relationship (first order polynomial)
  \[ \chi = 0.42\Delta\rho \]

- \( g_x, g_y, g_z, g_{xx}, g_{yy} \) and TMI data are computed and used as observed data in the inversion

An airborne gravity and magnetic survey was first simulated for a synthetic model with a linear relationship between the density and susceptibility. Vertical and horizontal cross sections of this model are shown. The anomalous body extends from -250 m to 250 m in both X and Y directions, and from the surface to 200 m in the Z direction. This body is divided into four parts along the vertical direction. The deeper part has a higher density and susceptibility. This is used to simulate the situation in the real earth: as the depth increases, the strata become more compact. Five components of the gravity field with four gravity gradient components and total magnetic intensity (TMI) data were simulated and used as the observed data in the inversion.
Model 1: joint inversion parameters

- Gramian constraint $G(\tilde{m}^{(1)}, \tilde{m}^{(2)})$
w ith $\tilde{m}^{(1)} = \Delta \rho$, $\tilde{m}^{(2)} = \chi$

- Inversion domain:
  
  $[-500, 500]$ by $[-500, 500]$ by $[0, 700]$ m$^3$ in x-, y-, z-axis

- Inversion cell size:
  
  50m by 50m by 50m

- Total cell number: 5, 600

- Inversion done in log space

- Alpha relaxation coefficient: 0.7

- Terminated at 50 iterations

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The inversion parameters are summarized. We ran the smooth inversion only with the minimum norm stabilizer. Convergence plots showing how the normalized misfit decreased with the number of iterations are also shown. After 50 iterations, the joint inversion reached a similar (or even lower) error floor compared to the separate inversions.
Model 1: joint inversion result

- Separate inversions are done with similar inversion parameters except Gramian constraint

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We present the final predicted models obtained by joint (top panels) and independent (bottom panels) inversions. The same five components were used as the observed data in the independent inversions. The joint and independent inversions shared almost the same inversion parameters. Compared to the independent inversion results, the joint inversion with the Gramian constraint produced a more compact density distribution in the predicted model.
Model 1: comparison of joint and separate inversions

- Cross plots of the density and susceptibility
- Each dot represents one inversion cell
- Joint inversion recovered the linear relationship

The cross plots of density and susceptibility recovered by independent (left) and joint (right) inversions. The advantage of the joint inversion is clear, it successfully recovered the linear relationship between the two model properties.
Model 2: forward modeling parameters

- Quadratic relationship (second order polynomial)
  \[ \chi = 0.13\Delta \rho^2 + 0.26\Delta \rho \]
- Anomalous domain, receiver positions are the same as the previous model
- \( g_z \), \( g_{zz} \), \( g_{xx} \), \( g_{yy} \), and TMI data are computed and used as the observed data for the inversion

The second model is almost the same as the previous one, except that there is a quadratic relationship between the density and susceptibility. Figure shows vertical cross sections of this synthetic model. The previous and current models have the same density distribution, while only the susceptibility is different. Same synthetic data components were computed.
Model 2: joint inversion parameters

- **Gramian constraint** $G(\tilde{m}^{(1)}, \tilde{m}^{(2)}, \tilde{m}^{(3)})$
  with $\tilde{m}^{(1)} = \Delta \rho$, $\tilde{m}^{(2)} = \Delta \rho^2$, $\tilde{m}^{(3)} = \chi$

- **Inversion domain, cell size, alpha relaxation coefficient are the same as the previous inversion**

- **Inversion also done in log space**

- **Terminated after 50 iterations**

---

Same inversion parameters are used as in the previous inversion. The convergence plots showing the normalized misfit behavior are shown in the figure. After 50 iterations, the joint inversion reaches a similar error floor compared to the separate inversions.
Model 2: joint inversion result

- Separate inversions are done with similar inversion parameters except Gramian constraint

The final predicted density and susceptibility is shown in the figures. As in the previous synthetic model study, the joint inversion helps get a more compact density distribution of the predicted model.
Model 2: comparison of joint and separate inversions

- Cross plots of the density and susceptibility
- Each dot represents one inversion cell
- The joint inversion recovered this quadratic relationship between the two model parameters

The cross plots reveal the advantage of using the Gramian constraint in the joint inversion again. The joint inversion recovers the quadratic relationship between density and susceptibility, which agrees very well with the synthetic curve.
Case study in the area of the McFaulds Lake, Ontario
Regional geology

- McFaulds Lake is located in northwest Ontario. It is the host to the “Ring of Fire”, which is a north-south trending Archean green belt.
- Now it is known to host deposits, including magmatic Ni-Cu-PGE, magmatic chromite mineralization, volcanic massive sulfide mineralization and diamonds hosted by kimberlite.

McFaulds Lake is located in northwestern Ontario approximately 50 km east of the town of Webequie. McFaulds Lake is the host to the “Ring of fire,” which is a roughly north-south trending Archean green belt (Figure 13). This westward-concave belt sits on the west edge of the James Bay Lowland in far northwestern Ontario. Currently, the Ring of Fire becomes home to major mining explorations. Various economic mineral deposit types are known to exist in this area, including: magmatic Ni-Cu-PGE, magmatic chromite mineralization, volcanic massive sulfide mineralization and diamonds hosted by kimberlite. The Ring of Fire is composed of mafic metavolcanic flows, felsic metavolcanic flows and pyroclastic rocks and a suit of layered mafic to ultramafic intrusions that trend subparallel with and obliquely cut the westernmost part of the belt, close to a large granitoid batholith lying west of the belt. The major layered intrusion at its base, hosts Ni-Cu-PGE deposits of exceptional grade as well as overlying stratiform chromite deposits further east and higher in the layered intrusion stratigraphy (Ontario Geological Survey and Geological Survey of Canada, 2011).
Airborne gravity gradiometry and magnetic survey

SURVEY AREA

Line km: 19,733
Line spacing: 250m
Flight height: 100m
Area: 4,577 sq. km
AGG: Falcon
Mag.: single sensor

* This slide is taken from Desmond Rainsford, 2011, Ontario geological survey.

In order to map regional geology and locate potential mineral resources in Northern Ontario, the airborne geophysical survey was carried out in the McFaulds Lake region between 2010 and 2011. Both airborne gravity gradiometer (AGG) and magnetic data were collected. This project was collaboratively operated between the Ontario Geological Survey (OGS) and the Geological Survey of Canada (GSC). Figure shows the McFaulds Lake region survey block, which was flown over with the Fugro Airborne Surveys gravity gradiometer and magnetic system. Survey parameters are also shown.
As a preliminary study, we focused on a subset of the AGG and magnetic data covering the known chromite mineral. The chromite is hosted by a large ultramafic to mafic layered intrusion in this area. There are four major mineral deposits here: Big Daddy, Black Creek, Black Thor and Black Label. The Big Daddy chromite deposit is the southwest extension of the Black Thor and Black Creek deposits. Vertical gravity component and three gravity gradient components along with TMI were used in the inversion.
Joint inversion parameters

- **Gramian constraint:** \( G(\tilde{m}^{(1)}, \tilde{m}^{(2)}, \tilde{m}^{(3)}) \)
  \[ \tilde{m}^{(1)} = \Delta \rho, \quad \tilde{m}^{(2)} = \Delta \rho^2, \quad \tilde{m}^{(3)} = \chi \]

- **Inversion domain size:**
  9km x 10km x 2km, in x-, y-, z-axis

- **Inversion cell size:**
  100m x 100m x 50m in x-, y-, z-axis

- **Total cell number:** 360,000

- **Ratio of smooth to Gramian stabilizer:** 1:100

- **Inversion terminated at the 100th iteration**

In the previous synthetic studies, we found that the joint inversion algorithm with quadratic Gramian constraint is capable of recovering both the linear and quadratic relationships between the anomalous density and susceptibility. Some of the inversion parameters are listed. The inversion was terminated after 100 iterations because the normalized misfit curve flattened and little decrease in the misfit would be obtained if the inversion continued. Figures show convergence of the normalized gravity and magnetic data misfits.
Vertical sections of the predicted anomalous density and magnetic susceptibility. Location of the E-W profile is shown on the geologic map (top right). Black line indicates the location of the known thin chromite belt. Inverted results show that the recovered anomalous density and susceptibility are not fully correlated. High density anomaly is more eastward to the chromite belt, while high magnetic susceptibility is more westward. We can find this trend more clearly from the horizontal sections in the next slide.
Joint inversion result: horizontal slices

- Density/susceptibility distribution at a depth of 100 m
- Chromite belt separates two types of rocks: to its east the rock is more dense and non-magnetic; to its west the rock is light but magnetic

Joint inversion enforces the correlation between density and susceptibility in the areas where it exists, while preserving the correct physical properties of different types of rocks

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Horizontal sections of anomalous density (top left) and susceptibility (bottom right). Area circled by black line is the known chromite belt. (Animation by two clicks) We can zoom in the area around Big Daddy deposit. High density anomaly is more SE to the Big Daddy while high magnetic anomaly is more NW. This agrees with local geology that rocks NW of the chromite belt are more ultramafic, whereas the rocks to the SE tend to be more mafic.
Comparison of the E-W anomalous density profile (top):
The inversion parameters were almost the same for the independent inversions as for the joint inversions, except for Gramian constraint. The joint inversion reached a similar error floor as the separate inversions after 100 iterations. The joint inversion recovered a more compact anomalous density distribution compared to the independent gravity inversion. This was due to the Gramian constraint used in the joint inversion, which creates a strong correlation between the anomalous density and susceptibility.

Comparison of the E-W susceptibility profile (bottom):
The predicted susceptibilities are similar in the joint and independent magnetic inversions. Unlike the model study, in this case study, the anomalous density and magnetic susceptibility are not fully correlated. So cross plot was not provided here.
Conclusions

- By using Gramian constraints, we are able to invert jointly multi-modal geophysical data by enforcing correlation between different model parameters.
- Compared to separate inversions, more meaningful relationship is revealed in the cross plots by the joint inversion, which brings more lithological/geological information.
- Both linear and nonlinear relationships were tested in the synthetic model studies; the joint inversion with Gramian constraint did a good job.
- For the case study, the inverted density and susceptibility in the subset around Big Daddy and other deposits showed good match with the known local geology.

The interpretation of geology from geophysical data represents a data fusion problem, as different geophysical fields provide information about different physical properties of the earth. In many cases, the various geophysical data are complementary and self-constraining, making it natural to consider their joint inversion based on the correlation between different physical properties of the rocks. By using Gramian constraints, we are able to invert jointly multimodal geophysical data by enforcing the correlations between different model parameters. Importantly, the method assumes that a correlation between the different model parameters or their attributes exists, but the specific forms are unknown. In addition, the Gramian could be used to enhance the nonlinear relationships between different model parameters as well. Our case study for joint inversion of gravity gradiometry and magnetic data from Ni-Cu-PGE deposit from McFaulds Lake, Northern Ontario, demonstrates how the joint inversion may enhance the produced subsurface images of a deposit.
Acknowledgement

- The authors acknowledge support from the University of Utah's Consortium for Electromagnetic Modeling and Inversion (CEMI)
- The authors also acknowledge TechnoImaging for support of this research and permission to publish
- The authors thank Dr. Desmond Rainsford from the Ontario Geological Survey (OGS) and the Geological Survey of Canada (GSC) for providing information and assistance with the case study
Magnetization Vector Inversion

Robert Ellis and Taronish Pithawala*

Geosoft Inc.

Great Basin and Western Cordillera Mining Geophysics Symposium
November 23, 2013
Abstract

Magnetization Vector Inversion

Robert Ellis and Taronish Pithawala, Geosoft Inc.

3D gravity and magnetic voxel inversion software has been available for a number of years, but with recent advances in algorithms and the ability to harness the available computing power of the cloud, the time taken to run even quite complex inversions has reduced dramatically. This has allowed inversion to be done quickly and easily at earlier stages of the exploration cycle.

All potential field inversion is inherently non-unique, and much research has gone into ways to improve inversion results by allowing additional geological or geophysical information to be integrated into the process. There are still significant challenges with inversion of potential field data, and this presentation reports on recent progress in the key areas of handling remanent and other magnetization problems in the inversion process.

Magnetization Vector Inversion (MVI) is a method to incorporate induced and remanent magnetization without prior knowledge of the magnitude or direction of the remanent field. MVI inverts directly for the magnetization vector rather than susceptibility, giving a more realistic interpretation tool that honours the true source of the magnetic response. Data from the Osborne mine in Queensland Australia are used to illustrate the method.
Overview

- Introduction
- Why do we need a new inversion for magnetic data?
- Magnetization Vector Inversion
- Case study: Osborne Deposit
- Case Study: Quadrilátero Ferrifero
Introduction

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. The earth model must conform with other project information, in particular, geology and drilling.

3D gravity and magnetic voxel inversion software has been available for a number of years.

With recent advances in algorithms and the ability to harness the available computing power of the cloud, the time taken to run even quite complex inversions has reduced dramatically.

This has allowed inversion to be done quickly and easily at earlier stages of the exploration cycle.
Why do we need to consider an extension to conventional susceptibility inversion for magnetic field data interpretation?

1. A significant percentage of magnetic inversions yield geologically inconsistent models.

2. Conventional inversion ignores:
   1. Self-demagnetisation,
   2. Anisotropy of susceptibility,
   3. Koenigsberger ratios, all effects related to remanence,
   4. Local field perturbations from intense anomalies.

3. Research is suggesting the widespread importance of remanence in magnetic response on regional scales, in addition to usual the expectations at the deposit scale.

Continuing with our theme of effective and efficient exploration, we now turn to an improvement to the inversion of magnetic field data. We need to improve the existing magnetic methods because they are based on susceptibility inversion whereas the Earth’s magnetic response is due to complex rock structures and materials which cannot be simply described in terms of susceptibility. For example, conventional susceptibility fails to account for demagnetization, anisotropy, and most importantly, any effects related to magnetic remanence. Remanence is known to be important in mineral exploration however recent research indicates that remanence is also important in the magnetic response at regional scales.

Research by David Clark, Clive Foss among others at CSIRO and a recent paper by Sue McEnroe and others have shown the more widespread effects of magnetization issues.
Let us consider a volume of rock with magnetization $M$, buried in the Earth. The rock magnetization can thought of as a collection of oriented magnetic dipoles, as shown in the upper image. Maxwell’s equations show that the magnetic response $B$ is computed from the magnetization $M$ via the equation on this slide. Consequently the natural parameter for magnetic field inversion is the magnetization $M$ and not the susceptibility as is often assumed.
The Magnetic Field Inverse Problem

In geophysical studies it is customary to consider the rock magnetization as having two sources:

1. Induced sources
2. Remanent sources

Conventional susceptibility inversion assumes:

\[ M = M_i + M_r \]

\[ M_r = 0 \]
\[ M_i \propto B_e \]

That is,

1. There is no remanent magnetization
2. The induced magnetization is in the same direction as the earth's field.

Both assumptions are often violated in practical exploration geophysics.
To understand the magnetization vector consider a simple model containing a cubic rock mass with a remanent magnetization component in the direction of the blue arrow and a vertically down Earth IGRF field. The combination of induced and remanent magnetization yields a total magnetization vector pointed in the easterly direction shown by the green arrows in the image on the left hand side of the slide. Using Maxwell’s equations to compute the TMI response gives the image shown on the right-hand side of the slide. This image represents synthetic geophysical data which we will now invert using MVI. The result of this process should be a vector magnetization model which is similar to the true model shown on the left.
Here we see the true magnetization rock model on the left and on the right the model recovered by MVI. We can see that the direction of the magnetization has been correctly recovered at the correct depth. This is a validation of the MVI concept and demonstrates that MVI provides robust results in the presence of remanence.

Extensive experience using MVI on field data and the analysis of the resulting vector models leads us to suggest that the most robust quantity to interpret from an MVI process is the amplitude of the magnetization vector. In the following slides we will only show the amplitude in any MVI results.
In this slide we compare MVI with conventional susceptibility inversion. We do this by taking a slice through the center of the model shown in the previous slide. Slicing through the true model we see the magnetic prism as a magenta square, while slicing through the MVI inversion result we see a target body located at the corrected depth, and finally we compared with susceptibility inversion which fails dramatically being completely corrupted by the presence of the remanent magnetization. This demonstrates that MVI is essential in any situation which has remnant magnetization, or for that matter, demagnetization, or magnetic anisotropy, etc. (As mentioned earlier we show the amplitude of the magnetization vector for MVI results.)

Again, MVI forms part of our overall theme of efficient and effective exploration: it provides significantly improved geophysical inversion and consequently interpretation, with little effort on the part of the Explorer.

Next we show MVI applied to a field data set from the Osborne mine in northern Queensland Australia.
Magnetization Vector Inversion Display

Vector magnetization models in 3D are difficult to interpret directly in all but the simplest cases. In real-world exploration we need some simpler derived scalars which highlight the important information in the vector model.

\[ \mathbf{M}_r \]

\[ \mathbf{M}_p \]

\[ \mathbf{E} = \text{Earth field direction} \]

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(</td>
<td>\mathbf{M}</td>
</tr>
<tr>
<td>(</td>
<td>\mathbf{M}_r</td>
</tr>
<tr>
<td>(</td>
<td>\mathbf{M}_p</td>
</tr>
</tbody>
</table>
Magnetization Vector Inversion Display

Simpler derived scalars which highlight the important information in the vector model.

Vector Model

MAmplitude

A

B

C

D

MPperpendicular to E

MPparallel to E
In this example we will demonstrate that MVI provides a better inversion result on which to base an interpretation than does susceptibility inversion. The Osborne mine is located in northwestern Queensland.

The coordinates are not what's important in this slide, instead, it is the general structure associated with the deposit and accompanying text. I would say most deposit models are defined in terms of local coordinate system like this one. Definitely check out the paper by Rutherford if you want more details about Osborne.
The history of the Osborne mine is well described elsewhere, see for example, Rutherford et al. 2005. Briefly, significant Cu-Au mineralization beneath 30-50 m of deeply weathered cover was confirmed in 1989. Intense drilling between 1990 and 1993 defined a total measured and indicated resource of 11.2 Mt at 3.51% Cu and 1.49 g/t Au. Exploration since 1995 has delineated high-grade primary mineralization dipping steeply East to some 1100 m vertical depth. As of 2001, total mined, un-mined and indicated resources are reported to be about 36 Mt and 1.1% Cu and 1 g/t Au (Tullemans et al. 2001). Current exploration is focused on mapping the high-grade mineralization to greater depths and mapping similar structures in the surrounding area. The geophysics includes total magnetic intensity (TMI) data over the property, which is shown in Figure 6. The TMI data were acquired in 1997 flown at 40 m clearance on 40 m line spacing.
The history of the Osborne mine is well described elsewhere, see for example, Rutherford et al. 2005. Briefly, significant Cu-Au mineralization beneath 30-50m of deeply weathered cover was confirmed in 1989. Intense drilling between 1990 and 1993 defined a total measured and indicated resource of 11.2 Mt at 3.51% Cu and 1.49 g/t Au. Exploration since 1995 has delineated high-grade primary mineralization dipping steeply East to some 1100 m vertical depth. As of 2001, total mined, un-mined and indicated resources are reported to be about 36 Mt and 1.1%Cu and 1 g/t Au (Tullemans et al. 2001). Current exploration is focused on mapping the high-grade mineralization to greater depths and mapping similar structures in the surrounding area. The geophysics includes total magnetic intensity (TMI) data over the property, which is shown in Figure 6. The TMI data were acquired in 1997 flown at 40m clearance on 40m line spacing.
Here we show the TMI data acquired over the Osborne deposit which will be the input to our MVI inversion. This is high quality data collected on a 40 m clearance with 40 m line spacing.
This slide shows a section through the MVI model. Of particular note is the clear indication of a easterly dipping magnetic structure. Superimposed on the MVI model is known mineralization based on extensive drilling. (As mentioned earlier we show the amplitude of the magnetization vector for MVI results.) To put this result in context, we next compare with conventional susceptibility inversion.
In this slide we compare magnetization vector inversion with conventional susceptibility inversion, in the left and right panels respectively. Notice that the conventional susceptibility inversion completely fails to support for the eastward dipping extension. We interpret this failure to indicate the presence of remanence, magnetic anisotropy, and or demagnetization effects, etc. in the Osborne ore zone. It is evident that the magnetization vector inversion produces a result much closer to the known mineralization than does the susceptibility inversion.
Quadrilátero Ferrífero

Example
The Quadrilátero Ferrífero, (Iron Ore Quadrilateral) in the state of Minas Gerais, Brazil, is the host to perhaps the largest commercial iron deposits in the world. A coloured surficial geology map of the area is shown in Figure 4 (Baltazar et al, 2005), on which the axis of the primary magnetic iron formations are shown and used to provide spatial reference in all figures.
This figure shows the TMI anomaly map and the analytic signal, with the magnetic unit axis shown as a white dashed line.

The Quadrilátero Ferrífero is an interesting subject for the study of magnetic interpretation for a number of reasons:

- The strength of magnetization;
- The relatively low latitude of the geomagnetic field (inclination -29°, declination -21°);
- The fact that the magnetized formations include sections oriented perpendicular to and roughly parallel to the current geomagnetic field, each of which interact very differently with the inducing magnetic field.

The TMI map clearly demonstrates the challenge of modelling rock properties when assuming magnetization only in the direction of the geomagnetic field. While the East-West feature in the Northwest part of the map has a strong negative anomaly, as would be expected at this latitude, the more Northerly-trending features on the East side of the map cannot be easily explained. In the experience of the authors, the magnetic patterns observed here are typical of Archean terrains in Brazil, with magnetic response from changes in topography interspersed with strong negatives and positives that can only be explained by introducing a rotated magnetization vector.

Magnetic anisotropy plays a significant role in the iron formations of the Quadrilátero Ferrífero, where the dominant rock magnetization is the consequence of induced magnetization, but the vector of magnetization in rock is rotated to align with the bedding of the iron formation (Rosière et al, 1998). We also note that the analytic signal does a very good job in identifying the surface location of the most magnetic rocks, particularly at such low magnetic latitudes (MacLeod et al, 1992).
Quadrilátero Ferrífero—Inversion results

Conventional Susceptibility
- Red: >0.05
- Blue: <0.05

MM Susceptibility
- Red: >0.10
- Pink: >0.02

10 km scale

Conventional susceptibility

MM
We have again used the Geosoft VOXI Earth Modelling system to invert the TMI anomaly data for both conventional susceptibility, which constrains the magnetization vector to the direction of the earth’s field, and using MVI susceptibility.

This figure shows a comparison of the susceptibility from two results at a plan elevation slice of 900m, which is just beneath the lowest topographic elevation of the area. Note the conventional susceptibility model requires significant negative susceptibilities to fit the data together with a predictable displacement of the positive susceptibility parts of the model. Notable is that even the East-West striking feature to the Northwest requires a strong negative susceptibility component. This is somewhat surprising given that our initial casual interpretation was that this anomaly appeared more “normal” for this latitude. The scalar MVI susceptibility more accurately follows the expected axis of magnetic rock and is also consistent with a simple interpretation of the analytic signal.

Quadrilátero Ferrífero
Mesh points 233 x 185 x 33 (1,422,465 cells)
Smallest voxel cell 250, 250, 125m (x, y, z)
Data points 28,730
IRI focussing 2 passes

Conventional susceptibility
CPU time 38 minutes
Number of CPUs 32

MVI susceptibility
CPU time 93 minutes
Number of CPUs 32
This figure shows a section across A-A', which compares conventional susceptibility and MVI susceptibility in profile. We have presented conventional susceptibility as vector cones to reinforce our appreciation that this approach constrains the magnetization direction to align with the geomagnetic field.

The geology map is draped onto the terrain surface for reference, and the expected axis of magnetic rock is indicated by the white band superimposed on the geology.

The conventional susceptibility model (left) does not agree with the geology, while the MVI model (right) agrees very well. Extensive surface bedding dip measurements indicate that the formation dips between 65 and 80 degrees to the North in this area, which is also consistent with the MVI model. It is interesting to note how the MVI vector aligns with the dip of the model in this case, which is consistent with our expectation that magnetic anisotropy has rotated the induced magnetic vector to align with the formation bedding.
Summary

The magnetization vector is the "natural" quantity to recover for the magnetic field inversion problem.

Magnetization Vector Inversion aids in the interpretation of magnetic field data regardless of the source of the magnetization.

It is the experience of the authors that MVI inversions in general produce much more consistent geological models than susceptibility inversions. MVI should be a serious consideration for all magnetic field inversions.

To summarize our observations on magnetization vector inversion we note that the magnetization vector is the natural quantity for magnetic field inversion. The important practical implication is that MVI is robust in the presence of magnetic effects which otherwise cause conventional susceptibility inversion to fail. The Osborne example demonstrates that MVI is essential for TMI data inversion. Furthermore, it has been experience of the authors, and in particular our collaborator, Barry de Wet, that MVI inversions in general produce much more consistent geological models than susceptibility inversions. MVI should be a serious consideration for all magnetic field inversions.
Acknowledgements

The Osborne example was done in conjunction with Barry De Wet, then of Ivanhoe Mines, now of High Power Exploration (HPX).

Airborne TMI data of the Quadrilátero Ferrífero, Brazil was provided by the Companhia de Desenvolvimento Econômico de Minas Gerais (CODEMIG).

Ian MacLeod, Geosoft Inc. conducted the Quadrilátero Ferrífero modelling

All inversions were completed using Geosoft’s VOXI Earth Modelling cloud services.
Is remanence an issue in your project area?

www.geosoft.com/voxi

We love to hear from our customers, so if you have any questions, e-mail us at explore@geosoft.com or visit www.geosoft.com
Joint 3D Inversion of Time- and Frequency-Domain Airborne Electromagnetic Data

Leif H. Cox¹, David A. Sunwall¹, Masashi Endo¹, and Michael S. Zhdanov¹,²
Abstract

Three-dimensional joint inversion of frequency domain and time domain airborne electromagnetic data

Leif H. Cox\textsuperscript{1}, David A. Sunwall\textsuperscript{1}, Masashi Endo\textsuperscript{1}, and Michael S. Zhdanov\textsuperscript{1,2}
1-TechnoImaging, 2-University of Utah

Airborne electromagnetic (AEM) surveys can be flown relatively cheaply and rapidly, with sampling along line approximately every 3m. However, time domain AEM surveys often have poor resolution in the near surface, while frequency domain surveys are unable to penetrate conductive cover. In addition, each survey type may have its own systematic data biases. Combining frequency and time domain surveys provides the benefits of both methods: collecting high resolution data in both the near surface and at depth. In addition, the use of two independent data collection methods reduces biases in the final reconstructed geology.

We present a 3D inversion algorithm that jointly inverts frequency and time domain AEM data. The algorithm uses the moving sensitivity domain method, which makes it applicable to very large scale (1000s line km) surveys. The use of both data types significantly increases the resolution of the final images compared with each system individually. It also reduces the systematic bias from using a single survey. We demonstrate the effectiveness on joint inversion of RESOLVE frequency domain and SkyTEM time domain data along the Murray River, South Australia. The results show noticeable noise reduction and enhanced resolution than with either method below. New surveys can be flown with planning for joint inversion, or legacy data can be re-inverted with the technique.
Outline

- Introduction
- Inversion methodology
- Synthetic model study
  - Frequency-domain, time-domain, and joint inversions
- Case study: Bookpurnong, Australia
- Conclusions
Introduction
AEM methods

- Frequency domain
  - Bird transmits at 5-6 frequencies (400 Hz – 120 kHz)
  - 30m flight height
  - High resolution for shallow mapping

- Helicopter time domain
  - Bandwidth: ~20 Hz - 50 kHz
  - 30m flight height
  - Short tx-rx offsets
  - Lower resolution than frequency domain
  - Deeper penetration

- Fixed-wing time domain
  - Bandwidth: ~20 Hz - 50 kHz
  - 100m flight height
  - Long tx-rx offsets
  - Lower resolution than helicopter time domain
  - Faster flying and cheaper survey costs
  - Deeper penetration

Haas and Hendricks (2013)
Airborne EM systems

DigHEM (FD)
http://www.fugroairborne.com

HeliTEM (TD)
http://www.fugroairborne.com

GEOTEM (TD)
http://www.fugroairborne.com

RESOLVE (FD)
http://www.fugroairborne.com

VTEM (TD)
http://www.geotech.ca/
Logistics of AEM surveying

- 100's to 1000's kilometers of survey lines
- 10's to 100's of square kilometers
- Along line data sampling: 3m - 10m
- Line spacing: 50m - 250m
- Before 2007, only 1D inversion was feasible for large AEM data sets.
Moving sensitivity domain

- Airborne surveys may have 5 million data points and inversion may require 10 million cells for a total of $5 \times 10^{13}$ values in the sensitivity matrix (5PB to store).

- Transmitter-receiver pairs are only sensitive to those cells which are within the sensitivity domain.

- All cells are simultaneously inverted yet the modelling domain for an individual transmitter-receiver pair remains relatively small.
Frequency vs. time domain AEM

**Frequency domain**
- Higher frequencies/higher resolution.
- More difficult to "see" through conductive overburden.
- Shallower depth-of-investigation (DOI)—less than 150 m.

**Time domain**
- Lower frequencies/lower resolution.
- Easier to "see" through conductive overburden.
- Deeper depth-of-investigation (DOI)—up to 500 m.

JOINT INVERSION
Inversion methodology
FD/TD joint inversion

Based on the conjugate gradient method with Tikhonov regularization:

\[ P^\alpha (\sigma) = \|W_d (A(\sigma) - d_{obs})\|^2 + \alpha |W_m (\sigma - \sigma_{\text{apr}})|^2 \longrightarrow \text{min} \]

For joint inversion, a simple matter of concatenating FD/TD observed data matrices and combining data weighting matrices and forward operators:

\[ d_{obs} = \begin{bmatrix} d_{obs}^{FD} \\ d_{obs}^{TD} \end{bmatrix}, \quad W_d = \begin{bmatrix} W_d^{FD} & 0 \\ 0 & W_d^{TD} \end{bmatrix}, \]

\[ \phi(\sigma) = \left\| \begin{bmatrix} W_d^{FD} & 0 \\ 0 & W_d^{TD} \end{bmatrix} \left( A_f (\sigma) - \begin{bmatrix} d_{obs}^{FD} \\ d_{obs}^{TD} \end{bmatrix} \right) \right\|^2. \]

Only one misfit functional and one trade-off parameter. Weighting controlled by \( W_d \).
Data weighting

SkyTEM (TD) 24 Channels of Z
- Linear plot

SkyTEM (TD) 24 Channels of Z
- Log base 10 plot

- Data vary by orders of magnitude within and between FD and TD surveys.
- A simple error model is developed to account for errors introduced by inconsistent transmitter-receiver attitudes, inaccurate flight-height measurements, data below instrument sensitivity levels and other noise sources.
- Data are weighted according to their error,

\[ W_{d,i} = \frac{1}{\varepsilon_i} \]
Model Weights

\[ P^\alpha(\sigma) = \| W_d (A(\sigma) - d_{obs}) \|^2 + \alpha \| W_m (\sigma - \sigma_{apr}) \|^2 \rightarrow \text{min} \]

- Modeling weighting matrix is computed from the sensitivities.
- Model weighting matrix naturally includes both model sensitivities and data uncertainties.

\[ W_m = \text{diag} (F_{wd} \ast F_{wd})^{1/4} \]

* is the transposed complex conjugate matrix

\[ F_{wd} = \begin{bmatrix} F_{FD} & \cdot & \cdot \\ \cdot & F_{wd} & \cdot \\ \cdot & \cdot & F_{TD} \end{bmatrix} \]
Synthetic model study
Frequency domain inversion

True model
- Shallow and mid-depth conductors recovered with FD data.
- FD inversion has difficulty recovering thickness of conductors.

FD-only inversion
Time domain inversion

True model
- Deep and mid-depth conductors are recovered.
- TD does better recovering conductors’ thicknesses.

TD-only inversion
Joint inversion

- Joint inversion recovers all conductors, and thicknesses are better resolved.
Summary

- Joint inversion captures the benefits of FD and TD surveys.
- FD: good resolution in the near surface.
- TD: deeper penetration/ability to see through conductors.
- Joint inversion recovers all conductors and thicknesses are more accurate.
- Joint inversion retains the advantages of FD/TD data.
Case study: Bookpurnong, Australia
Bookpurnong Survey Lines

- RESOLVE frequency domain
  - ~150 line km
  - No. Stations: ~45,000
  - Channels:
    - CP 390, 1798, 8177, 39460, 132,700 Hz
    - CX 3242 Hz

- SkyTEM time domain
  - ~160 line km
  - No. Stations: ~5,5000
  - Channels:
    - 30 Channels of x and z component data
Mapping saline water tables using FD and TD AEM

- **RESOLVE** frequency domain
  - ~150 line km
  - 6 frequencies (382Hz-130100Hz)
- **SkyTEM** time domain
  - ~160 line km
  - 22 Channels X and Z data
  - For inversion only high moment used.

Source: Munday

SkyTEM: Blue
Resolve: Red

Google Earth (2012)
3D inversion results—

**perspective view**

- Cutoff values for conductive features: 0.16 Ohm·m to 1.09 Ohm·m (hot colors).
- Cutoff values for resistive features: 6.7 Ohm·m to 36 Ohm·m (cool colors).
Conclusions

- FD inversion has higher resolution, but shallower sensitivity while TD inversion has lower resolution but deeper sensitivity and sees through conductive cover better.

- Joint inversion of FD and TD synthetic data demonstrates the ability to recover typical FD/TD AEM conductive targets.

- Joint inversion of Bookpumong FD/TD data produces better images at depth and in the near surface compared to FD only and TD only inversions.

- Historical FD and TD data which overlap can be reevaluated using joint inversion, even if survey lines have different orientations.

- In mature provinces of mining and petroleum development where FD and TD exist, joint inversion will improve inversion images and geologic understanding.
Acknowledgements

- The Riverland AEM data presented were financed in part by the South Australian CNMR Board Project 054127: The application of airborne geophysics to the prediction of groundwater recharge and floodplain salinity management, and the CSIRO National Flagship program Water for a Healthy Country through the Regional Water theme. We acknowledge their permission to publish this work, and thank Dr. Andrew Fitzpatrick at CSIRO Earth Science and Resource Engineering for his assistance with regard to the Riverland AEM data.

- Tim Munday who helped interpret the results.

- The authors acknowledge TechnolImaging for support of this research and permission to publish.

- Authors also acknowledges support from the University of Utah's Consortium for Electromagnetic Modeling and Inversion (CEMI).
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http://psc.apl.washington.edu/sea_ice_odr/Sources/airborne_em.html
Questions
ABSTRACT

Geophysical Case History for the Oquirrh Mountains, Utah

Donald Hinks 9th Sept 2013

The use of physical property data has helped understand and interpret the geophysical responses in the Oquirrh Mountains in Utah. Understanding of the physical properties has also helped determine which geophysical techniques to use for further exploration. With the physical property knowledge and the known occurrence of the Bingham Mine within the exploration area, a large magnetotelluric survey was carried out over a four year period.

A magnetotelluric survey has the ability to map resistivity changes over a large volume of the earth. Porphyry systems cover a large area and require a large scale survey to map them adequately. The final 3D inverted magnetotelluric model confirmed the dip of the known quartz monzonite porphyry intrusion at Bingham, as well as identifying a previously unknown porphyry system.
Wasatch to Oquirrh Mountains

Rio Tinto

Barneys / Melco
Bingham
Stockton
Optir
Mecan
Canyon Williams
Alpine
Heber
Park City
Salt Lake City
Sandy
Tooele

10 Km

5000 10000 15000
5000 10000 15000

(meters)
NAD27 / UTM zone 12N
Wasatch to Oquirrh Mountains - RTP Magnetic Data

RioTinto

DIGHEM Survey

Tertiary Intrusives

RTP Magnetic Data (nT)
The Oquirrh Mountains geology consists of a thick sequence of folded and faulted Cambrian, Pennsylvanian and Mississippian sediments, which are mostly quartzite and limestone units with lesser shale units. The sediments have been intruded by Tertiary age porphyry stocks and partly overlain by Tertiary volcanic units.
The Oquirrh Mountains geology consists of a thick sequence of folded and faulted Cambrian, Pennsylvanian and Mississippian sediments, which are mostly quartzite and limestone units with lesser shale units. The sediments have been intruded by Tertiary age porphyry stocks and partly overlain by Tertiary volcanic units.
A helicopter-borne magnetic survey was flown over the Oquirrh Mountains. Discrete magnetic highs appear to indicate sub-volcanic cupolas. These cupolas occur within a broader magnetic feature which is interpreted to be a deeper batholthic magma chamber.

The porphyry systems in the Oquirrh Mountains occur close to the cupolas.
A helicopter-borne magnetic survey was flown over the Oquirrh Mountains. Discrete magnetic highs appear to indicate sub-volcanic cupolas. These cupolas occur within a broader magnetic feature which is interpreted to be a deeper batholithic magma chamber.

The porphyry systems in the Oquirrh Mountains occur close to the cupolas.
Rio Tinto

2 Km

QMP

PQM

MZ

DEM (m)

2937
2454
2254
2112
1989
1877
1780
1703
1647
1606
1570
1543
1512
1484
1461
1408
1358
1314
1292
1280
Rio Tinto

Reduced to Pole Magnetics

>1200 nT anomaly

2 Km
Rio Tinto

Reduced to Pole Magnetics

2 Km

QMP

PQM

MZ

RTP (nT)
Age of Emplacement and Remanent Field Direction

Black bars indicate fields with the same direction as today's magnetic field, white areas are reversed. Ages are Ma.

* Parry et al., U-Pb dating of Zircon and Ar/Ar Dating of Biotite at Bingham Utah. Economic Geology 2001.
69 Samples collected in 1962 by MacDougall
Magnetic Susceptibility of Drill Core

- Median
- Average
- 95th percentile
- 5th percentile

Approx 0.5% magnetite by volume

RioTinto

Oquirrh's Core Measures

Magnetic Susceptibility (SI units)

Intrusives

Extrusives

Sediments

Sample counts

November 23, 2013
Geophysical Case Study, Oquirrh's, Utah
Magnetic Data

- Useful for mapping Tertiary intrusives within the sediments.
- Locates unaltered monzonite and not mineralized QMP.
- Can locate mineralized skarns.
Average Density from Core

Gravity High

Gravity Low

922 data points
A number of 2D and offset pole-dipole surveys have been collected.

Generally depth penetration was not sufficient.
Rio Tinto

Ground MT Survey program to explore for additional porphyries around Bingham.

2007 to 2010 - 680 MT sites collected at between 400m and 800m station spacing.
RioTinto

2007 – 116 sites collected by Quantecc.

Full tensor
0.001Hz to 250Hz
Rio Tinto

2008 – 360 sites collected by WesternGeco.

Full tensor
0.001Hz to 10,000Hz
Bingham MT Survey

Rio Tinto

2009 – 127 sites collected by Quantec and WesternGeco.

No Hz collected.
Quantec 0.001 to 250Hz
WesternGeco 0.001 to 10,000Hz.
Bingham M1 Survey

Rio Tinto

2010 - 77 sites collected by WesternGeco.

No Hz collected 0.001Hz to 10,000Hz
MT 3D inversion

3D MT Inversions were run in 2008, 2009 and 2010 by WesternGeco.
Mesh approx 117 x 118 x 151 cells (2,000,000 cells)
Minimum size in X/Y was 200m.
Minimum Size in Z was 30m.
Frequency Range 0.065 to 1392Hz.
13 frequencies, 3 frequencies per decade
623 sites inverted
1994 DIGHEM resistivity survey used to set the near surface resistivities.
Rio Tinto

2010 – 77 sites collected by WesternGeco.

No Hz collected
0.001 Hz to 10,000 Hz
16" Resistivity for Bingham

RioTinto

Sediments

Intrusives

Resistivity (ohmm)

- Median
- Average
- 95th percentile
- 5th percentile

Sample counts

21 drill holes

November 23, 2013
Geophysical Case Study, Oquirrh, Utah
Geological Cross Section for Drilling.

Rio Tinto

WEST

EAST

MZ

QMP

Resistivity (ohm m)

1935
971
691
491
374
292
216
160
118
84
56
35
17

November 23, 2013
Geophysical Case Study: Oquirrh's Utah
The MT model indicates a low resistivity feature coincident with the mineralized Quartz Monzonite Porphyry dyke at the Bingham Mine. A similar but less intense feature was identified as the target for the porphyry system at Lark.

Location of mineralized Quartz Monzonite Porphyry Dyke at Bingham Mine

2 Km

Lark

Target

East

West
Lark Holes 16" Resistivity

- Intrusives
- Extrusives

Median
Average
- 95th percentile
- 5th percentile

Sample counts

11 drill holes

Rio Tinto

November 23, 2013
Geophysical Case Study, Oquirrh, Utah
Resistivity of Altered and Unaltered Lithologies

Rio Tinto

Unaltered

Unaltered

Bingham

Lark

Bingham

MZ

MZ

MZ

MZ

OZ

OZ

OZ

OZ

Median
Average

Sample counts

Resistivity (ohmm)

47814
1762
22218
37661
3575

0
200
400
600
800
1000
1200
1400
1600

November 23, 2013
Geophysical Case Study, Oquirrhs, Utah
Inversions by Condor Consulting

Main conductor is Manning Canyon Shale which occurs within a resistive sequence of quartzite.
Inversions by Condor Consulting

Main conductor is Manning Canyon Shale which occurs within a resistive sequence of quartzite
Inversions by Condor Consulting

Main conductor is Manning Canyon Shale which occurs within a resistive sequence of quartzite.
Inversions by Condor Consulting

Main conductor is Manning Canyon Shale which occurs within a resistive sequence of quartzite.
Conclusions

Magnetic surveys will map fresh monzonite, volcanic units and skarns. Good for locating Tertiary intrusive in the magnetically quiet sediments, but may not detect mineralization.

Resistivity surveys in the northern Oquirrh Mountains can map altered intrusive within the electrically resistive sediments. Elsewhere in the Oquirrh Mountains a shale unit causes problems with interpretation.

MT surveys can be conducted and collected at a large enough scale to map an entire porphyry system. MT data can also be inverted and viewed in 3D, therefore are excellent a providing the big picture. However a resistivity anomaly is not definitive of a porphyry system and there are many causes of resistivity anomalies.
Multi-disciplinary airborne and ground geophysical survey results for porphyry copper exploration in the Canadian Cordillera

By: Jean M Legault – Geotech Ltd.

Presented at Great Basin & Western Cordillera Mining Geophysics Symposium
Sat 23-November, 2013 – Elko, Nevada
Abstract

Multi-disciplinary Airborne & Ground Geophysical Survey Results for Porphyry Copper Exploration in the Canadian Cordillera

Jean M Legault, Geotech Ltd, Aurora, Canada

Porphyry copper deposits in Western Cordillera have been extensively studied with airborne and ground geophysics, but it’s only with the advent of 3D inversion, that these deposit responses be accurately compared based on derived physical properties.

For example the Mt-Milligan alkaline cu-mo porphyry in the Mackenzie region of central British-Columbia, Canada, where the geology is well known and the geophysics is available in the public domain making it an ideal inversion case-study example. As a result, it has been extensively studied since 1990’s, mainly by the UBC-GIF, with 1D-2D-3D inversions (Airborne HFEM, HTEM, AFMAG-EM, Aeromagnetics, Ground IP/Resistivity and Magnetics as well as gravity). However, the results have sometimes been contradictory – for example the borehole physical property, ground DC resistivity and airborne AFMAG have indicated that the deposit is resistive, where airborne TEM-FEM had initially suggested the opposite. More recent 3D TEM-AFMAG inversions have shed new light on the source of this discrepancy.

The Pebble calc-alkaline cu-au-mo porphyry is another example where widely different geophysical measurements have been presented (ie., Ground DC/IP, Airborne TEM, airborne AFMAG-EM, aeromagnetics, ground gravity, ground MT, drill hole data) with seemingly varied results. Yet a consistent resistivity model has been obtained as a result of 3D inversion of ground and airborne EM.

The Silver Queen cu-pb-zn-au-ag porphyry deposit case-study demonstrates successful application of reconnaissance airborne EM and ground methods that have lead to discovery thanks to 3D inversions. In this case-study example AFMAG-aeromagnetics were obtained over a deposit area that was originally surveyed with conventional ground IP/Resistivity. After analysis using 3D inversion, the AFMAG and Mangetic results were then successfully followed up by distributed array DC/IP-MT ground and the data integrated together using 3D inversion. This resulted in the newly discovery of Itsit cu-mo-au porphyry deposit in single field season.
Outline

• Introduction

• Multi-Disciplinary (airborne & ground) Examples
  • Mt Milligan - Ground DC/IP, Airborne Mag-TEM-ARVAG
  • Pebble - Ground DC/IP, Airborne Mag-TEM-ARVAG

• Multi-Disciplinary Case-study
  • Silver Queen - Airborne Mag-ARVAG, Ground DC/IP-AVIT

• Conclusion
Mt. Milligan - Porphyry deposit

- Situated in the Mackenzie region of central British-Columbia.
- Alkalic copper-gold porphyry deposit, consists of two principal zones, the Main Zone (MBX+66) and Southern Star (SS) Zone.
- Mineralization spatially associated with Monzonite stock & breccias, hosted within volcanics. Tilted and faulted stratigraphy.
- Geology is well known and geophysics available in the public domain, extensively studied geophysically (Ground gravity, magnetics, DCIP, Airborne HFEV, HTEM, ARVAG), mainly by UBC-GIF (published 1997 to 2012), making it an ideal inversion case-study example.

After Holtham and Oldenburg, 2010
Mt Milligan - Magnetics

Physical property variations related to alteration zoning not necessarily lithology!

3D Magnetic Inversion Section

Regional Aeromagnetics

Ground Magnetics

Figure 4b: Magnetic responses of Mt. Milligan Camp.

800m Line-Spacing

Resolution Depends on Sampling Density!

50m Line-Spacing

3D Geologic Model

3D Magnetic Inversion

Rock/Model Mag. Susc. Zoning

Mount Milligan intrusions, faults, ore zones (plan)

Magnetics useful for distinguishing potassic alteration from background

Constrained Inversion more Geologically Accurate than Unconstrained

Mt Milligan – Magnetics

- Why Use Geologic Constraints?
- What is Benefit with Including what we already know?
- Don’t we Prefer “Unbiased” Interpretation?

3D Magnetic Inversion Sections

- Because All Inversions are by their Nature Non-Unique!
- Adding Geologic Constraints reduces Model Ambiguity
- Allows Inversion to Better Focus on Unexplained Signatures
- Geologically Constrained 3D Inversion Improves Model in Undrilled Areas and at Depth!

after Mitchinson (PDAC 2010)
DC Resistivity

Archived DC resistivity data was re-inverted using a newer 3D inversion code. The pole-dipole survey was collected with N=1:4 and a=50m.

Figure 9. Measurement locations for DC resistivity survey

1D Layered – Disagrees with Geology!

Modern 2D Inversions Should Include Depth of Investigation Index (DOI)

High/Low IP Zonation – Agrees with Geology

2D IP Chargeability Inversion

Notice 2D Inversion Section shown to 300m – Too Deep for Avg. Penetration N=1/4A=50m Array (150m more likely!)

1D HFEM Resistivity Inversion

DC/IP Resistivity Assumed to Provide Best Estimates of Electrical Properties – but Beware of Depth of Investigation and 2D-3d Nature!

3D Rock Model (Z=75m)

3D Resistivity (Z=75m)

1D-2D DC & HFEM Inversions Indicate Layered Resistivity

3D DC Resistivity Inversion Indicates Resistive MBX Stock at Surface and at Depth – Agrees with Geology!

Mt Milligan - HTEM

Geology & HTEM Line-Locations

3D EM Inversion Covers Part of HTEM Survey Area

HTEM dBz/dt Tau

HTEM 1D Resistivity (-100m)

SS Resistive / MBX Conductive
SS Resistive / MBX Conductive

Conductive MBX Stock from HTEM Results & 1D Disagrees with Known Geology!

Resistive MBX Stock in 3D HTEM & 3D DC Agrees with Geology!

After Mitchinson (2010); Yang & Oldenburg (2012)
Why the Discrepancy Between 1D and 3D EM Inversion?

- As HTEM Fields Penetrate Vertically - also Expand Laterally (Footprint)!
- Phyllic Alteration Halo also Detected = False Deep 1D Conductive Layer!
- 3D Accurately Solves for 3D Nature of Resistivity Model!

After Yang & Oldenburg (2012)
Figure 1: Flight path of VTEM and ZTEM surveys overlain on the geology of the Mt Milligan porphyry system.

ZTEM: EM Conductivity Results

90Hz In-phase DT
90Hz In-phase TPR

ZTEM 2D Conductivity Block Model

2D ZTEM Indicates Resistive MBX Stock (1st EM Method in 2008) but Vertical Geometry?

ZTEM 3D Conductivity Block Model

3D ZTEM Resistivity (2009) Agrees with Geologic Model!

After Witherly & Sattel (2011); Holham & Oldenburg (2009)
- Pebble Porphyry Cu-Mo-Au deposit, approx. 320km SW of Anchorage.
- 5.94 billion tonnes (0.42% Cu, 0.35 g/t Au, and 250 ppm Mo- measured + indicated resource).
- Calc-alkalic porphyry formed in association with granodioritic intrusions. Occupies a large ~5 x 3 km area.
- Pebble West subcrops discovered 1994, Pebble East (richer) buried, drilled 2005
Pebble – Case Study

Multiple Geophysics Data Sets!

- Ground DC/IP
- Spectrem Airborne EMI
- ZTEM Airborne ARVIAG EMI
- Aeromagnetics
- Ground Gravity
- Ground MT
- Drill-hole data

Goal: Unify Physical Property by Determining Consistent Model across all data using 3D Inversion

After Pare and Legault (2010)
3D Inversion Results:

- Three consistent conductivity Models!
- Three widely different Survey Types:
  - Airborne ATEVI
  - Airborne ARVAG EMI
  - Ground Electrical
- One consistent resistivity scale!

After Holtham and Oldenburg (2012)
Silver Queen – Case Study

- Silver Queen property is situated in central BC, approximately 36 km south of Houston.

- Cu-Pb-Zn-Au-Ag discovered 1912, later mined ’72 to ’73.
- Intrusion-related, Vein-type mineralization, suspected to be related to Cu-Au Porphyry-style.

- IP/Resistivity conducted in 2005 defines known veins
- ZTEM airborne ARMAG EM & Magnetics, with follow-up TITAN-24 DC/IP + MT in 2011
- 3D Inversion & Analysis by Mira Geoscience

- 2011 drill program based on ZTEM & TITAN-24 results in discovery of Itsit Au-Cu-Mo porphyry.

(Ref: www.newnadina.com)
### Silver Queen – Case Study

#### Criteria for a buried bulk Tonnage Target

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Source of data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Close to known mineralization</td>
<td>Old mine workings plotted in 3D, with a corroborating resistive feature seen near surface in the ZTEM inversion</td>
</tr>
<tr>
<td>Close to or at the boundary of intrusive body</td>
<td>Intrusive boundaries were interpreted using ZTEM inversion conductivity isosurfaces and Magnetic inversion susceptibility isosurfaces</td>
</tr>
<tr>
<td>In a regional structure at a thickening of the structure, a kink, or a dilational zone of accommodation transferring movement between parallel structures</td>
<td>Linear zones of enhanced conductivity in ZTEM inversion associated with linear features and magnetic lows in airborne magnetic data were interpreted as zones of brecciation mapping regional structures</td>
</tr>
<tr>
<td>In a zone of increased brecciation</td>
<td>Interpreted from local zones of increased conductivity indicated by ZTEM inversion</td>
</tr>
</tbody>
</table>

*After Kowalcyk and van Kooten (2012)*
Silver queen stock is shown – likely magnetic and non-magnetic phases as the isosurfaces do not coincide exactly. Note volcanics have different trend in SE corner of project area.
Note NW trending shallow resistor on SQ vein trend, with conductor underneath it.

Remark on Silver Queen intrusive stock identified by resistor, and volcanic terrain with NW trends in SE corner. Note structures marked by yellow dotted lines follow linear conductive trend shown as NE trending linear brown features. Red ellipse marks spot close to intrusive stock and old mine, where movement in the structures transfers across from one to the other, and the small conductive feature sits at depth in the middle of it.
Magnetic isosurfaces with plan slice of conductivity from ZTEM inversion. Note the magnetic isosurfaces and the blue regions do not correspond, indicating multiple phases of the SilverQueen intrusive. Note immediately NNW of the Silverqueen intrusive the limits of a younger intrusive can be mapped, it is nonmagnetic and has yellow green colours, and the magnetic volcanics wrap around it.

Click 1, the geology fades in.
Click 2, the outlines of the intrusive outcrops and the mapped structures appear
Click 3 the geology fades out, showing the correspondence between the inversion and the features of interest. Note the conductive finger pointing at the SE end of the SilverQueen vein. This is a possible buried breccia, structurally in the right place. The mapped structures shown here are regional, and we have refined their location using the ZTEM and Mag inversion results.
NS section – note small buried conductive zone under SE end of Silver Queen vein.
Silver Queen Vein

Titan 24 survey
4 lines across target area
150m dipoles, 300m traverse line separation
IP (Resistivity & Chargeability) & MT

After Kowalcyk and van Kooten (2012)

Repetitive slide just to show location of Titan 24 survey talked about next.
View of Titan24 results from south. A slice from a 2005 IP survey previously inverted shows the good correspondence between the shallow Titan A anomaly and the older IP survey. The deep Titan B anomaly is only seen as a weak 2nd order anomaly in the old data.

The old data was of good quality, but just did not penetrate deeply enough.
Silver Queen – Case Study

TITAN-24 IP Survey – 3D Chargeability Inversion

The airborne survey, data inversion and interpretation, Titan24 data acquisition, data inversion and interpretation and drilling were completed in one field season!

Note no mineralization near surface. A shallow dipping fault exists above the target. “very difficult drilling”

DH S11-03
Top of mineralization @84m
End of hole @ 777M
693 metres of mineralization

IP Chargeability anomaly shell from 2011 Titan24 inversion

After Kowaloyk and van Kooten (2012)
Conclusions

- Porphyry copper deposits in Western Cordillera extensively studied with airborne and ground geophysics, but only with advent of 3D inversion, can deposit responses be properly compared based on derived physical properties.

- Mt-Milligan alkaline cu-mo porphyry has been extensively studied with 1D-2D inversions (Airborne HFEM, HTEM, ARMAG-EM, Aeromagnetics, Ground IP/Resistivity) but more recent 3D EM/Electrical inversions (ZTEM-HTEM-IP/Resistivity) provide most consistent results between survey types.

- Pebble calc-alkaline cu-au-mo porphyry is latest/best example of consistent resistivity model obtained from 3D inversion of ground and airborne EM.

- Silver Queen case-study demonstrates successful application of ZTEM-aeromagnetics as reconnaissance tool, followed up by TITAN-24 ground follow-up and integration using 3D inversion. Results in new discovery of Itsit cu-mo-au porphyry deposit in single field season.
Acknowledgements

Our thanks to the following authors for contributing their slides:

Elliot Holtham — Computational Geoscience (Pebble and Mt Milligan)
Dikun Yang and Doug Oldenburg — UBC (Mt Milligan and Pebble)
Ken Witherly — Condor Consulting (Mt Milligan)
Pascal Pare — Anglo American (Pebble)
Peter Kowalcyk — Mira Geoscience (Silver Queen)
Diane Mitchinson — Mira Geoscience (Mt Milligan)

We acknowledge the data contributions from the following Companies:

Terrane Minerals/Thompson Creek Metals
Anglo American Exploration & Northern Dynasty Mines
New Nadina Exploration & Quantec Geoscience
North Bisbee

A Case Study in Geophysical 3D Magnetic Modeling

Western Cordillera Mining Geophysics Symposium
Nov. 23, 2013

Carl O. Windels

North Bisbee Project: A Case Study in Geophysical 3D Magnetic Modeling
The North Bisbee project is a porphyry copper exploration target located near Bisbee, Arizona and immediately north of the Lavender Pit and Cochise copper projects controlled by Freeport-McMoRan. Because the area is covered by 700 to 1000 meters of post mineral cover, initial target generation relied on 3D magnetic modeling in combination with district-scale geologic/structural relationships.

Early stage projects do not have a significant physical property database to be used as constraining parameters.

This presentation will discuss using spectral information and simple inferred rock models to constrain the first 3D inversions as a grass roots exploration tool.
Abstract

North Bisbee - A Case Study in Geophysical 3D Magnetic Modeling

Carl O. Windels, Consultant, c.windels@comcast.net

Comparison of 3D Magnetic Models for Copper Exploration in the Bisbee District

The North Bisbee project is a porphyry copper exploration target located near Bisbee, Arizona and immediately north of the Lavender Pit and Cochise copper projects controlled by Freeport–McMoRan. Because the area is covered by 700 to 1000 meters of post mineral cover, initial target generation relied on 3D magnetic modeling in combination with district-scale geologic/structural relationships.

Various 3D magnetic models using University of British Columbia (UBC) - Mag3D, Geosoft -VOXI and FastMag3D are presented for both regional and detailed aeromagnetic data.

1. The UBC Mag3D inversion using the FastMag3D model as a reference model is compared to the UBC Mag3D default results.
2. The UBC Mag3D inversion using an interpreted pre-mineral rock model for the Cretaceous Bisbee Formation as reference model is compared to the UBC Mag3D default results.
3. The VOXI Iterative Reweighting Inversion (IRI) with defaults is compared to using the FastMag3D as a starting model and parameter reference model.

Magnetic features and an induced polarization anomaly at depths greater than 700 meters suggested potential of a porphyry target. Two holes were drilled to test the anomalies. Drill hole results are compared with the various 3D magnetic models.

Conclusion

• Initial interpretations of the Bisbee FastMag3D block model are supported by lithologies encountered in two drill holes combined with magnetic susceptibility measurements. The combination of FastMag3D with other 3D mag inversions provides a more useful model for exploration.
• IP/Resistivity methods using a 300 m dipole-dipole array, n-spacing 1-12 are sufficient to identify valid chargeability anomalies at depths in excess of 700 m. Drill results confirm the presence of sulfide mineralization as the cause of chargeability anomalies with anomalous Cu 10-700 ppm and Au 1-287 ppb.
The North Bisbee project is a Jurassic porphyry target located in Cochise County, southeastern Arizona.
Porphyry Style Schematic Cross Section

In the early 90’s, FastMag3D was first used in southern Peru and northern Chile. The porphyry style FastMag3D pattern was first recognized at the Toquepala Copper Mine, Southern Peru and more recently in the SW US copper porphyry district - specifically Arizona and New Mexico.
3D Magnetic Modeling

FastMag3D
FastMag3D
Spectral Mag 3D Visualization
Flow Chart

Data
RTP
Band Pass Filters
Relative Intensity
Apparent SI

UBC Mag3D
Statistics

Relative Intensity
Apparent SI

University of British Columbia (UBC) Mag3D inversion

Geosoft Vooxi Iterative Reweighting Inversion
Link:

FastMag3D Spectral Analysis

I: Create Reduced to the Pole Grid

II: Create FFT Band Pass slices to an assigned max depth of ⅓ of the shortest grid dimension
    Depths 25, 50, 100 meters, then 200m to max depth at 100m +/- intervals

III: Multiply by an assigned K factor to sharpen structures

IV: Build relative intensity 3D Model and normalize the results using the mean and standard deviation.

V: Using the statistical results from the UBC Mag3D Default inversion calculate apparent SI values for the FastMag3D Model
Flow Chart: FastMag3D Spectral Analysis

UBC Mag3D input Parameters (http://www.eos.ubc.ca/ubcgif/iag/sftwrdocs/mag3d/mag3d-manual.pdf)
Depth Weighting: Distance
Wavelet Compression: Default
Mode: GCV (generalized cross validation)
Bounds: Default
Initial Model: Default
Reference Model: Default ---- (FastMag3D Apparent SI units))

Starting Model Voxel File: Not Used - Default Value: 0 ---- (\model_fm3d_app_si.geosoft_voxel)
Parameter Reference Model Voxel File: Not Used - Default Value: 0 ---- (\model_fm3d_app_si.geosoft_voxel)
Gradient Reference Model Not Used - Default Value: 0
Upper Bounds Model Not Used - Default Value: 1e+20
Lower Bounds Model Not Used - Default Value: -1e+20
Parameter Weighting Model Not Used - Default Value: 0.0001
EW Gradient Weighting Model Not Used - Default Value: 1
NS Gradient Weighting Model Not Used - Default Value: 1
Vertical Gradient Weighting Model Not Used - Default Value: 1
Active Model Not Used - Default Value: 1
Iterative Reweighting Mode Not Used - Default Value: 1 ---- (-1 IRI Focus Factor: 2)
Reweighting Model Not Used - Default Value: 1
Regional Aeromagnetic Data

- USGS OF 65-004 (AZ-528)
  - Flown 1964
  - 1 mi. line spacing
  - NS flight lines
- Barometric 2744 meters (9000 ft.)

Regional Aeromagnetic Data
Regional structures near the Jurassic Bisbee porphyry system from publish geologic maps and literature search

GEOLOGIC MAP OF THE UPPER SAN PEDRO VALLEY, ARIZONA
USGS Open File Report 00-138
[http://pubs.usgs.gov/imap/i1109/i1109_e.pdf](http://pubs.usgs.gov/imap/i1109/i1109_e.pdf)

Post Mineral Cover: Kba – Bisbee Formation – Lower Cretaceous
Qal – Alluvium – Quaternary

Pre Mineral Lithology: Precambrian Pinal Schist, Paleozoic Sediments, Jurassic Intrusive
III: Interpreted deep seated intrusive related to the Bisbee District

UBC Mag3D Inversions and FastMag3D Model

Observed Magnetic Data
10731 data, I = 58.6, D = 12.8

Predicted Data
UBC Mag3D with FastMag3D Reference Model

UBC - Geophysical Inversion Facility
Regional 1 mi. Aeromagnetic Data

UBC Mag3D Inversions and FastMag3D Model – Observed Magnetic Data – Predicted Data from inversion results
Comparison of the default UBC Mag3D Inversion with the model using the FastMag3D (spectral mag response) as a reference model

UBC Mag3D input Parameters
Depth Weighting: Distance
Wavelet Compression: Default
Mode: GCV (generalized cross validation)
Bounds: Default
Initial Model: Default
Reference Model: Default / (FastMag3D Apparent SI units)
Regional Magnetic Inversions

UBC Mag3D Default – FastMag3D - UBC Mag3D with FastMag3D Constraints

Post Mineral Cover

Deep Seated Magnetic Low

Regional 1 mi. Aeromagnetic Data
Detail View Sections Only: UBC Mag3D Inversions and FastMag3D Model
Deep seated magnetic low
Regional 1 mi. Aeromagnetic Data
Geosoft VOXI Inversions and FastMag3D Model – Observed Magnetic Data – Predicted Data from inversion results
Comparison of the default Geosoft VOXI Inversion with the VOXI Iterative Reweighting Inversion using the FastMag3D as a starting model and a parameter reference model.
Regional Magnetic Inversions
Geosoft VOXI Default – FastMag3D- Geosoft VOXI IRI with FastMag3D Constraints

Regional 1 mi. Aeromagnetic Data
Deep seated magnetic low
Detail View Sections Only: Geosoft VOXI Inversions and FastMag3D Model
Regional Aeromagnetic data
3D Model
Geosoft VOXI 3D with FastMag3D Constraints
Deep Seated Magnetic Low: ISO-SURACE 0.011 SI units
Windowed to the Detailed Data Extents (1/3 mi. Detailed Data)
Regional Observed-Predicted Data, with limits of 1/3 mi. line spacing detailed data
Detailed Aeromagnetic data

• EDCON-PRJ NON-EXCLUSIVE AEROMAGNETIC DATA
  • SE ARIZONA
    • 0.33 mi. line spacing
    • NS flight lines
  • Draped mean radar altimeter 230 m
Slide showing the relative position of the detailed data set to the regional model

- Geologic VOI 3D Inversion - Default
- Interpreted deep seated intrusive related to the Bisbee District
- North Bisbee Project
- Detailed Data Extents - Overlay
  (EDCON-PDJ SE Arizona Data 0.33 mi line spacing)

- Regional Data
- Reduced to the Polar Plate

- JURASSIC RELATED MINERALIZATION
  Courtland-Gleeson District
  Bisbee District
  Lavender Pit
  Cochise Project
Deep Seated Magnetic Low with Interpreted Bounding Structures referenced on the following detailed sections

The detailed sections that follow show the relative position of the deep seated regional anomaly and the interpreted bounding structures.
Detailed 1/3 mi. Aeromagnetic Data
UBC Mag3D Default – FastMag3D- UBC Mag3D with FastMag3D Constraints
Observed and Predicted plan views
Detailed 1/3 mi. Aeromagnetic Data
Detail View Sections Only: UBC Mag3D Inversions and FastMag3D Model
Magnetic low apothyses above the deep seated feature on or adjacent to the interpreted bounding structures
See Magnetic Low Apothesis – on FastMag3D section
Deep seated magnetic low is not apparent on the UBC Mag3D inversion
Detailed 1/3 mi. Aeromagnetic Data
Geosoft VOXI Default --FastMag3D --Geosoft VOXI IRI with FastMag3D Constraints

V: Magnetic low apophysis above the deep seated magnetic low.
Detailed Magnetic Inversions

Geosoft VOXI Default – FastMag3D - Geosoft VOXI IRI with FastMag3D Constraints

- Post Mineral Cover
- Magnetic Low Apothysis
- Deep Seated Mag Low

Detailed 1/3 mi. Aeromagnetic Data
Geosoft VOXI Default --FastMag3D –Geosoft VOXI IRI with FastMag3D Constraints
Magnetic low apothyses above the deep seated feature on or adjacent to the interpreted bounding structures
See Magnetic Low Apothesis – on FastMag3D section
Deep seated magnetic low and the magnetic low apothyses are also apparent on the Geosoft Voxi inversion
Post Mineral Cover
Structure Contour Map
Base of Cretaceous Section interpreted from digitized sections at 1 km spacing using the FastMag3D Model.
The UBC Mag3D Reference models are formatted in the same way as UBC mesh and model. The bounds model contains two constants representing lower and upper bounds respectively for each cell.

Ref. Cretaceous = 0.005 Si
Bounds (0.0000 to 0.005 Si)

Ref. Host = 0.025 Si
Bounds (0.0000 to 0.0000 Si)

UBC - Geophysical Inversion Facility
Simple Rock Model
The UBC Mag3D Reference models are formatted to be the same as UBC mesh and inversion model. The bounds model contains two constants representing lower and upper bounds respectively for each cell.

Ref. Cretaceous = 0.005 Si
Bounds (0.0000 to 0.005 Si)

Ref. Host = 0.025 Si
Bounds (0.0000 to 0.9000 Si)

UBC Mag3D input Parameters
Depth Weighting: Distance
Wavelet Compression: Default
Mode: GCV (generalized cross validation )
Bounds: 0.000 – 0.005 for the Post Mineral Cover
       0.000 - 0.900 for the Pre-Mineral Host
Initial Model: Default Mag3D Inversion
Reference Model: FastMag3D Apparent SI units
  0.005 for the Post Mineral Cover
  0.025 for Pre-Mineral Host
VII: Complete conventional ground geophysics to locate drillable targets.

North Bisbee Target
IP Lines – Drill Holes

20 km

RTP First Order Residual Map
IP Line Locations
Drill Hole Locations
IP Results Line 4
Weak to Moderate IP response spatially related to the southern portion of the magnetic low apothysis. Tested with drill hole 1

IP Results Line 1
Weak to Moderate IP response west of shallowest portion of the magnetic low apothysis. Shallowest portion of the magnetic low was tested with Drill Hole 2
Conclusion

Initial interpretations of the Bisbee FastMag3D block model are supported by lithologies encountered in two drill holes combined with magnetic susceptibility measurements.

The combination of FastMag3D with other 3D mag inversions provides a more useful model for exploration.

IP/ Resistivity methods using a 300 m dipole-dipole array, n-spacing 1-12 are sufficient to identify valid chargeability anomalies at depths in excess of 700 m. Drill results confirm the presence of sulfide mineralization as the cause of chargeability anomalies with anomalous Cu 10-700 ppm and Au 1-287 ppb.
Summary of North Bisbee Targeting Process

Location of interpreted deep seated intrusive related to the Bisbee District, and bounding structures
Location of apophyses from the deep seated magnetic feature near the interpreted structures
Interpreted base of the post mineral undifferentiated Bisbee Formation
Drill hole results
Example section through the Resolution Porphyry Cu-Mo Deposit, Arizona
The Schematic Model used for porphyry style patterns is based on this section.

Regional Data: Arizona Aeromagnetic Compilation 500 meter grid

AZ04, 1968, NS, 3 mi., 9000ft Barometric
Regional section from Resolution Deposit to the Ray Mine

Geology and Exploration Progress at the Resolution Porphyry Cu-Mo Deposit, Arizona
Hehnke, C. et al, SEG SP16 2013, Figure 3

Fastmag3D, Geosoft Voxi Default Inversion, UBC Mag3D Default (Data: 500 meter grid)
Regional section from Resolution Deposit to the Ray Mine

Fastmag3D, Geosoft Voxi Default Inversion, UBC Mag3D Default (Data: 500 meter grid)

Location of interpreted deep seated intrusive related to the Ray and Resolution, and bounding structures

The location of apotyses from the deep seated magnetic feature will require detailed data with 500 – 1000 m flight lines. (Non-exclusive data with 400 m lines is available: CGG Block 3329 Superior)
3D Gravity Modeling
Quince Iron Project, Region III, Chile

The same color stretch is used for all sections. Note that only the FastGrav3D and the Geosoft Vooxi IRI with FastGrav3D constraints coincide with the high density magnetite zone in the drill holes.

Acknowledgments: The author wishes to thank Agulia del Sur, SpA for permission to release this Case Study.
The FastGrav3D and the Geosoft Voxi IRI with FastGrav3D constraints show a good correlation with the high density magnetite zone in the drill holes. Fe > 25% (>3.53 g/cc)
High Resolution Aeromagnetic and Radiometric survey over the El Aguila and La Arista Epithermal Gold Deposits, Oaxaca State, Mexico

Robert B. Ellis, EGC. Inc. and Amer Smailbegovic, Ph.D., Teraelement Ltd.
Abstract

High Resolution Aeromagnetic and Radiometric survey over the El Aguila and La Arista Epithermal Gold Deposits, Oaxaca State, Mexico

R. Ellis and A. Smallbegovic, EGC Inc. & Teraelement Ltd.

The El Aguila and La Arista Au-Ag and base metal deposits are located approximately 120 km southeast of the capital city of Oaxaca, Mexico and operated by Don David Gold S.A.I.C. (DDG), a subsidiary of Gold Resource Corporation (NYSE MKT: GORO). Epithermal mineralization at El Aguila was mined by open pit and produced 345,000 tonnes at an average grade of 4.4 g/tonne Au and 43 g/tonne Ag. Mineralization consists of high grade structural feeders into a "manto" of silicified permeable Tertiary volcanic rocks consisting of volcanic breccia and tuff. Structurally controlled Au-Ag and base metal mineralization at La Arista consists of quartz veins and stock work hosted in strongly silicified Tertiary rhyolite intrusive, breccia, andesite, and tuff. Within the same deposit Cretaceous carbonate and sandstone units below and or adjacent to the mineralized volcanic host are targets for base metal skarn mineralization in addition to the epithermal veins. From initial startup July 1, 2010 through June 30, 2013 the El Aguila-Arista Project has processed a total of 811,496 tonnes averaging 3.85 g/t gold and 290 g/t silver to recover 82,409 ounces of gold and 6,813,685 ounces of silver.

A "high resolution" airborne magnetic and radiometric survey was flown over the contiguous property holdings of DDG to identify structure, magnetite associated with possible skarn mineralization, and alteration associated with epithermal mineralization. The term "high resolution" implies certain survey specifications, equipment configuration, and sampling and processing criteria to get the best signal-to-noise data in the steep topography surveyed.

Interpretation of the magnetic data was done using standard digital image processing techniques and inversion modeling. The magnetic data helped to extend known mineralized structures and identify areas of potential magnetite destructive alteration and skarn mineralization. Magnetic vector inversion (R. G. Ellis, 2012) provided a better correlation of source location than other inversion approaches particularly where remanent magnetization is suspected to be a significant component to the total magnetization.

Integrating the 3D model with geology has been helpful in targeting at the mine scale and provides better understanding of the regional geology. Radiometric data was important to characterize the known mineralization and identify targets in the broader survey area. The radiometric detector consists of three main channels: uranium (U), thorium (Th) and potassium (K). These channels are traditionally combined in the analysis into various ratios to map the relative distribution and abundance of U-Th-K in the particular area. However, with the improvement in the overall design of recording instruments and available analysis software, now it is possible to use some of the additional statistical tools, namely the Principal Component (PC) transformation and Minimum Noise Fraction (MNF) to better investigate the relationship of the channels, their ratios or derivatives and outline the some correlative features with the other elements of data.
High resolution aeromagnetic and radiometric data are important for mapping structure, lithology, and alteration at both the prospect and regional scale for targeting in epithermal gold systems. I'm will focus on the aeromagnetic data and illustrate the value of the 3D magnetization vector inversion modeling. Amer will focus on the radiometric data and illustrate enhancement techniques common in the processing of hyper spectral data but not commonly utilized in geophysics. Epithermal mineralization at El Aguila was mined by open pit and produced 345,000 tonnes at an average grade of 4.4 g/tonne Au and 43 g/tonne Ag. Mineralization consists of high grade structural feeders into a "manto" of silicified permeable Tertiary volcanic rocks consisting of volcanic breccia and tuff. Structurally controlled Au-Ag and base metal mineralization at La Arista consists of quartz veins and stockwork hosted in strongly silicified Tertiary rhyolite intrusive, breccia, andesite, tuff, and agglomerate. Within the same deposit Cretaceous carbonate and sandstone units below and or adjacent to the mineralized volcanic host are targets for base metal skarn mineralization in addition to the epithermal veins. From initial startup July 1, 2010 through June 30, 2013 the El Aguila-Arista Project has processed a total of 811,496 tonnes averaging 3.85 g/t gold and 290 g/t silver to recover 82,409 ounces of gold and 6,813,685 ounces of silver.

I want to thank Gold Resource Corporation (NYSE MKT: GORO) and their operating subsidiary Don David Gold S.A.I.C. (DDG) for permission to present their data and particularly Mr. Barry Devlin, Vice President of Exploration for Gold Resource Corporation for his support and guidance on the geology and help in getting these data published.
Slide 2: The property shown here in blue is located in the State of Oaxaca in southeastern Mexico 4 km north of the village of San José de Gracia approximately 40 kilometers southeast of the Capital City, Oaxaca. The El Aguilla and La Arista deposits are located on the southeastern part of the property.
We commonly refer to helicopter airborne magnetic surveys as "High Resolution" which can imply a variety of specifications not always clearly outlined. The first I remember hearing this terminology was the shift from flying proton precession magnetometers to cesium vapor magnetometers. It's come to be more about specifications and processing of the data. This is addressed in some detail by Ted Urquhart in a presentation he gave at the 2013 PDAC which is available at www.new-sense.com. Of particular importance in the 50Hz sample rate not commonly utilized in airborne systems today and how it allows the better identification and removal of helicopter source noise from in the data.

For best results - fly with helicopter

- Best and safest choice of helicopter -- Astar 350B3
- By far the best and safest configuration -- Stinger
- Need to fly with variable speed.
- Essential to collect data at 50 HZ
- One needs to be vigilant with Safety.
Slide 4: This is a composite image of four of the 1:50,000 geology maps published by the Servicio Geológico Mexicano showing the airborne survey boundary in black. The survey was flown in a northeast direction at a spacing of 300m with infill areas shown in blue at 100m line spacing. The mean terrain clearance was 31 meters.

Regionally, the district consists of Tertiary rhyolite to dacite flows overlying Cretaceous sediments consisting of arenites and carbonaceous sediments. This sedimentary package is intruded by Tertiary rhyolite and granodiorite stocks responsible for much of the mineralization in the region. For purposes of the review of the aeromagnetic data we will focus on the area identified in red around the La Arista and El Aquilla deposits.
Slide 5: This is a shaded (45º) total field aeromagnetic image of the full survey. The La Arista and El Aguilla deposits are located in the central part of the red focus area.
1. The complex pattern of high magnetization volcanic flows are identified.
2. Overprint of west-northwest linear fabric consistent with the structural controls at La Arista
3. Termination of west-northwest structural fabric commonly by northerly trending structures bound younger volcanic flows
4. Relatively smooth magnetic areas caused by non-magnetic sediments or rhyolite flows and intrusives, and possible magnetite destructive alteration of the volcanic flows.
Slide 6: This is a shaded (45°) reduced to pole image of the full survey. The La Arista and El Aguilla deposits are located in the central part of the red focus area.

1. Complex pattern of magnetic highs and lows in various volcanic flows in reduced to pole suggests remanence is part of the total magnetization.

2. West-northwest fabric of magnetic linears appears to terminate at a north-northeast magnetic boundary suggesting volcanics to the west are younger.

3. Structural fabric picks up again around the El Rey deposit area.

3. Relatively smooth magnetic pattern caused by thin volcanic cover over the Cretaceous sedimentary package or the intrusion of non-magnetic rhyolite. Note the area 5km west of the La Arista boundary may identify alteration or rhyolite intrusion. This indicates most intrusives are not magnetic and probably granite or rhyolite composition.

4. Higher amplitude magnetic circular highs (north and northeast edge of red focus area) are suspected to identify granodiorite (?) intrusive or andesite feeders.
Slide 7: This is an idealized stratigraphic section of the La Arista property.

1. Note the Cretaceous sediments with overlying Tertiary volcanic stratigraphy intruded by Tertiary granite, diorite, and rhyolite.

2. Epithermal Au-Ag mineralization presently being mined at La Arista is hosted in locally derived volcanic breccias, lithic tuffs and agglomerate, rhyolite and andesite with economic grades of base metal mineralization as skarn mineralization in the carbonates of the lower sedimentary section.
Slide 8: This is a property geology map prepared by DDG exploration team.
1. Mineralization at El Aguilla (red diamond) occurs as veins in rhyolite flows and underlying mantos in sediments.
2. The El Aire epithermal deposit (small black lines 150m southwest of La Arista) identifies some of the historical mining in the area.
3. Oldest rocks exposed are Cretaceous sediments shown in green.
4. Next are lithic tuffs, andesite, and rhyolite flows which host mineralization shown in blue.
5. The sediments and rhyolite flows are intruded by non-magnetic rhyolite (pink) with associated silicification (veined and massive).
6. Surrounding areas are covered by generally post mineral rhyolite to dacitic volcanic flows (tan).
This is a shaded image (45º) of the total field aeromagnetic data. The earth's field characteristics in this are: total field 39,180 nT, inclination = 44.33º, declination = 4.09º.

1. The complex pattern of high magnetization post mineral ignimbrites southwest of the focus area. The ignimbrites are ridge formers in the district. The northwest boundary is a structural contact with up to the south.

2. A smooth magnetic pattern is defined in the central part of the focus area over the exposed non-magnetic rhyolite and sediments. Subtle magnetic highs on southern boundary of the sediments, but extending into the sediments is a bit of a dilemma. If sediments are not magnetic as suggested by physical property work then what is the source of the magnetic high rimming the sediments. Could this be skarn developed on structural boundaries of the sediments? If there is higher magnetization of the sediments than suggested by physical property work then the magnetic highs should be shifted more on to the exposure of sediments.

3. Irregular northwest trending magnetic linears in the andesite going through the El Aguilla deposit (black diamond) and the La Arista deposit. The magnetic highs just northwest of El Aguilla are culture but those helping define the trend to the southeast geology. Some of the magnetic low defining structure may identify magnetite destructive alteration or windows to the underlying non-magnetic sediments.

4. A northerly trending magnetic linear identifying a normal fault with strongly magnetic post-mineral andesite agglomerates to the east and northwest. The agglomerates are post mineral but linear in the magnetic data still apparent suggesting the structure effected paleo-surface on to which the agglomerates were deposited.

5. On the north part of the focus area is a high magnetic response interpreted to identify a buried diorite intrusive. This is important because dikes of diorite at La Arista appear to be syn-mineral to pre-mineral. Adjacent intense magnetic low suggests possible remanent magnetization as part of the total magnetization of the intrusive. Rhyolite intrusive into the volcanics is an alternative source for the adjacent magnetic lows but there is no support for this in the geology.
This is a shaded image (45º) of the reduced to pole aeromagnetic data. The earth's field characteristics in this area: total field 39,180 nT, inclination = 44.33º, declination = 4.09º.

1. The reduced to pole has done little to minimize the complexity of the magnetic ignimbrite flows to the south of the focus area. This was expected because the ignimbrite likely has a strong remanent component to the total magnetization. We have all been plagued by such magnetic environments.

2. The area of non-magnetic sediments and rhyolite in the central part of the focus area is now a smooth magnetic high with higher susceptibility sources indicated. This could be important to us in targeting skarn mineralization.

3. The east central part of the focus area covered by pre-mineral andesite flows (mineralized) identifying a broken pattern caused by structure. Magnetic linears are not as well defined in the reduced to pole image. This is not uncommon in my experience.

4. The post-mineral andesite agglomerate is identified as a "plate-like" magnetic high with edges which fit the geology. I expect the agglomerate does not have as strong a remanent component as the ignimbrites to the south or the component in more randomized.

5. The buried diorite (?) intrusive or andesite feeders on the north side of the project area is better defined by a magnetic low response "tails" off to the south which does not fit the geology we know in this area.
This is a shaded image (45°) of the analytic signal. It's been upward continued by 25m to minimize some of the near surface noise in the data.

1. The analytic signal starts to correlate better with what we know about the geology and their physical properties. A characteristic of this operator is that it places a high over the source independent of induced field parameters and remanent magnetization direction and amplitude for dike-shaped sources. For plate-shaped sources it puts a high on the edges.

2. Subtle magnetic highs over the pre-mineral andesite with possible indication of alteration along northwest structure.

3. The boundaries of post mineral magnetic flows and the circular magnetic high interpreted to identify magnetic intrusive are clearly defined.

4. The area non-magnetic sediments intruded by non-magnetic rhyolite is characterized by the lack of clearly defined sources. This suggests magnetic highs defined by the total field and reduced to pole within the sediments may have resulted from the response of magnetic andesites outside the boundary of the sediments containing remanent magnetization.

5. Yellow stars identify some anomalies we will track in the modeling.
Slide 12: This is an illustration of the magnetic vector inversion developed by Robert G. Ellis at Geosoft Inc. (www.geosoft.com). I'm not an inversion expert but basically the software inverts on the total magnetization vector allowing its direction and amplitude to vary.

1. I have used this inversion extensively in many different magnetic environments over the last year since it became publically available in April 2012.
2. The amplitude component seems to be relatively robust is defining the position of magnetic sources independent of induced field direction and remanent magnetization.
3. I have not found the perpendicular and projected component to be particularly useful in interpretation. I would like to see these converted to an azimuth and inclination of the total magnetization vector.
Slide 13: This is a depth slice 200m below topography through the MVI susceptibility (amplitude component) voxel using the Geosoft® VOXI software.

1. 80m x 80m x 40m cells in MVI inversion
2. Good correlation to what we understand about the geology and reasonably good correlation with the analytic signal result
3. Small magnetic highs within the sediments are skarn targets or small diorite intrusives that are contemporaneous with mineralization at La Arista. The results are consistent with the interpretation of the analytic signal result.
4. Northwest axis of the magnetic low suggests this may be the axis for the intrusion of the rhyolite and subsequent silicification.
5. We will compare these two inversion along these two sections.
6. Black stars identify anomalies being tracked from the analytic signal.
We did a conventional susceptibility inversion of the total field magnetic data using the Geosoft® VOXI software. This is a depth slice at 200m below surface of the inverted magnetic susceptibility. This result is similar to what we would qualitatively interpret from the reduced to pole transform (Slide 10) where magnetic sources derived from the edge of the magnetic plate to the south are projected into the area of non-magnetic rocks. Black stars identify anomalies being tracked from the analytic signal.
Slide 15: This is a section A-A' showing the results of the MVI susceptibility (top) and the conventional susceptibility (bottom).

1. The green in the drill holes are the sediments, the grey is the andesite, the brown is skarn mineralization and black is the trace of the epithermal veins.

2. The MVI inversion fits what we know about the geology and physical properties. We don't see evidence in the susceptibilities of the sediments or rhyolite of appreciable magnetic susceptibility except where there is skarn mineralization. Skarn is weakly magnetic (0.003 SI) but generally small sources so they are difficult to resolve in either inversion. There is hope that some of the higher susceptibility or larger magnetic sources in the sedimentary section are larger skarn bodies.
Slide 16: This is a section B-B’ showing the results of the MVI susceptibility (top) and the conventional susceptibility (bottom).

1. The green in the drill holes are the sediments, the grey is the andesite, the brown is skarn mineralization and black is the trace of the epithermal veins.
2. Similar correlation of MVI result what we know about the geology.
3. Possible feeder for the rhyolite at depth.
4. Decent skarn targets but possibly deep. Shallower skarn targets on boundary on the interpreted diorite intrusive to the northeast.
Observations about Aeromagnetics

Aeromagnetic data useful for mapping lithology, alteration, structure in epithermal environments

Survey specifications, contractor selection, and qualified oversight make a difference when it come to defining specific targets

Magnetic vector inversion appears to do a good job of identifying the source locations in environments where remanence is present.
Radiometric data analysis have been customarily processed as three-color composite made up from gridded channels and/or ratios of U, Th and K. This method, while effective, may not reveal and take advantage of the full complexity of radiometric data. Furthermore, with the advancement of sensors and software, one can actually use gamma-ray spectral data to discern features of interest. Spectral matching, unmixing and identification have been successfully used in remote sensing spectroscopy and there is no reason why similar classification techniques should not be used with the gamma-ray spectroscopy/radiometric data.
Slide 19: Brief overview of how Principal Component Analysis (PCA) works and how it can be used to seek correlations in the various data elements or channels.
Two ways to get there:

1. Use PCA and look for dimensionality in the Channels and Ratio components (Easier)

2. Use the spectrum (spectral domain) and try to create a spectrum you can use

Problems:
1. Oasis Montaj is not suited for this
2. Praga is only moderately capable
3. You need to re-create a spectrum and use a program suited for spectral analysis

Australians caution against using whole-scene analysis in Gamma ray

Slide 20: Slide outlines challenges one encounters when trying to use classification tools on the gamma ray spectroscopy data as there are no dedicated software packages so one needs to use several. On top three ternary diagrams are visible showing relationships between different classes selected through the PCA, while the graph outlines the regions of gamma-ray spectrum that can be used for “spectral features” of interest. Australian geoscientists advise against using whole-scene classification as they argue that there are no unique statistical identifiers in the gamma ray data, which may be the case in the “simple” approach, but not if you use the whole spectrum.
The focus is on looking for similarities (similar spectra) — same as it is in reflectance or thermal emission spectra. The classification is Data and Expert driven as the geology is known, so particular spectral features can be assigned to the particular rock type.

Hence one should look for “signatures” of:
1. sediments,
2. Rhyolite and/or altered rhyolite,
3. andesite and
4. post-mineral volcanics

Inappropriate Use of Statistics

3 different rock types

Gamma-ray signatures are not unique
Whole scene classification is dangerous

From Bruce Dickson:
The “Easy” way

Components: 1 2 3 4 5 6 7

This is similar to ratios, but you expend them with additional 4 permutations (you split the curve in more segments versus the full range of the spectrum)

You are adding the two-versus-one combinations (e.g. K+U versus Th)

Slide 22: Slide shows how the spectral emission curve is split into different components (spectral regions) where particular K, U or Th features are emissive or absorptive – in this test approach, about 7 “bands” were chosen in the gamma-ray emissive spectrum. K tends to dominate the emissive spectrum, but can be used to distinguish some of the volcanic rock units and/or alteration types.

In majority of the cases, spectrally, K is the dominant feature, but will vary with the type of the rock and the amount of alteration. This is also evident spectrally
Slide 23: Slide shows some of the spectral features (averaged from about 300 “hits” in the andesite and rhyolite unit regions) that can be used to differentiate andesite from rhyolite and how the two differ in the particular classes. Rhyolite group tends to have more emission features in the U-region of the gamma-ray spectrum.
Slide 24: Brief description of the statistical analysis and class segmentation using Minimum Noise Fractionation function, Statistical Indices and N-dimensional visualizer that can be used to identify particular end member clusters along the Eigen-vectors.
With defined endmembers you carry out the classification...

...and validate how good is the match versus the input class spectrum.

Slide 25: Example of particular endmember classes from the gamma-ray data and plots of likelihood vs. infeasibility which can be used to further refine the class and isolate particular features from the background.
Slide 26: Comparison between the traditional ternary RGB ratio image and the spectral classification results; the latter showing better definition of units and more classes than the traditional RGB composite.
Slide 27: The spectral method is fairly good match with the mapped surface geology and alteration trends and highlights some of the alteration trends in the district.
Radiometric data can supplement lithologic inferences from the other types of geophysical data.

Slide 28: Slide showing correlation of spectral-derived radiometric composite map and modeled magnetic section with the geological interpretations of the area.
Radiometric observations

- With some a-priori knowledge and ability to observe radiometric data in spectral/ emissive domain, particular classes can be extracted.
- Traditional methods using ternary and/or individual channel ratios may not be able to reflect the full complexity.
- By expanding the classes and looking for particular signatures of target groups one can attempt classification of a wider scene area.
- Have barely scratched the surface as the full spectral analysis is far more complex and once the actual spectrum is built it needs to be compared against something — unlike reflectance and thermal spectroscopy labs there are no such things for gamma-ray data.
- Gamma-ray data should be treated as point-measurements rather than areal measurements now that the technology has caught up — no more need for ternary maps when better imagery can be created.
Geophysical Characterization of the Cahuilla Epithermal Gold-Silver Deposit, Imperial County, California

Chester S. Lide, Paul Stubbe, Thomas K. Mancuso, Frank Fritz, William C. Bagby
Abstract

Geophysical Characterization of the Cahuilla Epithermal Gold-Silver Deposit, Imperial County, California

Chester S. Lide, Paul Stubbe, Thomas K. Mancuso, Frank Fritz, William C. Bagby

The Cahuilla project is a low-sulfidation, hot springs, gold-silver deposit located in northwest Imperial County, California. The system occurs within Pliocene-Pleistocene rocks and is located along the western margin of the Salton Trough, an area of active crustal extension associated with the northwest-trending San Andreas and San Jacinto fault systems. The mineralization is closely associated with the Truckhaven Fault, which places Jurassic plutonic rocks of the Peninsular Batholith against the Palm Springs Group, a sequence of fine- to coarse-grained clastic sediments and rhyolitic pyroclastic rocks. Mineralization consists of Au- and Ag-bearing chalcedonic veins and stockwork veinlets, within a large tabular envelope of disseminated mineralization hosted in sediments of the Palm Springs Group in the hanging wall of the Truckhaven Fault zone. Silicification is commonly associated with precious metals and occurs as open-space fracture and fault filling and replacement of fine-grained sedimentary rocks. Clay alteration occurs along the Truckhaven Fault zone and in its hanging wall, likely resulting from descending steam-heated meteoric water. To date, 383 holes have been drilled and a NI 43-101 compliant indicated resource of 1.010 million ounces of gold and 11.855 million ounces of silver has been defined at a 0.008 oz Au per ton cutoff. Current exploration is primarily focused on the discovery of deeper high-grade vein or replacement zones with a secondary focus on the expansion of the near-surface resources.

Geophysical exploration programs conducted at Cahuilla include CSAMT, MT, IP/Resistivity, and gravity surveys.

The gravity data show a very strong gradient associated with the Truckhaven Fault and indicates that the presently-defined resource lies at the intersection of the Truckhaven Fault and a major northwest-striking fault zone. The CSAMT and MT surveys show the broad area of disseminated mineralization as a vertical wedge-shaped zone of high resistivity in the hanging wall of the Truckhaven Fault. This high-resistivity zone correlates with silicification that is spatially associated with the precious metal mineralization. Within the broad high-resistivity zone, coincident linear zones of higher resistivity and highs in the vertical derivative of the gravity are interpreted to reflect densification caused by increased silicification and/or veining associated with structural zones. Many of the highest grade gold-silver intercepts, to date, are within these areas of apparent densification. Linear resistivity lows and gravity lows correlate with zones of argillization along the Truckhaven Fault.

A moderate amplitude IP high is centered beneath and extends within a zone that contains many of the highest-grade intercepts within the presently-defined resource.
Acknowledgements

- Teras Resources Inc.

- Mine Development Associates
  - Steve Ristorcelli, Cindy Walker
Forward-Looking Information

This presentation may contain “forward-looking information” within the meaning of applicable Canadian securities legislation. All statements, other than statements of historical fact, included herein may be forward-looking information. Generally, forward-looking information may be identified by the use of forward-looking terminology such as “plans”, “expects” or “does not expect”, “proposed”, “is expected”, “budgets”, “scheduled”, “estimates”, “potential”, “forecasts”, “intends”, “anticipates” or “does not anticipate”, or “believes”, or variations of such words and phrases, or by the use of words or phrases which state that certain actions, events or results may, could, would, or might occur or be achieved. In particular, this presentation contains forward-looking information in respect of the potential deposits, mineralization, potential resources and exploration potential in respect of Teras Resources Inc.’s (the “Corporation”) projects and the potential costs, approvals and agreements in respect of the Corporation’s projects. This forward-looking information reflects the Corporation’s current beliefs and expectations and is based on information currently available to the Corporation and on assumptions the Corporation believes are reasonable. These assumptions and expectations, some of which can be found in the Corporation’s disclosure documents on the SEDAR website at www.sedar.com, include, without limitation, the following: the actual results of drilling and exploration being equivalent to or better than anticipated or historical results, continuing approvals from governmental authorities in respect of its projects, continuing positive relationships aboriginal nations that have interests in the Corporation’s projects and future costs and expenses being based on historical costs and expenses, adjusted for inflation. Forward-looking information is subject to known and unknown risks, uncertainties and other factors that may cause the actual results, level of activity, performance or achievements of the Corporation to be materially different from those expressed or implied by such forward-looking information. Such risks and other factors are disclosed in the Corporation’s regulatory filings and disclosure documents found on the SEDAR website at www.sedar.com, and may include, without limitation, the following: the early stage development of the Corporation and its projects; general business, economic, competitive, political and social uncertainties; commodity prices; the actual results of current exploration and development or operational activities; competition; changes in project parameters as plans continue to be refined; accidents and other risks inherent in the natural resources industry; lack of insurance; delay or failure to receive board or regulatory approvals; changes in legislation, including environmental legislation, affecting the Corporation; timing and availability of external financing on acceptable terms; conclusions of economic evaluations; and lack of qualified, skilled labor or loss of key individuals. Although the Corporation has attempted to identify important factors that could cause actual results to differ materially from those contained in forward-looking information, there may be other factors that cause results not to be as anticipated, estimated or intended. Accordingly, readers should not place undue reliance on forward-looking information. The Corporation does not undertake to update any forward-looking information, except in accordance with applicable securities laws.
The Cahuilla project is located along the western margin of the Salton Trough, an area of active crustal extension associated with the northwest-trending San Andreas and San Jacinto fault systems.

Previous exploration at Cahuilla has been conducted by Fischer-Watt, Homestake, Kennecott, and Newmont and Consolidated Goldfields.

The Cahuilla project is currently being actively explored by Teras Resources Inc.

Deep core drilling has recently been conducted during September and October 2013. Results are pending at the time of this writing.
Cahuilla Project - Geologic Map
Showing Approximate NI-43-101 Compliant Resource Area
The approximate trace of Modoc Fault Zone is shown as the heavy black line. The approximate boundaries of the NI 43-101 compliant resource is shown as the closed dashed line. This outline is used as a reference on all subsequent plan maps.

The mineralization is closely associated with the Modoc Fault, which places Jurassic plutonic rocks of the Peninsular Batholith against the Palms Springs Group, a sequence of fine- to coarse-grained clastic sediments and rhyolitic pyroclastic rocks.

Mapped units consist of the Jurassic Quartz Monzonite (Jqm), Canebrake Conglomerate (Qc) a fanglomerate unit, shown in green, the Palm Springs (Qps) sediments shown in light blue, rhyolite dikes (Qr), hot-springs sinter (Qs), arkose (Qa), older alluvial fans (Qaf), Recent alluvial fans (Qol) and Recent alluvium (Qal)

Cahuilla is low-sulfidation, hot-spring gold-silver deposit. It is currently thought to represent a shallow-boiling system as described by Albinson, et. al., 2001. Mineralization consists of Au- and Ag-bearing chalcedonic veins and stockwork veinlets, within a large tabular envelope of disseminated mineralization hosted in sediments of the Palm Springs Group in the hanging wall of the Modoc Fault zone.
3D perspective view of the Cahuilla project, looking to the northwest, showing drill-holes, the NI 43-101 compliant resource and the Modoc Fault Zone.

The pink surfaces are the resource at 0.008 ounce per ton gold-equivalent cut-off (Ristorcelli, 2012). Depth to mineralization increases to the east.

The teal surface is the Modoc Fault as defined by drill-hole intercepts. The green line along the topographic slope is the surface trace of the Modoc Fault. The Modoc Fault lies at the base of a steep range front rising approximately 400m in elevation in a distance of approximately a kilometer to the northwest of the surface trace.

Gold occurs as high-silver electrum and native gold and is contemporaneous with chalcedony deposition which occurs as open-space fracture and fault filling and replacement of fine-grained sedimentary rocks (Ristorcelli, 2012). At least two episodes of gold deposition and multiple phases of chalcedony deposition have been identified.

Vein and fracture mapping along the Modoc Fault by earlier workers observed that the wider vein and fractures where associated with dextral strike deflections, whereas, sinistral deflections tended to be closed (Byington, 1989). They noted that high vein density occurred along a N74W, 60SW dip orientation.

Prior to Teras’ 2013 drilling, 383 holes have been drilled and a NI 43-101 compliant indicated resource of 1.01 million ounces of gold and 11.855 million ounces of silver has been defined at a 0.008 oz. Au per ton cutoff.
Schematic interpretive NW to SE section of the Cahuilla vein system.

Key elements are;

1) Vein and disseminated mineralization along, and within the footwall of the Modoc Fault.
2) Roughly flat-lying tabular zone of disseminated mineralization in the hanging-wall of the Modoc Fault and or other sub-parallel faults.
3) Exploration for cross-cutting feeder veins and possible sub-parallel faults within and below the tabular mineralization.
4) Possible post-mineral offset of system down to the southeast, based on apparent offset of sinter horizons.

5) The primary target for 2013 drilling is high-grade vein mineralization along the Modoc Fault and/or parallel vein systems at depth beneath the resource area.
An example of altered core showing multiple stages of chalcedonic veining, breccias and silicified siltstones.
Geophysical Surveys

- IP/Resistivity surveys: 1989: 5 Lines
- CSAMT surveys, 1994, 1996: 19 Lines
- Gravity survey, 2013: 389 stations
- MT survey, 2013: 4 Lines
- Phase IP test line, 2013: 1 line.
Map showing locations of geophysical data shown in this presentation.
CSAMT inversion resistivity section for line 1. The view is to the northeast. This section is roughly correlative with the schematic section presented in the earlier slide. Interpreted features related to the schematic section are shown.

High resistivity is shown as blues to whites and low resistivity as purples.

There is a wide range of resistivity values from less than 2 ohm-meters in saturated, clay-rich sediments beneath the southeastern end of the line, to over 1000 ohm-meters for the quartz monzonite in the footwall of the Modoc Fault.

High-resistivity of 500 ohm-m is associated with strong silica replacement and veining associated with the gold resource.

Low-resistivity is associated with argillic alteration in the hanging-wall of the Modoc Fault, a parallel fault zone beneath approximately station 700 and clay-rich sediments beneath the eastern end of the line.
Drill log estimates for Depth 0 to 50m below ground surface.
Black Dots: Drill-hole intervals Silica Intensity of 3 greater.
Green Squares: All drill-hole intervals.

Silica

CSAMT Inversion Resistivity
50 m Depth Below Surface

Results of 2D smooth-model Inversion.
Contour Interval: Logarithmic, 7 per decade
Plan map of CSAMT 2D inversion resistivity for a depth of 50 meters below surface, with drill-hole estimates of silica intensity on a scale of 0 to 4 with increasing intensity. The black dots show estimated intensity of 3 or greater. The green squares show all assays for that depth interval that are below 3.

Within the resource area there is a general correspondence of the higher silica estimates with the high resistivity. A linear resistivity high extending to the southwest of the resource area is seen to gradually pinch-out to the southwest. This zone appears to be offset, in an apparent dextral sense, from the central resource area, on a northwest trending fault (Fritz, 2013).

Along the east and southeast side of the resource, high-resistivity zones appear to be displaced down to the east along northerly-trending faults.

High resistivity along the northwest edge of the survey area is quartz monzonite in the foot-wall of the Modoc Fault. Low resistivity along the southeast side of the Modoc Fault is argillic alteration in the hanging wall of the fault.

Low resistivity along the southeastern side of the survey area is largely due to clay-rich sediments of the Palms Springs Formation.

High resistivity at eastern edge of grid is near surface dry alluvial gravels.
Drill log estimates for Depth 0 to 50m below ground surface.
Black Dots: Drill-hole intervals with logged argillic alteration intensity of 3 or greater
Green Squares: All drill-hole intervals

Argillic

Plan map of CSAMT 2D inversion resistivity for a depth of 50 meters showing estimates of intensity of argillic alteration on a scale of 0 to 4 with increasing intensity.
The black dots show estimated intensity of 3 or greater.
The green squares show all estimates for the depth interval that are below 3.

Within the resource area there is a tendency of the higher argillic alteration estimates to occur within lower resistivity and flank the higher-resistivity silicified zones.
Drill assays for all depths.
Black Dots: Drill-hole intervals with Au of 0.1 opt. or greater.
Red Box: Au of 0.25 opt or greater.
Green Squares: All drill-hole intervals.

CSAMT Inversion Resistivity
50 m Depth Below Surface
Results of 2D smooth-model Inversion.
Contour Interval: Logarithmic, 7 per decade
Plan map of CSAMT 2D inversion resistivity for a depth of 50 meters below surface.

Shown on this map are drill-hole assays for all available drill holes.
The black dots show gold assays of 0.1 ounces per ton, or greater.
The red squares show assays of 0.25 ounces per ton or greater.
The green squares show all assays for that depth interval that are below this grade.

Within the resource area, the higher grade intercepts are closely associated with high resistivity which is consistent with increased silicification.

West-northwest trends in resistive (silicified) zones, with possible secondary north-northeast trends are possible controls on the distribution of higher-grade mineralization. Note that continuity of high-grade is not implied, these are simply apparent trends defined by the distribution of the higher-grade intercepts.

The west-northwest trends observed are consistent with trends of increased vein density by earlier workers (Byington, 1989).

Note the intercept in the vertical drill-hole in the center of the resistivity ridge that extends to the southwest of the resource area.
Plan map of CSAMT 2D inversion resistivity for a depth of 150 meters below surface.

Shown on this map are drill-hole assays of Ag for a depth interval of 100 to 200m below surface.
The black dots show assays of 1.0 ounces per ton Ag or greater.
The green squares show all assays below this grade.

The higher-grade silver values suggest WNW and NE trends and are suggest association with gradients observed in the CSAMT resistivity.
The highest grades cluster along a zone of higher resistivity at a change in strike of the Modoc Fault and/or intersecting structures.
Contour map of the Complete Bouguer Anomaly of the gravity at a reduction density of 2.25 gm/cc.

The gravity is dominated by a strong gradient of over 20 milligals decreasing to the southeast. This reflects the Modoc Fault and possible sub-parallel faults and a significant thickness of the sediments to the southeast. Steeper intervals within the gradient pass through the resource area.

The general northeasterly-trending contours take an easterly (dextral) deflection across the resource area which roughly mimics the orientation of the trace of the Modoc Fault. The zone of deflection of the contours defines a NW trending zone that extends across the survey area. The apparent offset of the high-resistivity silicified zone within the resource area appears to be related to this feature.
Horizontal Gradient of the CBA Gravity

Contour Interval: 0.0005, 0.002 mGal/m
Reduction Density: 2.25 gm/cc
Map of the Horizontal Gradient Magnitude (HGM) of the Complete Bouguer Anomaly of the gravity at a reduction density of 2.25 gm/cc.

The HGM has delineated several areas of increased gradient that delineate high-angle density contrasts/structures which include:

- A narrow gradient along the north and east side of the resource area that corresponds closely to the trace of the Modoc Fault.

- A broad gradient reflecting a deeper sub-parallel structure passes beneath the southern portion of the resource area. This gradient shows an easterly bend or offset across the NW-trending structure that crosses beneath the western portion of the resource area. This structure appears to be a relatively simple range front fault to the west of the resource area. It becomes more complex to beneath the resource area, where it may be associated with suspected faults that offset the mineralization. This gradient broadens to the east of the resource, suggesting increased depth. Shallow sourced gradients indicating northerly striking faults are superimposed on this broad gradient along the east side of the resource area.
Drill log estimates for Depth 0 to 50m below ground surface.
Black Dots: Drill-hole intervals with Silica greater than 3.
Green Squares: All drill-hole intervals.

SILICA

Calculated First Vertical Derivative of CBA Gravity
Contour Interval: 0.0005, 0.002 mGal/m
Reduction Density: 2.25 gm/cc
Map of the Calculated First Vertical Derivative (1VD) of the Complete Bouguer Anomaly. The vertical derivative enhances relatively shallow density variations.

Shown on this map are drill-log estimates of silica intensity on a scale of increasing intensity from 0 to 4. The black dots show estimated intensity of 3 or greater and the green squares show all assays for that depth interval that are below 3.

Within the resource area there is a close correspondence between highs in the 1VD, estimated silica intensity and high resistivity in the CSAMT data.

The central portion of the resource area lies within a complex zone of intersection of linear highs, which corresponds closely to the linear resistive highs observed in the CSAMT maps.

The high along the Modoc Fault may be related to fresh quartz monzonite, however silicification and mineralized intercepts are encountered locally along the footwall.

A pronounced change in the character of the highs beneath the western side of the resource area corresponds to the location of the NW-striking fault inferred from the CSAMT maps.

An area of subdued high, immediately east-southeast of the resource area, suggests densification at depth and is very sparsely tested.
Map of the Calculated First Vertical Derivative (1VD) of the Complete Bouguer Anomaly with drill-hole estimates of argillic alteration intensity on a scale increasing intensity from 0 to 4.
The black dots show estimated intensity of 3 or greater.
The green squares show all estimates for that depth interval that are below 3.

The most intense argillic alteration shows a tendency to correlate with 1VD lows.
Map of the Calculated First Vertical Derivative (1VD) of the Complete Bouguer Anomaly.

Shown on this map are all drill-hole assay intervals of Au in ounces per ton.  The black dots show intervals with Au of 0.1 ounce per ton or greater.  The green squares show all assays for that depth interval that are below 3.

Within the resource area, there is a close spatial correlation, in plan view, between the higher grade intercepts and high vertical gradient.
Drill log estimates for Depth 0 to 50m below ground surface.
Black Dots: Intervals with Pyrite of 2 percent or greater.
Green Squares: All drill-hole intervals.
Showing location of IP/Resistivity line.

Calculated First Vertical Derivative of CBA Gravity
Contour Interval: 0.0005, 0.002 mGal/m
Reduction Density: 2.25 gm/cc
Map of the Calculated First Vertical Derivative (1VD) of the Complete Bouguer Anomaly.

Shown on this map are drill-hole estimates of pyrite percent. The black dots show estimates of 2 percent or greater. The green squares show all assays for that depth interval that are below 2 percent.

A high occurrence of pyrite is noted beneath the central portion of the resource area. There is close correspondence of the pyrite content to the highest 1VD gravity and general proximity, in plan, to the higher-grade intercepts.

Also shown on this map is the location of the test IP line. A high occurrence of pyrite and a peak in the vertical derivative is observed beneath station 1050 to 1300 on this line.
IP/Resistivity) 2D inversion sections for the test line shown on the previous slide. The resistivity section is shown on the top and the IP (decoupled phase) section is shown on the bottom.

A high-resistivity wedge associated with silicification within the resource area centered beneath stations 1050 to 1350. The highest resistivity and thickest section of resistive wedge is located beneath the 1200 to 1350 which corresponds to the peak in the vertical gradient of the gravity.

A well-defined, moderate amplitude (16 milliradians) IP high is centered beneath Stations 1200 to 1300 and below the thickest segment of the resistive wedge. The location and dimensions of this anomaly agree well with the location of higher estimated pyrite content. This IP anomaly lies below a zone of higher-grade gold intercepts.

High-resistivity at surface beneath station 600 is associated with silicification /mineralization located in the footwall of the Modoc Fault.
MT Survey – Line 1
Two-dimensional inversion resistivity section.

Showing location of Modoc Fault from drill control and 2013 deep core hole CAH-303.

Drill hole intercepts of 0.25 opt and greater, projected from 50m either side of line, and a profile of the vertical derivative of the gravity, are shown for reference.

Drill hole CAH-303 was designed to test for deeper vein mineralization associated with the Modoc Fault. The hole encountered intensely-altered, silicification and veining at depth on the Modoc Fault as shown. Assay results are pending at the time of writing.

Note the resistive body at depths of approximately 300m below surface beneath station 1500.
Contour map of total magnetic field, reduced to the N. magnetic pole from 1995 Helicopter magnetic survey. Total magnetic field data were recovered by hand-digitizing counters from scanned contour maps.

Assay intervals of 0.1 ounces per ton Au and greater are shown as black dots.

There is subtle suggestion of spatial correlation a relatively narrow embayment/low beneath the center of the resource area and a suggestion of parallel trends to the south.

The broad magnetic low to the south of the resource area shows no correlation with the interpreted depth of the quartz monzonite along the east side of the map from the gravity data. Magnetite destructive alteration by hydrothermal fluids is a possible source of this low.
Summary

- The Resource Area lies within a complex area that appears to be a structural intersection.

- The flat-lying tabular resource area is defined as high resistivity in the hanging wall of the Modoc Fault.

- Silicification is mapped as high resistivity, as well as, highs in the 1st vertical derivative of the gravity.

- The linear nature of many of the high-resistivity/high-density zones suggest possible control of silicification/vein-density by higher-angle fracture zones within the flat-lying tabular resource.

- West-northwest trends are observed both the resistivity and gravity and are suggested in the distribution of higher-grade intercepts. North-northeast trends are also suggested.
Summary

- A northwest-trending fault zone is interpreted to cross the western side of the Resource Area and there is strong evidence in the CSAMT data of apparent dextral offset of the altered/mineralized zone.

- A broad zone of higher horizontal gradient defines a parallel fault zone to the south of the Modoc Fault.

- This structure passes beneath the southern portion of the resource area and takes an easterly bend beneath the Resource Area and continues to the northeast at greater apparent depth. The bend may reflect offset by the northwest-trending fault zone mentioned above. The relationship of this fault to the mineralization is not presently understood.
Summary

- A distinct, moderate amplitude IP high, observed on a single test line, peaks in the central portion of the Resource Area, beneath the highest resistivity, highest inferred density and highest grades.

- Coincident gravity and resistivity highs extending to the northeast, southwest and southeast of the Resource Area present under-tested targets.

- A high-resistivity zone at depths of approximately 300m, and located in the center and minima of a broad RTP magnetic low is untested.

References


GREAT BASIN AND WESTERN CORDILLERA MINING GEOPHYSICAL SYMPOSIUM
HYCROFT MINE GEOPHYSICAL CASE HISTORY
VORTEX ZONE DISCOVERY

James Wright / J. L. Wright Geophysics

APPARENT RESISTIVITY @ 865 Hz CO-PLANAR LOOKING NORTHEAST
Abstract

Hycroft Mine Geophysical Case History and Vortex Zone Discovery
Humboldt County, Nevada

James L. Wright, J. L. Wright Geophysics

The Hycroft Mine is located 86 kilometers west of Winnemucca in Humboldt County, Nevada and operated by Allied Nevada Gold (ANV) Corporation (NYSE-AMES: ANV). Figure 1 shows the mine’s location relative to topographic and physiographic features.

FIGURE 1: Hycroft Mine Location

Hycroft is a large, epithermal, low sulfidation, hot springs deposit. Gold and silver mineralization occurs as both disseminated and vein-controlled, with gold values ranging from detection to 8.8 ounces per ton (opt), and silver ranging from detection to 647.5 opt. Several styles of mineralization exist at the Hycroft deposit. An early silica sulfide flooding event deposited relatively low grade gold...
and silver mineralization, generally along bedding. This is cross cut by later, steeply dipping quartz alunite veins. Hypogene enrichment of gold and silver occurred at the base of the acid leach blanket. Late stage silver bearing veins are found in the Vortex zone and at depth in the Cut-5 area. Late to present supergene oxidation along faults has liberated precious metals from sulfides and enriched gold and silver, generally along water table levels. The mine produced 136930 oz Au and 794097 oz Ag in 2012 (Wilson, 2012).

Between 1989 and 1995 CSAMT, seismic, airborne (AERODAT), induced polarization (IP) and ground magnetic surveys were completed over portions of the property. Loss of data and/or lack of location information marginalized much of this early work. Nevertheless, structural and alteration features were extracted from the airborne survey, specifically the resistivity and radiometrics. Two phases of gravity and IP surveys were completed from 2007 to 2011, resulting in a data resource of 2117 gravity stations and 107.3 line-km of IP coverage. The gravity data required customized processing to remove surficial responses produced by leach pads and dumps, while the IP data underwent rigorous quality control due to extreme electrical interference from mine operations. Considerable structural information was extracted from the gravity, as well as the basin geometry along the Black Rock Basin margin. The basin geometry guided planning for the two subsequent IP surveys. Numerous north-northeast trending, linear chargeability anomalies were defined by the IP survey. High resistivity correlation was noted with several of the anomalous zones. The most prominent anomaly, detected in the 2007 survey, was termed the “Vortex Zone” due to the magnitude and size of the IP response. Drill testing of the anomaly in 2008 resulted in discovery of the Vortex Gold Zone.

Moore (2013) notes the upper elevation at Vortex is hydrothermally clay (kaolinite) altered. Strong silicification to depths greater than 1,500 feet is due to veining and phreatic hydrothermal brecciation. At least four mineralizing events are present as evidenced by crosscutting vein and breccia relationships. The hydrothermal venting may have contributed to the eruption breccias overlying the Brimstone Zone. Propylitic and/or clay alteration extends outboard of the silicification. The mineralization at Vortex is of both vein and disseminated type, with brecciated and altered rhyolite rocks and volcanic clastics acting as favorable hosts. In addition to gold mineralization, high grade silver has been encountered at Vortex; with values ranging from 10 to 647 opt. Oxide mineralization is present at a depth of approximately 500 feet below surface, with sulfide mineralization extending to 2,500 feet below surface. Mineralization thickness (true width) is 1,000 to 1,800 ft thick.

1 – Thanks to Allied Nevada Gold for permission to present and assistance.
2 – Note location relative to surrounding gold deposits.
3 - The Hycroft deposit is a large, epithermal, low sulfidation hot springs deposit. Gold and silver mineralization is noted as both disseminated and vein controlled, with gold values ranging from detection to 8.8 opt, and silver ranging from detection to 647.5 opt.
Late 1800s - Discovery of significant native sulfur deposits, mining of native sulfur sporadic from 1900 to 1950.

1908 - High grade silver mineralization discovered at Camel Hill.

1912 - Silver mining ceased with a total estimate of 165,375 ounces produced.

1914 to 1918 - Pure veins of alunite were mined in the southern part of the district.

1931 - Several hundred tons of alunite were mined as a soil additive.

1941 to 1943 - Cinnabar was mined from small pits in the exposed acid leach zone.

1966 - Great American Minerals Company began extensive exploration for native sulfur in the area.

1974 - Duval Corporation conducted exploration for sulfur—noted elevated gold values.

1977 - Cordex Syndicate mapped and rock chip sampled the property searching for precious metals.

1978 - Homestake Mining recognized similarities with the McLaughlin hot springs deposit in California.

1981 to 1982 - Homestake defined oxide gold/silver deposit, but dropped property.

1983 to 1988 - Lewis Crofoot Mine produced 1.114 million oz Au and 2.5 million oz Ag.

2007 - Allied Nevada Gold Corporation formed, Hycroft Mine reactivated and geophysical program commenced.
1 – Stratigraphy progresses from Auld Lang Syne, Kamma volcanics, Camel Formation, Quaternary lake sediments and Quaternary alluvium.

2 – Auld Lang Syne Formation composed of fine grained calcareous siltstone.

3 – Kamma volcanics are a diverse collection of andesites, rhyolite flows and intrusives, dacites and some conglomerates.

4 - Camel Formation composed of conglomerates over water lain and ash fall pyroclastics.

5 – Lake sediments are Quaternary lacustrine sediments.

6 – Qal are recent gravel deposits composed of clasts from all older units.

7 - Seven major north-northeast trending, west dipping, normal fault zones appear to broadly control the distribution of gold and silver mineralization. (Range, West Splay, Central, Break, Albert, Fire, and East faults )

8 – Number of east-west structures which offset and terminate north-northeast structures, most prominent being the enigmatic Hades Lineament.
1 – Note lacustrine sediments shown beneath the Camel conglomerate are part of the lower Camel Formation.
2 – East fault is major north-northeast trending structure bounding the range front along the east side of the district.
3 – Central, Break, Albert and other structures west of the East fault could well merge into the East fault at depth.
1 – Mineralization shallowest at Bay and deepens towards Brimstone / Vortex.
2 – Note silica development over clay alteration, but deep silica roots only in Brimstone / Vortex area.
3 – Acid leach layer thickest over deep feeders in Brimstone / Vortex area.
4 – Structures control feeders to near surface alteration / mineralization.
5 – Alteration at the deposit is dominated by acid leaching, silicification, argilization, and propylitization.
6 – Age estimate for mineralization 2-4 million years.
7 – Hydrothermal activity still present – 210F water encountered in deep drilling near Vortex.
1 - At Brimstone, the East Fault is a north-northeast striking, west dipping, normal fault with repeated episodes of movement, including approximately 150 to 200 feet of alluvial offset. Where exposed in the Brimstone Pit, the fault clearly shows steep normal movement, with slickensides that plunge 80° to 85°. At depth the fault shallows to 45° to 60° and may merge with the Central and Break Faults. The fault may have originally served as a conduit to hydrothermal fluids. Only minor mineralization is noted footwall to the fault zone.
1 – Note poor data archiving, of the seven surveys only three have usable data.

2 – Aerodat airborne most complete data set.

3 – No gravity and only two lines of IP data, leaving considerable opportunity for advancement of the project.
1 – Magnetic susceptibilities reported as cgs, but the exponent factor is unclear. Kamma volcanics are dominant in the magnetics with all alteration types being non-magnetic.

2 – Resistivity from the AEM for scinter and hydrothermal breccia exceed 1000 ohm-m with clay alteration in the tens to low hundreds ohm-m.

3 – Kamma volcanics are elevated in K, Th, and U. Scinter is low in all three.
GREAT BASIN AND WESTERN CORDILLERA MINING GEOPHYSICAL SYMPOSIUM
Hycroft Mine Geophysical Case History
Vortex Zone Discovery

Airborne Radiometric Survey
Potassium Counts
1 – Note pits and define Boneyard – Central corridor.
2 – Note airborne conducted in 1993 after substantial mining completed.
3 – Note radiometrics shown as counts not converted to equivalent concentrations.
4 – Kamma volcanics high, particularly the flow banded rhyolite along the range front (i.e. pink rocks in slide 4).
5 – Note transported dispersion anomaly down the Hades drainage and the pediment in general to the south.
6 – Considerable potassic alteration noted in the deposits, but not detected in the survey. The reason is unclear.
7 - Camel Formation is relatively low, likely due to sinter development.
8 – Band of low potassium along Boneyard – Central pit trend with a low on Silver Camel Hill.
9 – At Brimstone silica potassium feldspar alteration is observed.
10 – Lake sediments produce low counts to the northeast.
11 – Note various structural relationships to pits.
1 – Note airborne conducted in 1993 after substantial mining completed.
2 – Resistivities span from less than 10 ohm-m to over 1000 ohm-m, which is consistent with physical property data.
3 – Lowest values occur in lake sediments to the west and the fault bonded bowl to the northeast.
4 – Potassium lows and resistivity highs correlate along the Boneyard – Central corridor.
5 – Kamma volcanics east of East Fault are high resistivity as well, particularly the rhyolite flows.
6 – Significant change in character to south due to increased Qal cover.
1 - Two phases of gravity surveys were completed in May 2007 and December 2010, resulting in a data resource of 2117 gravity stations.

2 – Stations were acquired on a 200X400m grid with detailed 200X200m coverage in the immediate mine area. Regional stations along surrounding public roads were acquired with a spacing of approximately one kilometer.

3 - Standard reduction applied with the mine topography embedded in the USGS topography for the terrain corrections.

4 – Approximately 30 mgal drop over the survey area from east to west.

5 – High along east side produced by Auld Lang Syne basement.

6 – Bulls eye low related to bowl of lake sediment incised into Camel Formation rocks is prominent to the northeast and is structurally bounded.
1 – Considerable low density surface material (i.e. 1.9 g/cc) produced unwanted anomalies and required a “dump” correction be applied.
2 – The maximum thickness of surface material exceeded 55 meters.
3 – The correction exceeded one mgal over the large north-northeast leach pad.
1 – Note large north-northeast leach pad anomaly corrupts residual gravity.
2 – Remaining anomalous low at southwest end of north-northeast pad likely a result of later material added to the pad, but not reflected in the mine topography.
1 – Basement gravity effects (i.e. Auld Lang Syne) greatly diminished in the residual product. Density variations in the overlying rocks (i.e. Kamma volcanics and Camel Formation) not large, thus density variations produced by alteration are relatively strong.

2 – Areas of clay alteration expected to produce gravity lows and pervasive silica alteration relatively high gravity.

3 – Boneyard – Central corridor manifested as an alignment of highs bounded by mapped structures.

4 – Prominent gravity low “bowl” to northeast is structurally bounded by East Fault and two others. However, locations for the two other structures do not agree with the gravity.

5 – Overall, the residual gravity generally agrees with the mapped structures.
1 - Two phases of IP surveys were completed from August – October, 2007 and March – April, 2011, resulting in a data resource of 107.3 line-km of IP coverage.

2 – The array was dipole-dipole / a= 100 & 200m / n=1-6. Line spacing was usually 400m with adjustments required in the mine area.

3 – Line spacing selected to permit at least one line crossing any of the known deposits.

4 – Electrical interference from the mine site required considerable stacking with each individual chargeability decay curve examined.
1 – Every other inverted chargeability section rotated south about the survey line.
2 – Smooth body 2D inversion.
3 – Numerous strong chargeability anomalies which appear to connect from line to line.
1 – Note classic high resistivity near surface zones underlain by low resistivity blankets (i.e. Bay, Boneyard & Central).

2 – In other locations the high resistivities tend to form high angle bodies extending to depth (i.e. Brimstone & Vortex).
1 – Note color scale of the AEM data adjusted to match that of the IP.
2 – Again, note high resistivity along Boneyard – Central corridor.
3 – Low resistivity along northwest side of surveys related to Qal sediments.
1 – Depth slice extracted from inverted sections and gridded to produce plan map. Note the slice is a depth not fixed elevation.

2 – Vortex anomaly was identified in 2007 IP survey and the ore zone discovered in 2008 by drilling the strong chargeability anomaly on L4200N.

3 – The anomaly attains a maximum chargeability of 53 msec (Newmont Standard) and a resistivity of 630 ohm-m on the L4200n inverted section.

4 – Note prominent right lateral offset in the East Fault northeast of the main Vortex chargeability anomaly, suggesting some form of structural preparation is responsible for development of the Vortex deposit.

5 – The deposit is located approximately one kilometer southwest of the Brimstone deposit.
1 - Strong silicification to depths greater than 1,500 feet is due to veining and phreatic hydrothermal brecciation. At least four mineralizing events are present as evidenced by crosscutting vein and breccia relationships.

2 - The mineralization at Vortex is of both vein and disseminated type.

3 - In addition to gold mineralization, high grade silver has been encountered at Vortex; with values ranging from 10 to 647 opt.

4 - Oxide mineralization is present at a depth of approximately 500 feet below surface, with sulfide mineralization extending to 2,500 feet below surface. Mineralization thickness (true width) is 1,000 to 1,800 ft thick.
1 – Line 4200N best defines the Vortex anomaly.
2 – Line 1 to the north did not have sufficient depth penetration (i.e. a=100m) nor lateral extent to detect zone.
1 – Detailed portion of L4200N chargeability section.
2 - Chargeability anomaly 2500’ in width.
3 – Note sulfide intercepts as red and orange intervals along drill hole traces.
4 – Note upper hole traces marked as gray in low chargeability oxide material, thus no sulfides.
1 – Detailed portion of L4200N chargeability section.
2 – Note gold intercepts as red and yellow, and orange intervals along drill hole traces. Low values denoted with blue color.
3 – Note upper hole traces marked as gray in low chargeability oxide material.
1 – Detailed portion of L4200N resistivity section.
2 - Resistivity anomaly 2500’ in width and correlates directly with chargeability anomaly.
3 – Note sulfide intercepts as red and orange intervals along drill hole traces.
4 – Note upper hole traces marked as gray in low chargeability oxide material, thus no sulfides.
1 – Detailed portion of L4200N resistivity section.
2 – Note gold intercepts as red, orange yellow intervals along drill hole traces.
3 – Low values (i.e. blue colors) in low resistivity oxide materials.
1 – Note Vortex deposit starts on extreme east end of section and descends down above the East Fault.
1 – Vortex ultimate pit 1200X1900m and 600m deep.
2 – East pit slope will remove main part of Vortex chargeability anomaly as shown on the rotated to plan inverted section.
3 – Removal of surface oxide underway at Brimstone and the deeper Vortex mineralization scheduled to begin in 2-3 years.
GREAT BASIN AND WESTERN CORDILLERA MINING GEOPHYSICAL SYMPOSIUM
HYCROFT MINE GEOPHYSICAL CASE HISTORY
VORTEX ZONE DISCOVERY

VORTEX ZONE PIT DESIGN AND L4200N INVERTED RESISTIVITY SECTION
SUMMARY

- Compilation of Historic Data, Both Geophysical & Geologic
- Recognition of Opportunity to Apply Unused & Appropriate Tools
- Aggressive, Staged Application of Gravity & IP Techniques
- Integration of Geophysical Results with Drilling & Geologic Data
- Identification and Testing of Targets
- Discovery of Vortex Deposit
- Continued Integration of Geophysics with Geologic Data