Recent advances in the application of geophysics for gold exploration in the north-central Great Basin

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ABSTRACT

Geophysical prospecting techniques have been extensively applied in exploration for Carlin-type and intrusion-related gold deposits in the North-central Great Basin. Physical property contrasts are generally very subtle between unaltered rocks and rocks which have undergone alteration associated with mineralization. Therefore, direct detection of these target types using geophysics is challenging. Similarly, no systematic geophysical exploration approach exists in the Great Basin as the physical properties of host rocks are themselves highly variable. Comprehensive physical property studies characterizing host rocks and the structural, hydrothermal, and metamorphic events which overprint them can determine which, if any, geophysical methods will be effective. These studies, coupled with a strong understanding of geological controls on mineralization, will ensure the effective application of geophysics in an exploration program.

Recent advances in geophysics have played a major part in more accurately identifying alteration and structure associated with large gold occurrences. Detailed airborne magnetic data, coupled with advanced processing and inversion tools, has allowed explorers to better integrate magnetic data with geologic interpretations. Detailed gravity continues to be implemented at early stages in Great Basin exploration programs, where high-resolution (100 m station spacing) gravity acquisition on outcrop renews interest in this old method. For covered projects, detailed gravity gives insight to bedrock structure. High-resolution reflection seismic, or hardrock seismic, is especially suited to imaging low-angle structural architecture commonly associated with Carlin-type mineralization. Electrical methods for exploration of Carlin-type and intrusion-related gold deposits have seen greater application through advancements in acquisition technologies, particularly distributed array systems. These methods, however, have had limited impact due to geologic features contributing to chargeability/resistivity anomalies that are unrelated to mineralization.

Geophysical survey methods will play an increasingly important role in understanding geologic controls and targeting mineralized systems as near-surface exploration opportunities become harder to find. Advancements in technologies such as distributed array electrical methods, 3D seismic and airborne gravity will potentially bring about a step change in their application to exploration programs. The development of tools that assist with planning, processing and inversion of new survey types incorporating a-priori geological and physical property data into a 3D model is a focus for the future.

Key Words: gold, Great Basin, Carlin-type, intrusion-related, geophysics, physical properties, magnetics, gravity, seismic, chargeability, resistivity.

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INTRODUCTION

The North-central Great Basin is located in North-eastern Nevada and contains significant Carlin-type (CT) and Intrusion-Related-type (IR) gold mineralization. Geophysical prospecting techniques can be employed in exploration for these deposit types, given an adequate understanding of physical property of rocks (petrophysics) coupled with knowledge of geological controls on mineralization. Physical properties of mineralization in large CT and IR systems usually combine inherent primary host rock variations with overprinting structural, hydrothermal and metamorphic events, resulting in very complex distribution of physical properties. As geoscientists, we need to understand these relationships to effectively apply geophysical prospecting techniques for gold exploration in the North-central Great Basin.

Limited documentation exists for geophysical applications for gold exploration in the Great Basin (Corbett, 1990; Wright, 1996). The most comprehensive work to date is by Wright and Lide (1998). This paper is not aimed at replicating their work; instead it is a report on advances in understanding over the last decade. Examples are provided where these advances have had a positive impact on gold exploration programs. Future developments in geophysics are discussed, highlighting potential benefits to gold exploration in the North-central Great Basin.

PHYSICAL PROPERTIES OF ROCKS IN THE NORTH-CENTRAL GREAT BASIN

Geophysics is applied to map the distribution of physical property contrasts across rock packages. Quantitative analysis of the physical properties of rocks is termed petrophysics and is an essential consideration for geophysical prospecting techniques. Petrophysical studies throughout the Great Basin (Barrick internal studies; Wright, 1996) reveal high variability in physical properties of typical rock units. At the camp or target scale, this variability necessitates individual petrophysical studies to determine which geophysical methods can be applied to the exploration program. On a regional scale, considering broad rock packages in the North-central Great Basin, some petrophysical generalizations can be made.

The Paleozoic sedimentary basement group can be split into siliciclastic Upper Plate (UP) and carbonaceous Lower Plate (LP) components by the Roberts Mountain thrust. This division is crucial as LP units are the dominant host rocks for CT mineralization, where UP units are generally less attractive exploration targets. Density is the biggest physical property contrast in Paleozoic basement, where higher densities (2.60–2.80 g/cc) are observed in LP carbonate rocks, versus lower densities (2.30–2.40 g/cc) in the siliciclastic UP rocks. Unaltered UP and LP sedimentary rocks are both non-magnetic, except when these rocks undergo contact metamorphosed adjacent to an intrusive rock (see below). Galvanic resistivity of unaltered, unoxidized LP and UP is normally constrained within the ranges of 10's to 1000's of ohm meters (ohm.m). Resistivity varies logarithmically; therefore its unreliable to discriminate these units based on resistivity alone. Acoustic impedance (product of density and velocity), a measure of seismic reflectivity, is usually driven by stratification and facies variations in LP units and is difficult to generalize on a regional scale.

The Pennsylvanian-Permian overlap sedimentary sequence is predominantly derived from reworked UP and LP material, therefore the physical properties are very similar to the units described above. Given this lack of contrast, it is difficult to discriminate between these sedimentary lithologies using geophysical methods.

Hydrothermal alteration and metamorphism of sediments, both of which are of interest when targeting gold mineralization, impart the greatest variations in physical properties. Decalcification of the LP carbonates can lower their density as low as 2.20 g/cc. Silicification of carbonates can increase their resistivity by an order of magnitude, while hydrothermal oxidation of the same carbonates can lower the resistivity by an order of magnitude. Disseminated pyrite and other sulfides are sometimes introduced during mineralization, which results in low to moderate chargeabilities in material such as silica sulfide breccias. Coarser grained, diagenetic pyrite is also common in the Paleozoic basement and has similar chargeability characteristics, but is not physically or genetically associated with mineralization.

Mesozoic intrusive rocks, mostly of Jurassic and Cretaceous age, within the Great Basin have varied physical properties relating to their varied compositions and habits of emplacement. The intrusions generally have low to moderate magnetic susceptibility within the range of $0–15 \times 10^{-3}$ SI, largely driven by their composition (Clark, 1999). Different phases of the intrusions are known to be remnantly magnetized (e.g. Mill Canyon Stock, Cortez). Resistivities, densities and other physical properties generally do not contrast with the UP and LP Palaeozoic rocks. Dikes associated with large intrusive stocks are commonly conductive and chargeable when altered or weathered to clay mineral assemblages.

Metamorphism associated with Cretaceous and Jurassic Stocks intruding into carbonaceous sediments also has a profound effect on the physical property of rocks surrounding the intrusions. Formation of hornfels, calc-silicate marbles and skarns in the Palaeozoic sediments commonly increases density to over 2.80 g/cc, resistivity over 5000 ohm.m (skarns being the occasional exception), and, in some cases, magnetic susceptibility through formation of monoclinic pyrrhotite and lesser magnetite. Contact metamorphism of carbonaceous rocks may liberate carbon in the form of hydrocarbons or graphite, which commonly deposits outside of the metamorphic aureole on fractures and faults. This pre-mineralization, remobilized carbon is highly chargeable and can cause surrounding rocks to exhibit lower resistivity than expected of the unaltered parent rock.

Tertiary and quaternary extrusive rocks are typically interbedded with alluvial and colluvial gravels, and can be collectively referred to as cover. Cover units generally have lower density and lower resistivity than the Palaeozoic bedrock. Density can be as low as 1.60–2.20 g/cc and resistivity as low as 5–50 ohm.m. Volcanic and volcaniclastic components of the Tertiary gravels (valley fill) have varied moderate to high magnetic susceptibility, depending on their compositions. Basalt flows commonly have a high magnetic susceptibility and variable magnetic remnant characteristics, whereas air fall tuff usually has a low to moderate magnetic susceptibility and is normally magnetized.

Physical properties of rocks may be misrepresented when measurements are made on hand samples in a laboratory. Laboratory measurements are usually not able to replicate local conditions of water salinity, temperature and pressure—all of which can have large effect on rock petrophysics. To overcome this, acquisition of in situ data is recommended through downhole petrophysical logging methods. If downhole methods are not available, relative or qualitative measurements on hand samples are useful to gauge contrasts.

Mineralization in large CT and IR systems usually involves combining a number of the primary host rock physical properties described above with overprinting structural, alteration and metamorphic events, making for a very complex distribution of physical properties. Understanding these relationships is critical to effectively applying geophysical prospecting techniques for gold exploration in the North-central Great Basin.

RECENT ADVANCES IN THE APPLICATION OF GEOPHYSICS FOR GOLD EXPLORATION IN THE NORTH-CENTRAL GREAT BASIN

Recent advances in understanding have resulted in the successful application of geophysics to more accurately identify alteration and structure associated with large gold occurrences. Below are examples where petrophysical studies and understanding of the geologic architecture have been critical to the effective application of geophysical techniques. Examples are presented by geophysical method, including detailed airborne magnetics, detailed gravity, high-resolution reflection seismic, and electrical techniques. Brief conclusions are summarized for each technique.

Detailed Airborne Magnetics

Detailed airborne magnetic surveys remain the most effective first-pass reconnaissance mapping tool in early stage exploration programs, despite limited developments in the technology over the past decade. Airborne magnetic data, coupled with advanced processing and inversion tools, can be interpreted to reveal structure, lithology, metamorphism and alteration (where geologic mapping and/or drilling verifies these interpretations). Additionally, the cost of data acquisition has decreased due to the widespread availability of airborne magnetic systems.

Wright (1996) documented typical magnetic signatures seen in the Great Basin using examples from the north area of the Carlin Trend. Wright interprets basalt flows displaying a characteristic stippled response, due to strong remnant magnetization. In contrast, the Goldstrike and Little Boulder Basin intrusive bodies exhibit distinctive, longer-wavelength magnetic highs, with amplitudes above background of 350nT and 175nT, respectively. The magnetic response of these diorite and granodiorite intrusive rocks with susceptibility measurements in the range of 6.3×10^{-3} SI (Wright, 1996) is attributed to primary magnetite.

A similar magnetic response is observed in the intrusive rocks of the Cortez District, particularly the Gold Acres stock in the western part of the district. The Cortez District is located 70 miles southwest of Elko in Lander County and is a significant gold producer within the Cortez or Battle Mountain-Eureka trend of Northeastern Nevada. The Gold Acres stock is a buried quartz monzonite body which is only exposed in the Gold Acres Pit. Despite its limited exposure, it is a prominent magnetic feature of the western Cortez district (Figure 1). The shape of this buried intrusion is constrained in the geologic model by drilling, potential field modeling (3D gravity and magnetic inversion) and seismic reflection data. Figure 1 shows detailed airborne magnetic data acquired at 200m line spacing over the Gold Acres stock. Magnetic data are reduced to pole (RTP) and display a strong, positive magnetic signature, of equal intensity to the Goldstrike stock (350 nT). Magnetic susceptibility measurements on the Gold Acres Quartz Monzonite intrusion are below 2.0×10^{-3} SI, revealing the stock to be very weakly magnetic. In contrast, the marbleized skarn surrounding the stock is moderate to strongly magnetic (up to 46.1×10^{-3} SI). This magnetism is a product of contact metamorphism produced when the stock intruded carbonate sediments, introducing monoclinic pyrrhotite. Note that Wright (1996) does not mention the contribution of magnetic skarn to intrusive responses seen in the North Area on the northern Carlin trend.

The results of drilling, potential field modeling and high-resolution reflection seismic have also confirmed that parts of the Gold Acres Quartz Monzonite intrusion are laccolithic (see Figure 3). This detailed airborne magnetic example from the Cortez District highlights the importance of considering magnetic skarn and non-standard geometries when interpreting aeromagnetic data for gold exploration.

Detailed gravity

Detailed gravity surveys have been applied by most exploration groups working in the North-central Great Basin and this technique has proven its value as an early stage exploration tool. As with airborne magnetics, there have been only limited advancements in the gravity technique over the last decade, however the acquisition of higher-resolution datasets has led to a renewed interest in this old technique. High-resolution gravity data requires station-spacing of 100 m or less. For covered targets, however, acquisition of the highest-resolution data has

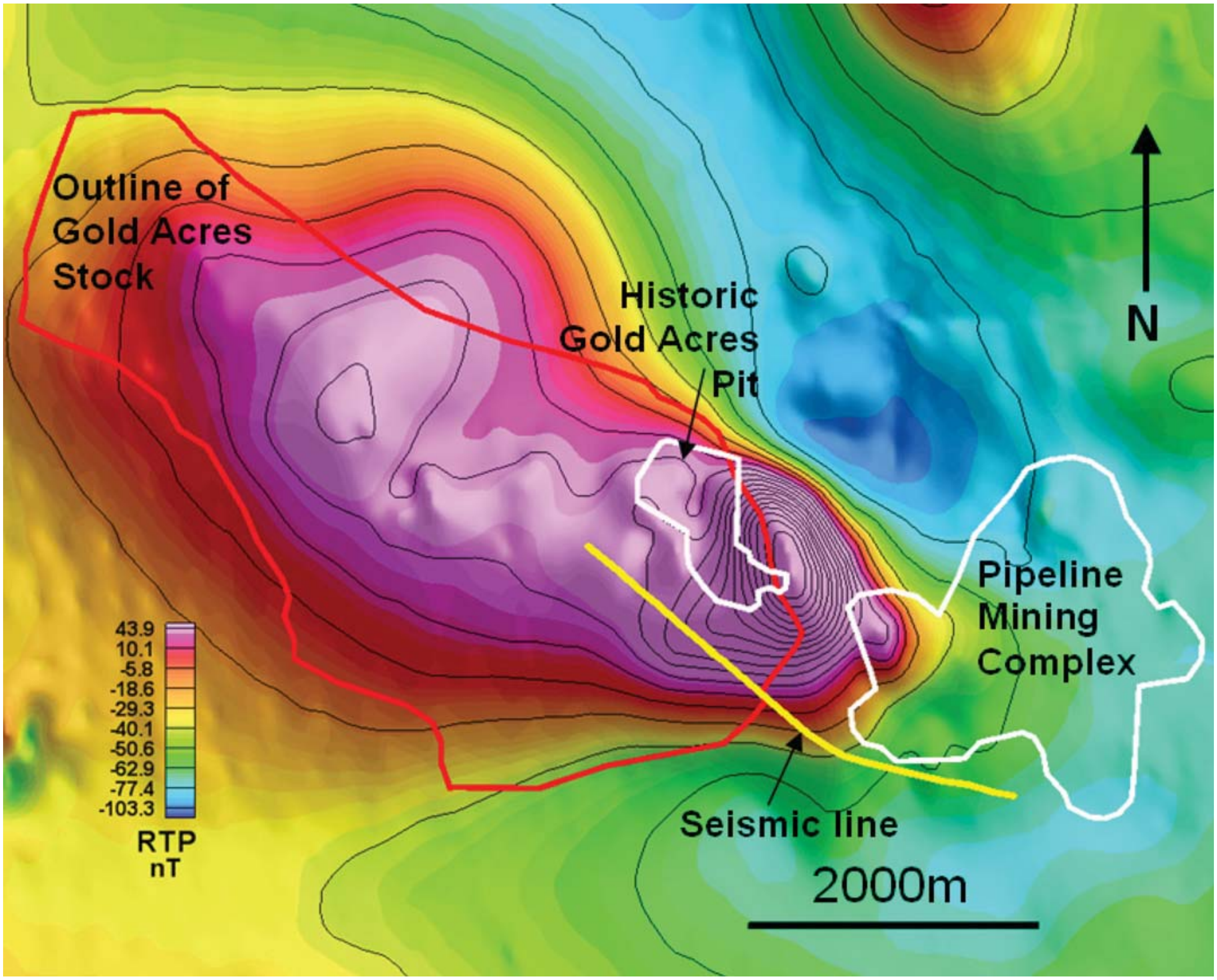

Figure 1. Image of Reduced to the Pole (RTP) magnetic data over the buried Gold Acres Stock. Contour interval is 20nT. Red boundary indicates the extent of the buried Gold Acres Stock which is constrained by drilling and a potential field model. Note highest intensity part of anomaly is in magnetic skarn outside and adjacent to the intrusion. White boundaries indicate open pit outlines, with the smaller Gold Acres and GAP Pit outline on the left, and the large Pipeline Pit on the right. Yellow line is location of Gold Acres seismic line (see Figure 3).

limited impact in mapping bedrock structure. A broader station-spacing, such as 300 m (1000 ft), can be effective where cover is thicker than 150m (500 ft).

Stonehouse, located immediately north of Newmonts Lone Tree mine in North-central Nevada, is a covered target where detailed gravity added high value to exploration targeting. The adjacent Lone Tree mine is a structurally controlled CT deposit. The Wayne Zone is the most significant zone of mineralization at Lone Tree, hosted on a north-south trending high angle structure (~75 westerly dip) on the western edge of a Paleozoic horst block (DeLong, 1996). This high-angle structure trends north onto the Stonehouse claims, and so Wayne Zone analogue mineralization was a high priority target. Bedrock on the Stonehouse property is covered by extensive (150m, 500ft) Quaternary and Tertiary gravels and volcanics, so this target could not be explored using surface mapping and conventional surface geochemistry.

Detailed gravity data were acquired at Stonehouse to assist in mapping the possible extension of the Wayne Zone, or an analogue, beneath cover. The square grid was acquired with 300 m (1000 ft) station spacing, consistent with limits of detailed gravity over covered targets. The residual gravity, processed to highlight density contrasts in the upper 600 m (2000 ft), clearly mapped a large (~500 m wide) and strike-continuous (~5 km long) north-south trending positive gravity anomaly immediately north of the Lone Tree horst. This was interpreted to be the northern continuation of the high-angle structure hosting Wayne Zone mineralization (Figure 2). Total horizontal gradient, or point of maximum gradient, maps were used to best interpret the exact position of the structure, and two dimensional

(2D) gravity modeling was used to produce a simple 2 layer gravity model of the cover-bedrock interface, clearly illustrating the target horst beneath gravels. Limited density data was available from which to construct this model, but densities 2.0 g/cc for the cover materials and 2.4 g/cc for the Paleozoic sedimentary rocks were judged to be reasonable approximations, based on other experience in the area.

A plan map of the detailed gravity is shown in Figure 2, along with the 2D model section defining the horst and target. This target was drilled between 2007 and 2009 and has confirmed the interpretation of the gravity model, with accurate displacement on the horst. This is just one example where an understanding of the geology, coupled with knowledge of petrophysical contrasts in the camp and detailed gravity data, can effectively direct exploration targeting. If the anticipated structure of interest or target footprint (through forward modeling) is smaller than the example presented from Stonehouse, tighter gravity sample intervals, down to 100m, may be required.

High-Resolution Reflection Seismic

High-resolution reflection seismic is termed hardrock seismic when applied in crystalline rock terrains. Hardrock seismic is an adaptation of longstanding softrock, oil and gas seismic methodologies. Applications of hardrock seismic in the Great Basin have enjoyed recent success on the back of research and development around the globe (Urosevic et al., 2008). Urosevic et al. (2008) noted that the seismic reflection technique does not fundamentally lose resolution with depth, unlike magnetic, gravity, and electrical methods. Geologic features from depths greater than 1 km (3000 ft) can be imaged with very good data

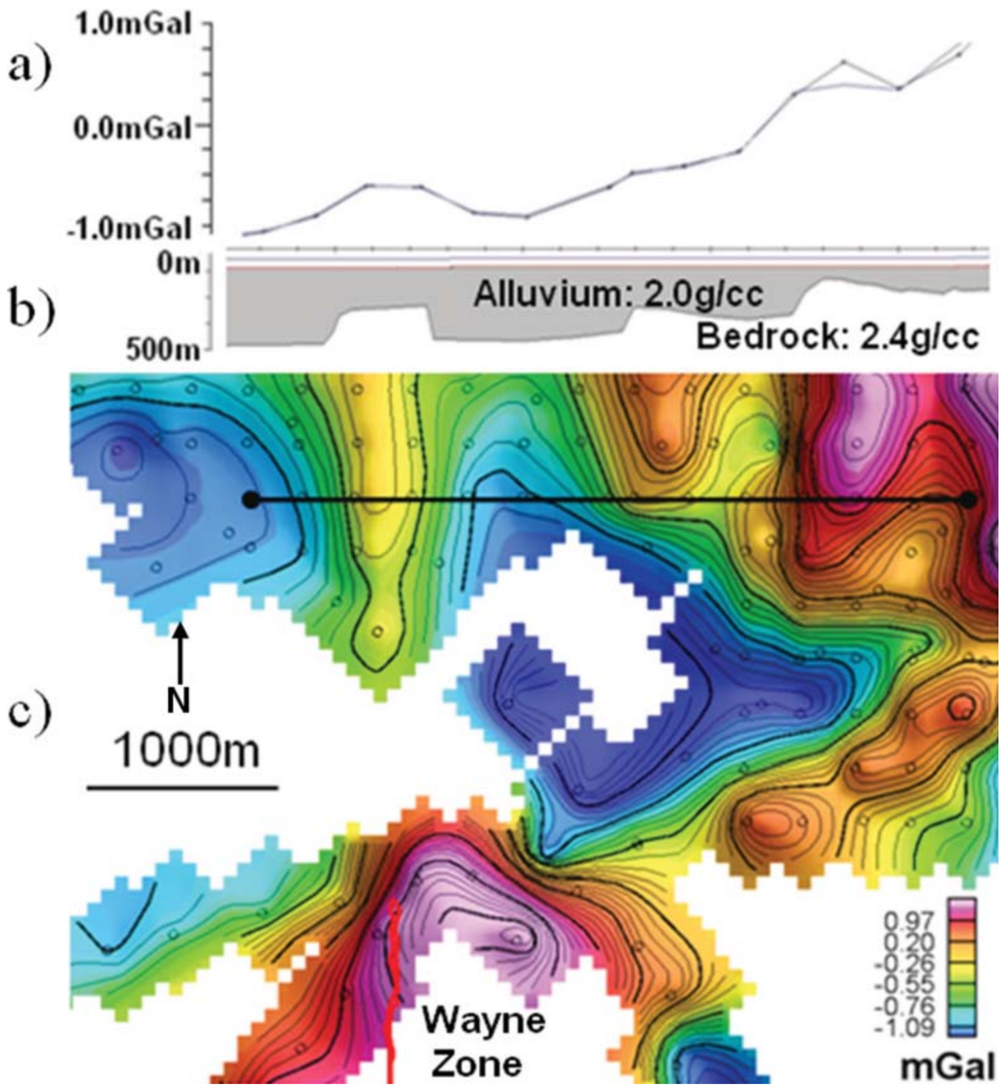

Figure 2. a) Measured and calculated profiles of residual gravity data. b) Simple two-layer earth model obtained through forward modeling. c) Residual gravity of the Stonehouse area which delineates a subsurface structure interpreted to be the extension of the high-angle Wayne Zone structure at Lone Tree Mine.

resolution by modern day seismic reflection surveys. This is important in the Great Basin as potential mineralization hosted in the LP sedimentary rocks are frequently concealed by cover, recent volcanic rocks, or UP sedimentary rocks.

Eaton et al., (2003) provides an overview of the specific challenges of hardrock seismic method. Additional to these challenges are data processing considerations of statics corrections in areas of variable topography and of large, inhomogeneous velocity contrasts in the near-surface weathered zones. Hardrock seismic is acquired with higher spatial and temporal resolution to offset these challenges. For adequate spatial resolution, 10 m is considered as maximum receiver spacing (2.5 m used by some specialists) and for temporal resolution, a source bandwidth greater than 100 Hz is recommended (Eaton et al., 2003). Fold, defined as the number of traces in the common mid point (CMP) gather, is a measure of spatial stacking and should be at least 120. To ensure sufficient illumination of a target with reflection seismic, 2D seismic data should be acquired to at least 0.5 mile (preferably 1 mile) beyond the area of interest.

Downhole seismic provides velocity information down the geologic section, which is critical for calculation of accurate depth of reflectors. Downhole seismic data acquisition is recommended while the seismic source is on-site for the surface program. Drillhole instability in the Great Basin is a huge logistical challenge to acquisition of downhole seismic. Acquisition of approximately 100 m (or 200–400 ft) segments of open hole beneath drill pipe is one method to effectively prevent damage to expensive seismic probes and to acquire velocity information before the hole collapses. Timing is critical to synchronize the downhole seismic program with the end of the drilling (unless drill casing can be left in the hole).

Reflection seismic is especially suited to imaging low-angle structural geometries, which are common associated with CT mineralization in the Great Basin. Host rocks are traditionally stratified carbonate lithologies, often in a thrust-dominated, low-angle (<45°), structural architecture. Acoustic impedance contrasts between different units and structure are the cause of seismic reflections. Two dimensional seismic lines are best oriented orthogonal to geologic strike and structural geometries to image seismic reflections in context with the subsurface geology. Integrating seismic results with some drill control, structural interpretations can be made on results to identify oil-trap like anticlines, thrust stacking, duplexing and over-thickening of normal section.

Cortez is an ideal district for hardrock seismic method because the geology and controls of mineralization are well understood and demonstrate low-angle control on structural architecture (Leonardson, 2010). Hardrock seismic (2D) was first acquired by Barrick in the Cortez district in 2008. A 2D line was run orthogonal to the strike of fold axes across the Gold Acres stock to the west of the Pipeline pit (line location shown on Figure 1). Figure 3 shows the resulting seismic section (brute stack) with depth conversion on the right and the location of drillholes used to constrain geologic interpretations. The seismic data images the deep Abyss thrust fault, with LP stratigraphy forming a rollover anticline above it. Acoustic impedance contrast between lithologies in this stratigraphic package is sufficient for thrust stacking to be interpreted from the seismic data. Elsewhere in the Cortez district, antiformal thrust stacks and rollover antiforms have been productive hosts for mineralization, so these features represent a possible target for mineralization. A drill hole located based on this interpretation intercepted repeated lithologies, verifying the geophysical interpretation of thrust stacking. Endoskarn intercepted at depth (beneath the Gold Acres intrusion) is coincident with a consistent reflector, interpreted to be the base of a laccolithic segment of the Gold Acres intrusion. The stock may be rooted further east, where seismic signal is devoid of reflectors and the magnetic anomaly appears to plunge off, but there is no deep drilling in the area to validate this interpretation.

This application of 2D seismic is a good example of where hardrock seismic can update and validate a well understood geologic model, and lead to directly to drill targets.

Magnetotelluric/Controlled Source Audio Magnetotelluric Resistivity

Resistivity and electromagnetic survey techniques for CT and IR gold exploration have seen greater application over the last decade through advancements in acquisition technologies, particularly distributed array systems and specialized magnetotelluric (MT) loggers for 3D inversion. Application of these methods requires a very good understanding of the physical property contrasts associated with lithology, metamorphism and alteration. Poor understanding of any one of these elements will likely result in incorrect interpretation of data. Base level geological information is imperative to complement interpretation.

The Ruby Hill tensor MT distributed array survey is one example demonstrating the value MT data can add when targeting at a local scale. Ruby Hill is a CT deposit with nearby carbonate-replacement style mineralization located on the southern end of the Battle Mountain-Eureka trend, adjacent to the town of Eureka, Nevada. Most gold in the camp has been produced from the Archimedes pit, where gold distribution is largely structurally controlled by the convergence of the north-south Jackson-Holley fault and the east-north-east/west-south-west Blanchard fault. A MT survey was acquired over the mine area in 2002. Figure 4 shows a 2D inversion of a line of MT data through the general area of the Archimedes pit, with a section through the 3D geological model and drillholes overlain (locations of anomalous gold are annotated on the drillholes). The MT data clearly maps the large Jackson-Holley and Spring Valley faults in the camp as conductors extending to depth. This conductor is interpreted to reflect deep oxidation along the major fault zones (likely both near surface and hydrothermal oxidation). Some remobilized graphite may also have deposited on these faults following the emplacement of Mineral Hill stock,

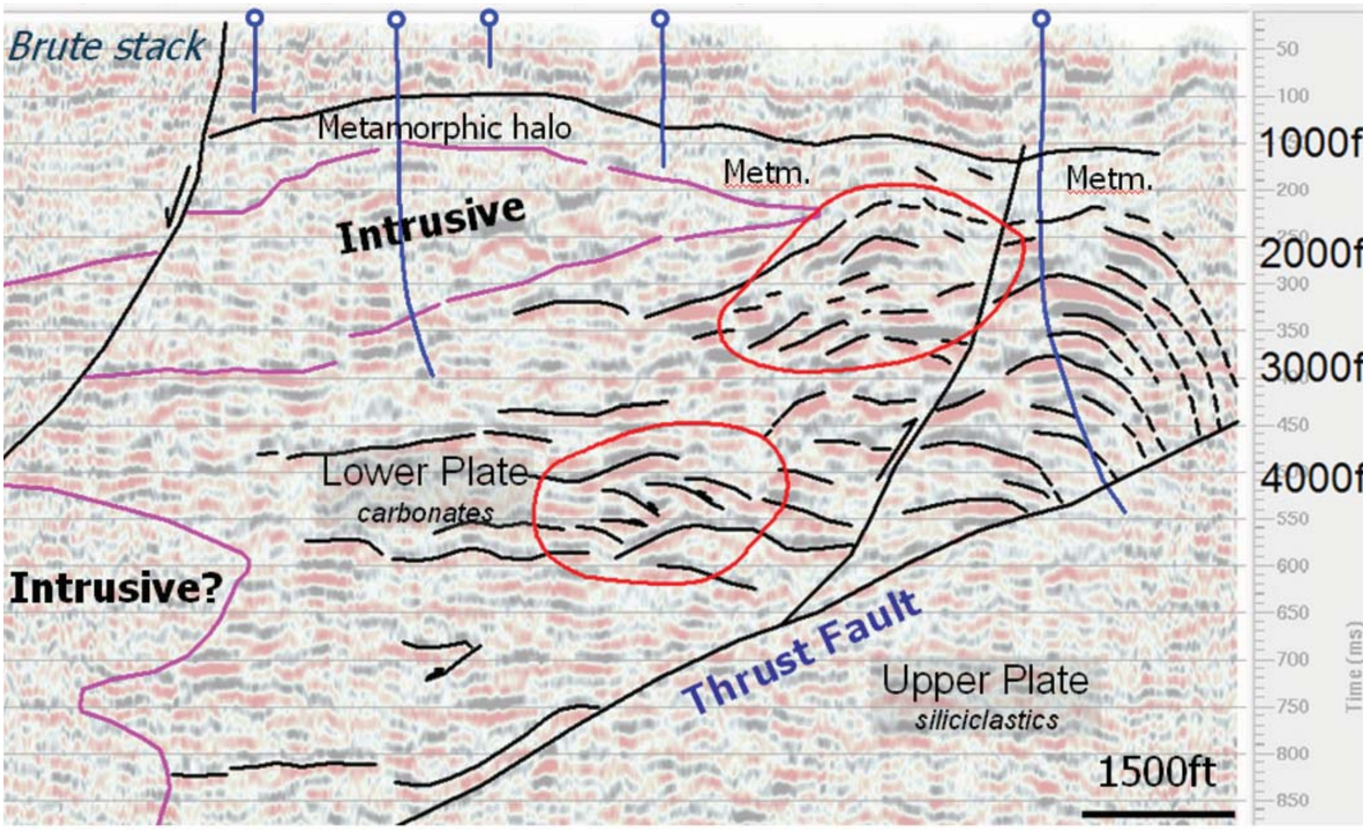

Figure 3. Brute Stack of Gold Acres seismic with interpretation overlain. Drill holes used to constrain interpretation are shown in blue. Deep thrust, laccolithic intrusive and metamorphic (metm.) halo are well imaged by the seismic. Thrust stacked complications are drill targets, highlighted by red circle.

Bullwhacker Sill, and Cretaceous Graveyard Flats intrusions. Gold mineralization largely sits adjacent to smaller conductive features, interpreted to be the secondary structures where oxidation has lowered the resistivity. Mineralization has disseminated into the adjacent host rock (generally resistive Cambrian Hamburg Dolomite). The resistivity data coupled with geological/structural information has been used to target exploration drilling in the camp.

Sphalerite-chalcopyrite-pyrite-bearing skarn mineralization at Deep East Archimedes (east of the Archimedes pit at depth) has a moderate conductivity. This is attributed to the chalcopyrite and pyrite stringers forming continuous conductors within these largely massive sphalerite, resistive zones.

The example shown here is from an area where the geology is fairly continuous along strike, which is a required assumption when working with 2D inversions of MT data. When the variations in the geology are important along strike a number of these assumptions are no-longer valid and the inverted sections can prove misleading. In these cases, full 3D inversion of the MT data is required in order to produce a valid section for interpretation. An example of the benefits of 2D vs. 3D inversion of MT data over Dee-Rossi is presented in Robert et al. (2007). These 3D inversion codes have become more common-place in industry (see future developments, below).

Controlled source audio magnetotellurics (CSAMT) can have an advantage over MT of better near surface resolution (upper 300 m or 1000 ft). The increased resolution comes from a surface transmitter dipole (i.e. controlled source) supplementing energy in the 300 Hz to 3 kHz frequency range. The lack of natural field energy in this spectral range is often termed the MT dead band. CSAMT over 3D geological features can be just as problematic as MT described above, due to the 2D nature of these techniques. Tensor CSAMT can better define 3D geometries, but is less commonly applied due to the time it takes to acquire. As with MT, the application of CSAMT requires some level of understanding of the underlying geology. Optimal survey design (remain in far-field of primary) and future acquisition may integrate both CSAMT and MT techniques to better define the entire resistivity section.

Induced Polarization

Induced polarization (IP) has seen developments in acquisition technologies and processing over the last 10 years, again, with distributed array systems and 3D inversion technologies becoming more commonplace (Goldie, 2007). The method, however, has had limited impact in the Great Basin due to several geologic features contributing to chargeability anomalies that are unrelated to mineralization. Remobilized carbon, graphitic shale and non-mineralized diagenetic sulphides will give similar IP response to sulphides associated with mineralization. Similarly, oxidation of sulphides, commonly seen in CT mineralization, will decrease chargeability. For these reasons, IP is applied carefully in the Great Basin, depending on the particular geologic setting.

An example from Bald Mountain shows IP data collected over the RBM IR deposit. The Bald Mountain mining camp sits south of the Ruby Mountains and hosts a number of open pit operations extracting both CT and IR mineralization. The RBM pit mined the oxidized gold mineralization above the refractory zone. Figure 5 shows an inverted chargeability section, acquired using a dipole-dipole array with 150 m (500 ft) a-spacing. Extensive refractory mineralization (fresh sulphides) is present under the pit, which correlates well with the inverted chargeability anomaly. The larger anomaly to the north-east of the refractory zone was drill-tested and confirmed due to the presence of disseminated chalcopyrite mineralization.

This is a key example where, given correct geologic considerations, the lateral footprint of the RBM refractory mineralization is well mapped by IP. Again, IP surveying in the Great Basin must be done taking into consideration geologic noise that will provide false chargeability responses.

FUTURE DEVELOPMENTS IN GEOPHYSICS AND THEIR IMPACT IN THE GREAT BASIN

Developments in geophysical applications that will assist exploration for concealed systems in the Great Basin are detailed below. These developments are split into fields of acquisition, processing and inversion, and geologic integration.

Future Developments in Acquisition

Developments in geophysical technologies like distributed array electrical methods, 3D seismic and airborne gravity will potentially bring a dramatic change to their application in the Great Basin.

Kingman (2007) details the benefit of electrical methodologies with many electrodes distributed in 2D or 3D arrays (incorporating downhole electrodes). Distributed arrays immediately increase the number of possible acquisition configurations, and therefore input parameters for inversion. More source-receiver combinations reduce the issue of non-uniqueness in any inversion. Distributed array IP/resistivity and MT acquisitions systems like Quantecs Titan-24/Titan 3D and X-Stratas (nee MIM) MIMDAS are commercially available. These surveys typically cost more than conventional 2D profiles, however future developments are directed towards making distributed array instrumentation, surveys and processing more affordable.

In hardrock seismic applications, 3D techniques are best equipped to deal with complex 3D geology and yield the most geologically-accurate interpretations. In past decades the cost of 3D seismic in the minerals exploration industry was cost-prohibitive. Recently, cost of 3D seismic has dramatically decreased, driven largely by technology borrowed from land hydrocarbon explorers. One example of technology developed by land hydrocarbon explorers is wireless, point-receiver systems, with differential GPS locators. Application of these technologies in the Great Basin would allow acquisition through highly-variable terrain which would otherwise be impossible to traverse with old seismic cable.

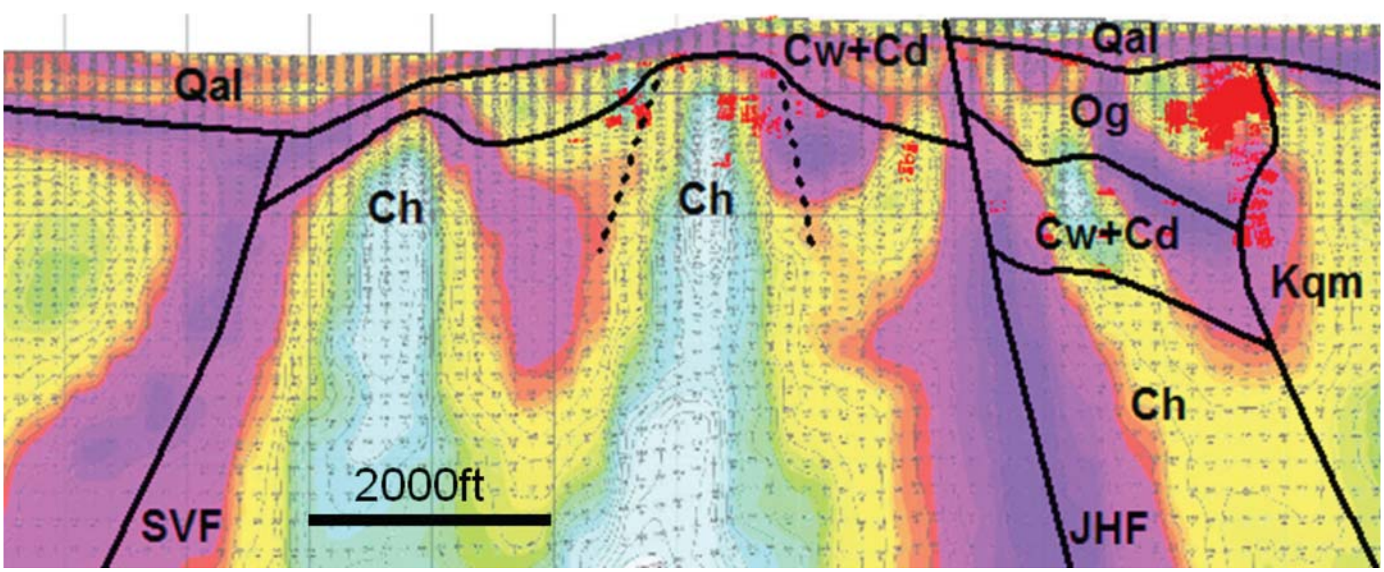

Figure 4. E-W oriented MT resistivity section south of the East Archimedes Pit, Ruby Hill. Cold colors are resistive zones, hot colors conductive. Modelled geology (black) and drill hole anomalous gold intercepts (red) overlain. Ch: Cambrian Hamburg fmt, Cw+Cd: Cambrian Windfall and Dundaburg fmt, Og: Ordovician Goodwin fmt, Kqm: Cretaceous Graveyard Flats quartz-monzonite intrusive. JHF represents the location of the Jackson-Holley fault, and SVF the Spring Valley fault. Mineralisation in the East Archimedes pit (eastern edge of section) is controlled by structures off section. Other gold mineralization on section largely sits proximal to structures interpreted from the MT resistivity (dashed lines).

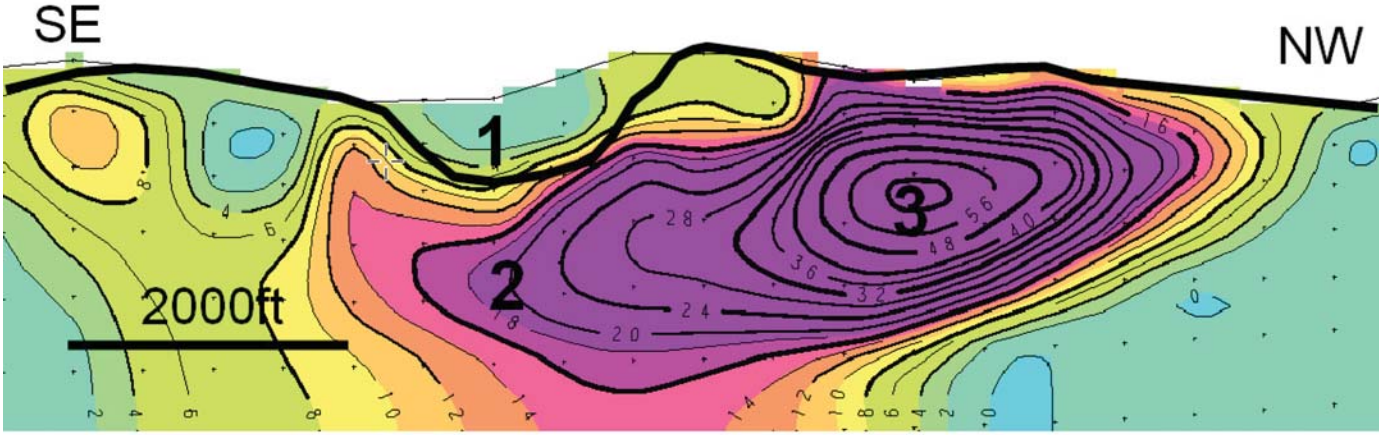

Figure 5. NE/SW inverted chargeability cross section through the RBM IR mineralization. Chargeability contours in msec. Black line is post-mine topography showing location of RBM pit. Point 1 shows the location of the oxidized RBM mineralization, point 2 the transition into the refractory sulphidic IR mineralization, and point 3 the gold barren Cu zone.

A recent synopsis by DiFrancesco (2009) best captures the onset of airborne gravity gradiometry (AGG). Low noise airborne gravity systems will allow smaller and lower amplitude mineralized systems to be detectable. In a short span of time, noise levels associated with AGG surveys have been reduced by roughly an order of magnitude since their inception earlier this decade. We will likely see another order of magnitude decrease in noise levels over the next 5 years, with the Gedex AGG system expected to be capable of 1 Eos per 100 metre wavelength. AGG acquisition will have its biggest impact on the district scale, currently lacking due to the point nature of ground gravity data. One impediment for greater application of airborne gravity in the Great Basin is mountainous terrain. The small, powerful survey aircraft required to adequately drape topography will probably not be consistent with the large, stable airborne platforms required for minimum noise levels with AGG surveys.

Future Developments in Processing and Inversion

Coupled with developments in 3D distributed acquisition technologies, the industry has been developing tools to assist with planning, processing and inversion of 3D surveys. Forward modeling tools for planning 3D surveys ensure the sample density and extent of the field surveys are optimized to image the geologic features of interest at the lowest possible cost. With the advent of 3D distributed acquisition systems, contractors and software vendors have recently adapted their systems to handle and process more voluminous data.

The processing area of greatest development and likely the area of accelerated activity in the future is the 3D inversion of geophysical data. Advances in the mechanics of inversions, such as the MUMPS algorithm used by the University of British Columbia (UBC) (Oldenburg, 2009), coupled with improved computation power, gives us greater ability to address increasingly more complicated problems. Full 3D inversion codes continue to be developed to address more complex geophysical techniques, such as EM methods (Haber, et al., 2008). Direct current (DC) and IP 3D inversion engines have reached a reasonable and functional stage of development, and at least three competing products now exist. For mining applications, 64-bit engines are preferred due to typically large spatial areas and requirement of high density mesh of at least two cells per dipole.

An example of 3D IP inversion from Gold Hill (Round Mountain, Nevada) is illustrated in Figure 6. Gold Hill is located north of the Round Mountain open pit and is a low-sulphidation epithermal vein system hosted in Oligocene volcanic tuffs. This location was selected as a test site for Quantecs new Titan-3D system a multichannel, full-3D IP, MT and resistivity acquisition platform (Quantec, 2009). Sulphide and clay development in and around the veins is well mapped by IP techniques. The model obtained from 3D IP inversion validated and replicated the 2D model results.

Incorporating a-priori geological and physical property data into 3D inversion models, and joint inversion of multiple datasets, has yielded good results. Joint inversion of detailed magnetic and gravity data is one of the simpler combinations. Williams & Oldenburg (2009) and Howe (2009) have demonstrated that introducing small, simple constraints into the inversion via reference, bound and weight models can significantly improve the geological confidence of the recovered model.

Future Developments in Geological Integration

Tools for integrating geological, geochemical and geophysical data and interpretations are another area that will see ongoing development heading into the future. Numerous visualization tools continue to be developed to integrate all datasets into a common workspace. Future developments are likely to involve more regular, rigorous application and spatial query of common earth models populated with multidisciplinary data.

Similarly, interpretation tools which can be used to create balanced 3D geological models incorporating geochemical and geophysical datasets and interpretations will also likely improve our understanding of the subsurface and increase our rates of exploration success. There are currently few tools which directly address this need.

CONCLUSIONS

The variability in physical properties of rocks in the Great Basin highlights the need for comprehensive physical property studies on a project area. These studies, coupled with knowledge of geologic controls on mineralization, will determine which geophysical prospecting methods will assist exploration. Physical properties of mineralization in large CT and IR systems usually combine inherent primary host rock variations with overprinting structural, alteration and metamorphic events. Understanding these relationships is critical to effectively applying geophysical prospecting techniques for gold exploration in the North-central Great Basin.

Recent advances in geophysics have played a major part in more accurately identifying alteration and structure associated with large gold occurrences. Detailed airborne magnetic data, coupled with advanced processing and inversion tools, has allowed explorers to better integrate magnetic data with geologic interpretations. Detailed gravity continues to be implemented at early stages in Great Basin exploration programs, where higher resolution acquisition can bring new applications to an old method. High-resolution reflection seismic, or hardrock seismic, is especially suited to imaging low-angle structural architecture commonly associated with Carlin-type mineralization. Electrical methods for exploration of Carlin-type and intrusion-related gold deposits have seen greater application through advancements in acquisition technologies, particularly distributed array systems. These methods, however, have had limited impact due to geologic features contributing to chargeability/resistivity anomalies that are unrelated to mineralization.

Ongoing developments are expected across the entire geophysical industry, and should complement the exploration drive for concealed gold systems. Advancements in technologies like distributed array electrical methods, 3D seismic and airborne gravity will potentially bring a step change in their application to exploration programs. Coupled with this the industry has been developing tools to assist with planning, processing and in-

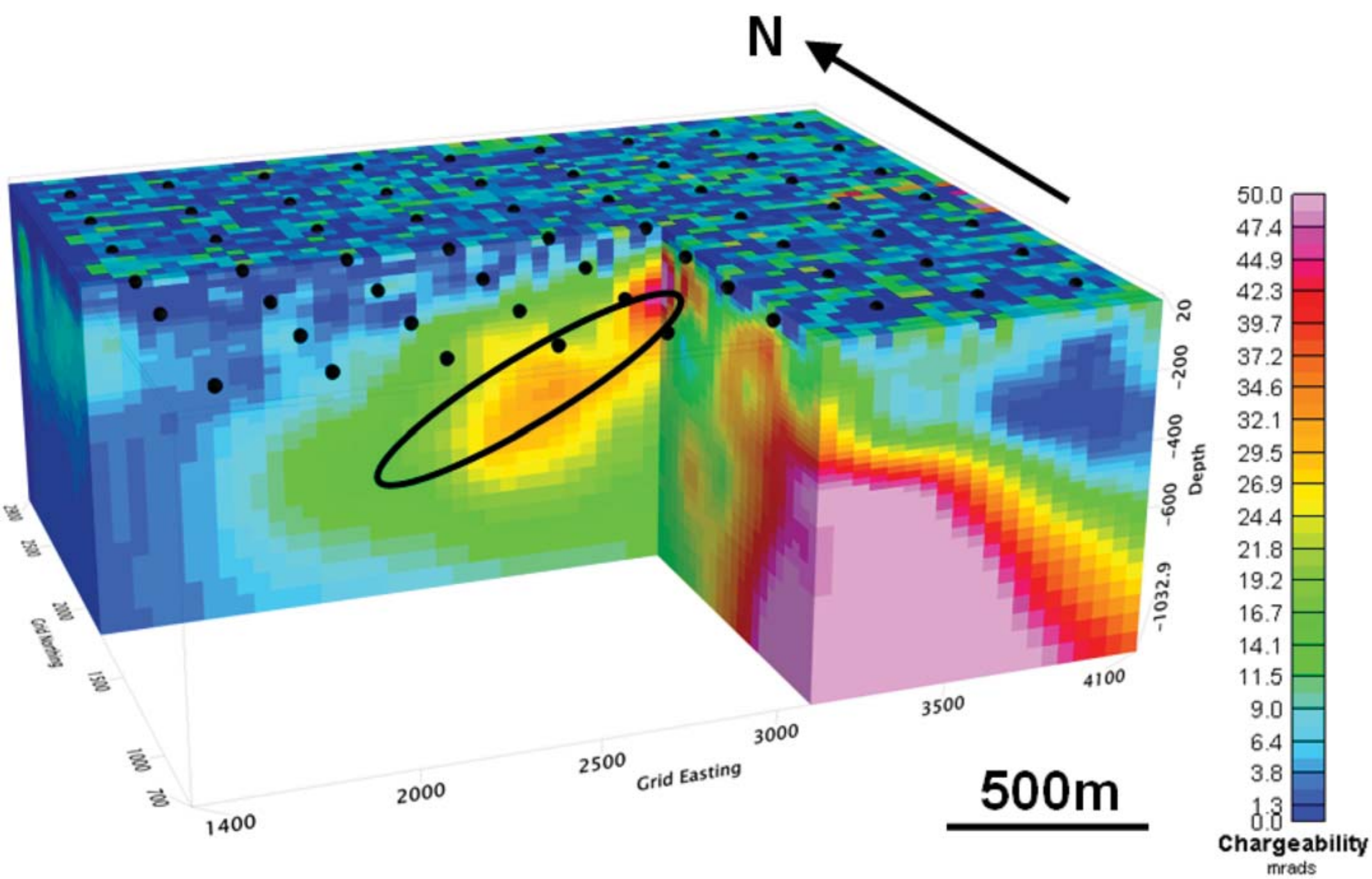

Figure 6. Slice through the Gold Hill 3D inverted chargeability model (Taken from Quantec, 2009). Black ellipse represents the plunge of the mineralized chute within the Oligocene volcanic tuffs, which is well mapped in the inverted chargeability model. The very strong chargeability anomaly south of the mineralisation is the carbonaceous Palaeozoic basement.

version of new survey types with the objective being 3D inversion models incorporating a-priori geological and physical property data.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Barrick Gold Corporation for allowing permission to publish geophysical data and geologic interpretations. Additional thanks goes to Meghan Jackson, Francois Robert, Susan Muir and Natashia Dallin for assistance in editing this paper to its final version.

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