*Paper 1*

# Ground and Borehole Geophysics 2008 to 2017: Into the Next Dimension

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## ABSTRACT

*Major advancements have been made with ground and borehole geophysics over the past decade with instrumentation, survey procedures, and interpretation by modelling and inversion. The goal of all of these advancements has been to increase the resolution and depth (range) of geophysical results in order to provide better knowledge and understanding of the geology of the subsurface. The key to success in mineral exploration is a detailed and correct knowledge of the earth in the area of interest, where mineral resources are suspected or even known about from previous drilling and surface geological investigations. And to obtain a more detailed and clearer understanding of the geology of the subsurface requires increased amounts and quality of geophysical data. Hence, the ever advancing sophistication and perfection of geophysical instrumentation (e.g. increased signal-to-noise); complexity of survey procedures (e.g. three-component and 3D data acquisition); and higher density 3D modelling and inversion tied to known physical properties of the subsurface. This paper will focus on two aspects of these advancements over the past decade: the increase in signal-to-noise, of instruments and of final results; and the continuing push into a 3D understanding of geology by 3D data acquisition and interpretation procedures.*

## INTRODUCTION

Major advances have been made with ground and borehole geophysics since the last Decennial Minerals Exploration Conference (DMEC) in 2007, with instrumentation, survey procedures, and interpretation by modelling and inversion. These developments have been extensively chronicled elsewhere, particularly in the annual reviews by Killen (e.g. 2017) published by The Northern Miner, with sponsorship by the Canadian Exploration Geophysical Society (KEGS) from 2007 to 2016, and now sponsored by DMEC. Rather than reviewing the highlights of these and other reviews of the advances in geophysics over the years, which can be downloaded free of charge from KEGS and other websites, I think it is more instructive to provide an overall framework of the advancement of the science and technology of ground and borehole geophysics: the "why" rather than the how or what.

Central to this discussion of the advancement of ground and borehole geophysics is the geological context of geophysical surveys and investigations. The change in attitude from applied geophysics leading directly to mineral discovery—to geophysics being applied to the broader problem of helping to attain a better, more detailed and truer understanding of geology—is what I feel is the most important aspect of ground and borehole geophysical advances over the past decade.

The mineral exploration industry, like previous major advances in petroleum exploration, is now able to routinely use 3D geophysics to better define the geological model. This technology has been advancing over the past 10 years and is now reaching a maturity with more widespread use of geologically constrained 3D inversion of all types of geophysical survey data applied to mineral exploration. And key to this development has been the continued advancement of true and complete 3D data acquisition, especially with the direct current and induced polarization (DCIP) resistivity method.

Also key to the continued improvement in the application of ground and borehole geophysics to the 3D geological model, has been the continued increase in the sophistication and technology of the geophysical measurements themselves: namely increased sensitivity of the measurements, increased density of the measurements, and generally a continuing increase in signal-to-noise. This is particularly the case with electromagnetic (EM) and DCIP resistivity with the general adoption of complete time series recording in the most advanced geophysical instruments, made possible by the latest advances in high speed and high dynamic range ADC.

I see this trend continuing into the next decade, because it rides on the back of the rapid and ever increasing technological sophistication of consumer electronics and IT. Also, survey techniques will continue to rapidly advance because consumer electronics will ultimately drive the cost of more sophisticated survey techniques down, through lower cost instrumentation on a cost per reading basis, resulting in survey data with greater sensitivity, greater density and greater signal-to-noise. This all leads to increased resolution of 3D geophysical inversions, constrained by physical properties and known geology, to provide better 3D geological models of the unknown subsurface.

## THE GEOLOGIC MODEL OF GEOPHYSICAL INVESTIGATION

In an overview of the advances in ground and borehole geophysics from the DMEC Exploration '07 conference, McMonnies and Gerrie (2007) highlighted the initiation over the previous decade of advanced 3D geological modelling (e.g. GOCAD) to provide a platform for the interpretation of ground and borehole geophysical survey data, in order to solve complex geological problems encountered in mineral exploration. Key to this new application was to bring together measured physical properties of rocks and mineralization into the 3D geological

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model, in order to constrain inversion of geophysical data over the area of interest.

The 3D geological model is flexible in that details of its form and structure are allowed to vary within constraints imposed by surface mapping and drill hole logging, in order to provide a better fit to the geophysical data. Key to the success of this geophysical interpretation methodology—to end up with a geological model that is detailed enough to advance the exploration program—is to have sufficiently dense and completely sampled (i.e. 3D) geophysical data of high precision.

The trend of using unified 3D geological models with geophysical interpretations, which began more than a decade earlier in the petroleum sector, was predicted by McMonnies and Gerrie (2007) to continue into the next decade in mineral exploration. Indeed, I see this trend continuing over the past decade, particularly with the advent of massive airborne geophysical data sets. I also see this trend gaining acceptance with ground and borehole geophysical data sets, however economic factors come into play more with ground and borehole geophysics because of the greater difficulty and higher costs of collecting sufficiently high density 3D geophysical data of sufficient precision and accuracy.

## 3D GEOPHYSICS IN MINERAL EXPLORATION

### Potential Field

Potential field geophysical data (gravity, magnetics and radiometrics) are inherently 3D, since surface potential field measurements can be used directly to invert 3D structure in the earth. The only issue is data density and whether borehole measurements are taken to expand the measurements into the third dimension. Ground gravity, magnetic and radiometric surveys have been essentially unchanged for several decades. All of the advancements in potential field surveying, which have impacted 3D inversion and geological models, have been with airborne surveys and specifically higher density measurements afforded by slower and lower flying platforms such as UAV.

Borehole gravity surveying was introduced in the previous decade but has seen some increased use over the past years, and primarily for massive mineralization exploration projects such as polymetallic volcanogenic massive sulphide (VMS). But there has been limited general application of borehole gravity in exploration because of the higher costs of this technique, unlike borehole magnetic and radiometric logging which is being used more routinely as a quick and relatively inexpensive way to provide constraints on 3D inversions.

### Electromagnetics

Active source geophysical methods present an extra challenge when moving into 3D data acquisition, because of the directionality defined by the receiver relative to the transmitter. Completely general 3D requires multiple receiver orientations for each separate multiple transmitter orientation. This is cost prohibitive for EM because of the relative high costs of individual receivers and transmitters, although there have been attempts at limited array TEM data acquisition such as the GeoFerret system developed by Western Mining in 2003. This system has not seen much use since the takeover of WMC by BHP Minerals in 2005.

Magnetotelluric (MT) EM surveys are routinely carried out using an array of instruments for mineral exploration, most notably by Quantec using their Titan24 and Orion3D systems. However, simultaneous recording from an array of MT receivers is not obligatory for the data to be interpreted by 3D inversion, because there is no transmitter involved with the measurements. 3D MT coverage can also be obtained from multiple MT measurements over the area of interest, similar to potential field surveys.

Magnetotellurics is most effectively applied to deep exploration situations where resistivity structure at depth helps to define the deep geological model underpinning mineralization systems such as in porphyry copper deposits.

### DCIP Resistivity

The most significant advancement in 3D geophysics applied to mineral exploration over the past decade has been with grounded electrical surveys of DCIP resistivity. The main reason for this advancement is simple: multiple individual receivers and the use of multiple transmitter current injections are not overly expensive survey techniques, so it is possible to have hundreds of simultaneous receivers or receiver channels recording the earth response from hundreds of different transmitter current injections.

The change from strictly 2D DCIP resistivity surveys along lines, to fully distributed arrays of receiver and transmitter sites over the area of interest began in about 2001 with the offset pole-dipole method. Instead of data being collected on one 2D line at a time, parallel lines of dipole receivers were installed along multiple lines and all recorded during transmitter current injections along a central parallel line. The data are primarily 2D along the survey lines, but the addition of the parallel dipole, cross-line measurements provided shallow 3D information that required 3D rather than 2D inversion.

Offset pole-dipole DCIP resistivity surveying became practical when the number of channels in commercially available DCIP receivers increased from 8 to 16 to 32, enabling multiple simultaneous recordings, particularly when two or more multi-channel receivers are linked through a common time base. The technique became much more practical and useful with the advent of 3D DCIP resistivity inversion at about the same time.

Fully distributed arrays of DCIP receivers were introduced during the period 1994–2002 by MIM Exploration Pty and Quantec Consulting, with the MIMDAS and Titan24 systems, and by Exploration '07 they were in wide use (Kingman, et al., 2007). Full-azimuth, "true" 3D surveys were introduced in 2011 with the Quantec Orion3D system. Other multi-receiver, distributed array systems have been introduced since 2010 (e.g. Volterra, gDAS24 and DIAS32), which facilitate greater flexibility of array design for full-azimuth 3D data acquisition.

The DIAS32 system from Dias Geophysical Ltd is a unique single-channel distributed array system that employs a common voltage reference (CVR), where the voltage at every receiver electrode is measured relative to the voltage on a common reference wire and dipole readings are derived from these single-channel recordings in any orientation or scale over the distributed array of electrodes and receivers (Rudd and Chubak, 2017).

## SIGNAL-TO-NOISE CONSIDERATIONS

### Potential Field

A prerequisite to higher resolution 3D geophysical data leading to more detailed and meaningful 3D geological models is greater sensitivity measurements and higher signal-to-noise. For ground potential field methods, little has changed over the past 10 years with the sensitivity of gravity, magnetic and radiometric measurements. Signal-to-noise is similarly unchanged. However, new and improved sensor technology is making a difference to airborne potential field survey results, and similar improvements are likely in ground surveys in the future, particularly with new innovative ways to measure magnetic field strength.

### Electromagnetics

Ground and borehole electromagnetic technology is constantly advancing with ever more sensitive sensors, both dB/dt (coils) and B-field (e.g. SQUIDs, fluxgates), and survey methods to increase signal-to-noise. One of the more obvious means of increasing signal strength is with the use of more powerful transmitters. Recent years have seen a 2 to 4 fold increase in transmitter power with higher currents in larger loops. But the most gain in signal-to-noise with ground and borehole EM is on the receiver side, most notably with the use of high sample rate and complete time-series recording, now integrated into all of the most recent TEM instrument developments. This revolution in EM signal recording and processing has been brought on by the revolution in digital electronics in every aspect of modern life: massively greater memory capability at a fraction of the cost, faster and more sensitive A/D, miniaturization, and the adaption of rapid advances in consumer electronics into EM receivers (e.g. GPS chips).

Improved EM receiver technology leads to more sophisticated EM signal processing to reduce noise and increase signal (e.g. more robust stacking in TEM) and these improvements lead directly to improvements in the precision and resolution of EM interpretations by modelling and inversion. The limiting factor now is with 3D inversion platforms—there are not enough of them to drive costs down and there are still significant size and speed limitations with the few 3D EM inversion methods available to the mineral exploration industry. But the main impediment now, to greater utilization of EM in 3D geological models is the high cost of sensors and receivers, and the means with which to collect 3D TEM data. EM surveying on the ground and in boreholes is difficult and expensive, and until technologies can be developed to bring down the cost of EM equipment and simplify a “distributed array” style of surveying, EM will lag behind other ground and borehole geophysical methods in adding value to the 3D geological model.

### DCIP Resistivity

The lower costs of equipment (i.e. a stainless steel stake in the ground versus an EM induction coil) and the relatively greater ease of 3D DCIP resistivity surveying with a distributed array of receivers and transmitter locations (i.e. current injections versus EM transmitter loop deployments), has led to a relative explosion of high resolution 3D resistivity and chargeability models helping to guide mineral exploration. As with EM technology, modern consumer electronics has made a significant positive impact on the new distributed array DCIP resistivity systems (e.g. DIAS32), and increased transmitter power has also increased signal-to-noise, although there are limitations in DCIP surveying due to the difficulty of overcoming ground contact resistance. Newer DCIP receivers also employ complete time series recording at high sample rate and mega storage capability, etc. which allows more robust signal processing and noise rejection.

The most serious noise, and hence resolution, limitation with DCIP resistivity surveying are telluric signals induced by geomagnetic fluctuations. Unfortunately these very large extraneous signals are readily picked up by all grounded electrode arrays, although some array designs are less affected than others. And the telluric signal frequency, although wide band, has a lot of power in the same 0.1 to 1.0 Hz range where DCIP measurements are taken. Various telluric cancellation methods have been developed to help improve signal-to-noise, but there is considerable room for improvement and undoubtedly, the most significant advancements in DCIP resistivity surveying over the next 10 years will be in telluric cancellation.

## CONCLUSION

There have been significant advances in the technology of ground and borehole geophysics over the past decade as a means of increasing the sophistication, precision and confidence of 3D geological models to assist the mineral exploration industry to discover, quantify and extract mineral wealth from the ground. The most significant advances with the most promise for providing real value to mineral exploration are those which have increased the resolution and reliability of 3D geophysical survey results: 3D data acquisition using full 3D distributed arrays and increased signal-to-noise of these 3D measurements.

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