KEGS-DMEC
Geophysical Symposium 2012

Exploration ‘07 plus 5: A Half-decade of Mineral Exploration Developments

Saturday, March 3rd, 2012
Intercontinental Hotel, Toronto

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Presenter gifts

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Lunch

Reception

Coffee breaks

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**Poster session**

*Posters will be displayed all day in the main hall*

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Following the symposium, the technical extended abstracts along with the PowerPoint presentations will become available on the KEGS website, at the link below:

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ORAL PROGRAM
A Radical Approach to Exploration: Let the Data Speak for Themselves!

Colin T. Barnett*, BW Mining, Boulder, CO 80304; and Peter M. Williams, BW Mining, Brighton, Sussex, UK.

Summary

The most critical decision in exploration is deciding where to look in the first place. This decision is often based on hunch or prejudice rather than systematic evaluation. We need to put more effort into objective targeting in order to improve the discovery rate. The best way of doing this, in more mature districts, is to use statistical data mining techniques, allowing the data to speak for themselves. The targets generated by this objective approach are highly focused, so that only limited budgets are needed for follow-up investigations. Expected ROIs of many hundreds are achievable.

Introduction

The last ten to fifteen years have seen a significant decline in the rate of new discoveries of valuable mineral deposits. This has happened despite increasing exploration budgets over the same period. Existing gold reserves are being depleted even at a time when the potential profitability of new discoveries is increasing.

The most critical decision in exploration is deciding where to look in the first place. If a team is put in the right place with modern exploration tools, it is almost certain to hit the target; in the wrong place, the team will never find anything and simply waste time and money. Unfortunately, the decision where to look is too often based on subjective hunch and conjecture rather than systematic evaluation. Time and time again, hasty decisions have committed companies to years of wasted effort. We need to put far more effort into targeting, or deciding where to look, in order to improve the discovery rate.

This same ten to fifteen years has seen a significant growth in the volume of accessible exploration data. Remote sensing such as Landsat, ASTER, SRTM, Google Earth is increasingly available. To stimulate exploration and mining, regional and national governments are releasing non-proprietary data sets, including geophysics and geochemistry, and compiling databases of known mineral deposits, such as MINEDEX for Western Australia or FINGOLD for Finland. This ever increasing quantity of information is overwhelming to the unaided human interpreter. In future, conventional approaches to exploration will be able to sample only an ever diminishing fraction of the available information.

Two other relevant developments have taken place over the same period. First, the costs of storage, transfer and processing of even very large quantities of data have reduced to a level at which they are no longer significant. Secondly, advances in data mining and statistical pattern recognition now make it possible to extract almost all the relevant information from this wealth of data. In sufficiently mature districts, multivariate correlations between exploration data and known deposits can be used to determine the statistical probabilities of similar economic mineral occurrences at any location in the region.

The targets generated by this approach are based only on measurable exploration data. While such data sets include geology—both lithology and structure—they do not include geological accounts of the ore genesis process. The advantage of the data mining approach, however, is that initial targets are based only on known facts; insights into the underlying mineralization process can still inform later stages of target ranking or screening. A further advantage is that targets are very tightly defined, and can be assigned numerical probabilities from which precise estimates of expected economic costs and rewards can be derived. For example, integrating the probability field over the target area, with respect to a monetary measure, provides the expected value of a target. Follow-up exploration costs can be estimated from its spatial extent. Since targets are usually no more than a few square kilometers in area, large expected returns on investment can be achieved.

To explain how statistical data mining works in more detail, we shall present a particular case study in the Yilgarn Craton of Western Australia, serving to illustrate all aspects of the approach.

Eastern Goldfields North

The Yilgarn Craton is so extensive that we chose to limit this study to an area that we call the Eastern Goldfields North (EGN) (see Figure 1). This area falls between longitudes 120–123° E and latitudes 25–30° S, and extends 300 km E-W by 550 km N-S, making a total of 165,000 square kilometers. The choice of this particular area was based on various factors: notably, the high concentration of known deposits, the availability of modern exploration data sets, and a stable political environment in which mineral exploration and mining are actively encouraged.

The EGN contains a known gold endowment of 70 million ounces and also provides a large collection of modern exploration data sets. These two critical ingredients make the EGN an excellent candidate for a successful data mining study.
A Radical Approach to Exploration

The data sets incorporated in this study were the known gold deposits, regolith mapping, Landsat TM, SRTM elevation, digital geology (lithology and structure), gravity, airborne magnetics and radiometrics, and biogeochemistry. The raw material for all these data sets are in the public domain, so no private or proprietary corporate data sets were used for this data mining study.

Data Mining Study

The data mining process used for this study is based on probabilistic modeling with neural networks, and is described in greater detail in recent publications by Barnett & Williams [1] and [2].

Figure 2 shows a close up of a typical target resulting from our data mining study. In this particular area there are five historic workings which produced over 500,000 ounces of gold. The process suggests that there is still more gold to be found close to one of the old workings on the east side of this map. The main red target zone is about 500m wide and about 2,500m long, which could represent a significant deposit.

Figure 3 shows the corresponding geological map of this area. It can be seen that the target occurs in mafic greenstone rocks close to a shear zone containing granite gneiss. Four of the five historic workings lie on regional structures, while the fifth occurs within an ultramafic unit. The new target indicated by the neural network also coincides with an ultramafic unit. It would be a relatively straightforward matter to follow up this target in the field with geologic mapping, regolith geochemistry, geophysics, and exploratory drilling if the results are positive.

The EGN study produced more than a dozen such high priority targets which merit further follow up work. While some are genuinely new, separate and sizeable areas of high favorability, the majority of these targets occur in established camps within a few kilometers of operating or historic gold mines. The odds are high that several of these targets will prove to be economic deposits of gold.

Conclusions

Exploration will always involve risk and uncertainty. But risk can be managed, provided (1) the maximum possible information is extracted from the available multi-layered data sets and (2) the results are expressed quantitatively, so that exploration decisions can be taken using numerical estimates of statistical risk.

To our knowledge, the results obtained using the data mining methods described here are unrivalled in these respects. Other attempts have mostly been hampered by inadequate representations of individual data sets or of the statistical dependencies between them. Compared with alternatives, the statistical neural network approach shows an order of magnitude improvement in probability discrimination.

References


A Radical Approach to Exploration

Figure 2: Closeup of a typical neural network target.

Figure 3: Closeup of the corresponding target geology.
Recent advances in 3D inversion of potential-field data in mineral exploration
Yaoguo Li, Center for Gravity, Electrical, and Magnetic Studies, Colorado School of Mines

SUMMARY
In this presentation, I provide a brief review of new developments in 3D potential-field inversion with emphasis on those since Exploration 07. We will focus on the advances in three areas: (1) inversion of magnetic data under difficult conditions, (2) inversion of new data types, and (3) inversion on super-large scales. The first area focuses on inversion of complex magnetic data sets affected by strong remanent magnetization and self-demagnetization effect. The second covers the inversion of multiple-component gravity gradiometry and magnetic gradiometry data, borehole gravity data, and the requisite processing techniques for these new data types. The third area consists of a suite of computational and algorithmic techniques for enabling and accelerating the solution of super-large scale problems on both district scale with high-resolution data and regional scale with expansive data areas. Associated with this direction is also the capability to invert global-scale data in spherical coordinates.

INTRODUCTION
3D generalized inversion of potential-field data has established itself as an effective interpretation technique in mineral exploration in the last decade. Many highly effective and mature tools are already available. Earlier algorithms (Li and Oldenburg, 1996; Pilkington, 1997) have been used widely in mineral exploration. A majority of such inversions pertains to the total-field magnetic anomaly and vertical gravity anomalies. Similar approaches have been extended to gravity gradiometry data (Li, 2001; Zhdanov et al., 2004). Many successful cases have been presented over the years.

The generic algorithms have the capability of incorporating a host of prior information through the use of a reference model, 3D weighting functions, and bound constraints. Although these functionalities were included as academic curiosities at first, they turned out to be highly valuable as vehicles for incorporating known geological information. For instance, McGaughey (2007) has made great contribution in combining geologic information in the form of reference models with 3D magnetic and gravity inversions. The research team at the Geoscience Australia also made tremendous progress by incorporating regional geology into 3D inversions. Their highly successful program generated predictive 3D geology maps for identifying prospective areas of mineral deposits (Lane and Guillen, 2005; Williams and Dipple, 2007). Fullagar et al. (2008) developed a mixed inversion algorithm that can directly incorporate the boundaries of major geologic units into an inversion together with the unknown susceptibility or density distribution.

Despite the availability of these algorithms, there has been a huge resurgence in research pursuit for faster and newer approaches in recent years with sustained support from the industry. This resurgence is no doubt spurred by many successful cases. More importantly, however, it is driven by the challenges to invert data under difficult conditions, by the availability of data from newer and improved acquisition systems, and by the need to solve increasingly large-scale problems. Many exciting advancements have been made: some are already making their contributions to exploration, some are on their way to become practical tools, and others have the promise to dramatically change the way we carry out inversion in the context of geological interpretation for mineral exploration.

In the following, I will summarize these recent advances by organizing them into three categories described above. Given the limited space and time, I will only touch on the major developments of practical importance. There will likely be unintentional omissions. However, my hope is to provide a guide to exploration colleagues the tools that are, or will become, available.

INVERSION OF MAGNETIC DATA UNDER DIFFICULT CONDITIONS
Quantitative interpretation of magnetic data through inversion for a susceptibility distribution has played an important role in exploration in recent years. Applications range from district scale to regional scales. Under normal conditions, standard algorithms are highly effective (Li and Oldenburg, 1996; Pilkington, 1997). These algorithms assume that there is no remanent magnetization, and that the self-demagnetization effect can be neglected. When these conditions are met, the magnetization direction is aligned with the inducing field and forward modelling can be simplified.

With the expanded use of 3D magnetic inversions, we encounter more and more data sets that do not satisfy these conditions. Two major scenarios are the presence of strong remanent magnetization and the presence of high magnetic susceptibility. The former superimposes on the induced magnetization and directly causes the total magnetization to deviate from the current inducing field direction and become an unknown. The latter leads to the self-demagnetization effect and produces a highly variable magnetization direction that depends on the geometry of the causative body. In these two scenarios, we lack a crucial piece of information to carry out the forward mapping in the inversion. Consequently, the greatest hindrance for inverting such data sets is the unknown magnetization direction.

Remanent magnetization
1. Inversion with estimated magnetization direction
The first and most straightforward approach is to estimate the magnetization direction and use it in the standard inversion. Given the prevalence of remanent magnetization, it is not surprising that a plethora of methods are available for direction estimation in the literature. Making use of these estimation
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methods, Li et al. (2010) demonstrated the effectiveness of this approach using both synthetic and field data sets. The advantage is that no new inversion algorithm or software is required and the direction estimation is simple to implement. This approach works well with isolated anomalies of simple geometry. Although there are many different estimation methods available, they have found that the Helbig’s method and cross-correlation methods (Dannemiller and Li, 2006; Gerovska et al., 2009) are good options in practice for their simplicity and reliability.

2. Inversion of magnetic amplitude data

A major limitation of the above approach is that a single magnetization direction may not be estimated due to either the complexity of the anomaly or the presence of multiple anomalies with differing magnetization directions. As an alternative, one may utilize quantities that can be computed from total-field anomaly data but are insensitive to the magnetization direction. For example, both the amplitude of the magnetic anomaly vector and the total gradient of total-field anomaly are independent of the magnetization direction in 2D problems (Nabighian, 1972). While such a property does not extend to 3D problems, both amplitude and total gradient are still weakly dependent on magnetization direction and therefore can be inverted directly to recover the magnitude of magnetization.

Shearer (2005) developed an inversion algorithm for both of these quantities. The approach first calculates either the amplitude or the total gradient, treats the calculated quantity as data, and then carries out a nonlinear inversion to recover the effective susceptibility. Li et al. (2010) have demonstrated that this approach can produce 3D models comparable to those from inversions based on direction estimation for single anomalies.

The advantage of this approach is the applicability to a wide range of complex magnetic anomalies and source distributions. In exploration applications, the amplitude data are preferred since they do not preferentially attenuate long-wavelength signals in the original data.

3. Full inversion for total magnetization vector

Instead of skirting around the issue of magnetization direction, Lelièvre and Oldenburg (2009) invert magnetic data for a distribution of three-component magnetization vector, as opposed to a scalar susceptibility. The magnetization vector is parametrized either in a Cartesian or spherical framework. In the Cartesian formulation, the total magnetization is split into one component parallel to and two components perpendicular to the Earth’s field. In the spherical formulation, they invert for magnetization amplitude and the inclination and declination of the magnetization direction. Although increasing unknown parameter sets to three scalar functions worsens the non-uniqueness of the magnetic inverse problem greatly, Lelièvre and Oldenburg (2009) have demonstrated that inclusion of additional information, such as the knowledge of magnetization or geologic structure, as constraints dramatically improves results.

In a similar approach, Foss and McKenzie (2011) formulates a parametric inverse problem that simultaneously recovers a set of geometrical parameters describing the shape of a causative body and a total magnetization vector assumed to be constant within the body. The parametric approach greatly reduces the non-uniqueness associated with the generalized inversion at the expense of the limited capability for automated inversion of large-scale data sets. However, the method provides a complementary tool of great practical value.

Self-demagnetization magnetization

In the presence of high magnetic susceptibility ($\kappa > 1.0$), such as in banded iron formations, the self-demagnetization effect becomes significant, in which the magnetic field at a location in the source body is altered by the induced magnetization from neighboring domains. This process is highly dependent upon the source geometry. The net result is the deviation of magnetization direction from the inducing field direction, which is similar to the case of remanent magnetization. The resultant magnetization direction, however, can be much more variable within a single body. Two generalized inversion approaches have emerged for automated inversion of such data sets.

1. Full inversion using self-demagnetization solution

Lelièvre and Oldenburg (2006) develop an algorithm to invert magnetic data produced by highly susceptible bodies. Their algorithm takes the rigorous approach of solving the full differential equation governing the magnetostatic field by using a finite volume discretization and a nonlinear regularized inversion. At each iteration, a forward solution is carried out to predict the magnetic data with the complete self-demagnetization effect, and a linearized inversion is performed to obtain the model perturbation through the use of implicit sensitivity calculation. The authors tested the algorithm with success on magnetic data from ferrous shipping containers, but it will be a valuable and versatile tool in mineral exploration since it provides the rigor, flexibility, and speed based on the implicit calculation of the sensitivity matrix.

2. Application of amplitude inversion

Aiming for a unified interpretation approach for both remanent magnetization and self-demagnetization, Krahenbuhl and Li (2007) examined the applicability of methods that have been developed for remanent magnetization in the interpretation of magnetic data produced by sources with strong self-demagnetization effect. They have found that the approach of direction estimation is, in general, not applicable because of the highly variable magnetization direction in high-susceptibility bodies. Either a representative direction cannot be estimated or such an estimate does not yield satisfactory inversion result. However, the inversion of amplitude data is an effective approach and can deal with the variable magnetization direction associated with self-demagnetization effect. The conclusion has been bolstered by subsequent applications to data sets from Australia, Brazil, and China using comparisons with known geology. The major advantage of this approach is that the same methodology can be used for both scenarios of magnetic inversions under difficult conditions. This simplicity could be significant to practicing geophysicists who may not have sufficient time to investigate the specific cause of the difficulties but simply desire a geologically interpretable result in order to solve the exploration problem at hand.
Advances in 3D potential-field inversion

In summary, we now have a set of tools at our disposal for the inversion and quantitative interpretation of magnetic data under difficulty conditions. These tools are approaching the maturity of the traditional inversion in the preceding decade. As a result, we can now invert any magnetic data and carry out quantitative interpretation.

INVERSION OF NEW DATA TYPES

Several exciting developments in data acquisition have materialized in the mineral exploration. These include the magnetic gradiometry flown concurrently with total-field acquisition, the availability of borehole gravity measurements Nind et al. (2007), and the wide spread commercial acquisition of airborne gravity gradiometry data (Murphy, 2004; Dransfield, 2007). Our community has expended much effort to stay abreast of the new data acquisitions, and achieve significant progress.

Joint inversion of magnetic gradiometry data

Acquisition of magnetic gradient data has been going on for several decades. These data have been primarily used to enhance total-field anomaly data. Historically, direct use of these data in quantitative interpretation has not been an emphasis.

Recently, Davis and Li (2010a) have developed a joint inversion algorithm for total-field and gradient data. The method makes use of a well known relationship between the derivatives of the magnetic field and the derivative of its source and relates both data sets to a common source distribution. This approach treats the observed gradients as an additional and independent data set instead of being just supplemental information. These data are incorporated to spatially constrain the recovered susceptibility model that simultaneously fit the total-field and gradient data. Applications to synthetic and field data sets demonstrate that the joint inversion noticeably improves the resolution of the recovered model.

Joint inversion of surface and borehole gravity data

Borehole gravity has been used in petroleum exploration and production, but only began to appear in mineral exploration recently with the advent of slim hole gravimeters (Nind et al., 2007). Given the widely available surface data, it is logical to carry out joint inversion to fully utilize the information in the newly acquired data.

In a systematic and meticulous study, Mosher et al. (2008) investigate the inversion of borehole gravity data for 3D density models at Voisey’s Bay deposit. The authors employ a forward modeling based on the finite-difference solution of Poisson’s equation. The study demonstrates the improvement in the recovered density variation that can be gained from the joint inversion of varying amounts of borehole and surface gravity data.

Sun and Li (2010) take a different approach and investigate the joint inversion using thresholding and localized density constraints. They demonstrate that incorporating borehole gravity data may help detect dipping structure in the density distribution. Once identified, the dipping structure can be imposed in the second stage of inversion together with the above-mentioned constraints to generate a highly refined density contrast model.

Inversion of airborne gravity gradiometry data

Airborne gravity gradiometry may be one of the most exciting addition to the tool set in mineral exploration geophysics in recent years. Currently, there are two active commercial systems (Murphy, 2004; Dransfield, 2007) operating in mineral exploration. Two next-generation systems are being developed (Anstie et al., 2010; Carroll et al., 2010). Airborne gravity gradiometry is poised to become the next revolution in the airborne geophysics for mineral exploration.

Mathematically, gravity gradiometry data behave exactly as do magnetic data. Both data sets are related to their respective source by the kernels depending on the same dyadic Green’s tensor. Thus, much of the intuition, pre-processing, and inversion algorithms we have for magnetic data is directly applicable to gravity gradiometry data. One major difference is the terrain correction. The terrain effect is the strongest component in the gradient data because the air-earth interface has the largest density contrast and is closest to the sensor.

Davis et al. (2011) developed a method for modeling the terrain response of gravity gradiometry surveys utilizing an adaptive quadtree mesh discretization. The data- and terrain-adaptive method is tailored to provide rapid and accurate terrain corrections for draped and barometric surveys. This method can reduce the computational cost by two orders of magnitude compared to the full calculation.

Martinez et al. (2010) carried out detailed analysis and inversion of a set of full-tensor gravity gradiometry data acquired for iron ore exploration in Brazil by using the algorithm developed by Li (2001). Even blind inversions with only bound constraints can characterize the high-density orebody well, defining its location, extent, and dipping structure. With dense data from 100-m spaced lines, a single-component inversion provides the bulk of the information needed and images the target sufficiently. However, additional components do carry extra information and have been shown to contribute to the improvement of the inversion and associated target and structure definition.

Two new algorithmic developments are noteworthy. The first is the $l_p$ inversion of multicomponent gravity gradiometry developed by Kirkendall et al. (2007) for cargo container imaging. However, the algorithm is general and equally applicable to mineral exploration problems. The use of $l_p$ norm with $p$ close to 1.0 can greatly improve the definition of the recovered density anomaly. The second is an extended method of growing bodies based on seeding and a known density contrast by Uieda and Barbosa (2011). The method is rapid and produces a large-scale first-order image of density anomalies. Carlos and Barbosa (2011) have used this method successfully to interpret the entire set of multicomponent gradiometry data from the above-mentioned area in Brazil.

As a community, we now have a suite of processing and inversion algorithms for various forms of airborne gravity gradiom-
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etry data. Studies have been produced to demonstrate the rich information content of the said data and their broad applicability in different prospects. Quantitative interpretation of these data using 3D inversions should become a routine approach as in the case of magnetic data.

INVERSION ON SUPER-LARGE SCALES

Solving large problems in potential-field inversion is a perennial desire and effort in the mineral exploration community. Some efforts are well publicized and others are simply being used. Recent developments have taken two distinct paths: hardware versus algorithm. There has been a great deal of advances in the latter, and all algorithmic developments are implementable in a parallel computing environment.

GPU and parallel computing

One approach to solving large-scale inversion lies in computer-science and utilizes the latest computer hardware such as GPU computing and massively parallel computing. Although many research groups and industry companies have been using this technology directly as a matter of course, it has been brought to the forefront of discussion recently by Zhdanov et al. (2011). Their work also incorporates a limited-footprint approach that was first developed by Hansen and Miyazaki (1984) for the inverse problem of equivalent source construction. The block sparse sensitivity matrix based on a limited footprint neglects the signal whose wavelengths are comparable or greater than the radius of a prescribed footprint. This approach may not be as effective in the presence of dense observations common in modern airborne surveys. It can be advantageous, however, when inverting sparsely distributed data covering a large area.

Octree, Hilbert space filling curve, and wavelet transform

Davis and Li (2010b) use the wavelet transform in an adaptive mesh application to form a three-step approach to compress large problems. The first component of the algorithm is the adaptive octree mesh discretization that decreases the number of model parameters. The second re-orders the model parameters through 3D Hilbert space-filling curves to increase compression properties prior to the 1D wavelet transform on the semi-structured mesh. Finally, the wavelet transform has a compression property by winnowing small coefficients that do not significantly change the function after the inverse transform. It is performed on the reduced and re-ordered model parameter set. In one test, the algorithm was able to invert an airborne data set in its entirety from a mineral exploration project on a single personal computer. For the particular example, the computational cost is reduced by more than 10,000 times compared to a standard non-compressed approach.

3D FFT approach

An interesting and noteworthy development in this area is the revival of the fast Fourier transform (FFT) in large-scale modeling and inversion. Phillips et al. (2008) presented preliminary work on using 3D FFT to calculate gravity or magnetic responses from a source distribution confined within a box-shaped region. The FFT formulation in 3D may allow arbitrarily located observations on an undulating surface, which would overcome a major drawback in 2D FFT based methods. The method remains to be fully developed but its implication is huge.

Inversion on the regional and global scales

As the size of areas of interest increase in potential-field inversion on regional and global scales, we inevitably grow out of the Cartesian framework and move into a spherical coordinate system. This requires retooling our current standard inversions based on rectangular cells and constant projection direction of anomaly (for both gravity and magnetics). Liang et al. (2011) have developed a new 3D inversion method for this class of problems in spherical coordinates. The inversion algorithm is formulated using a specially designed model objective function and depth weighting function appropriate for spherical coordinates. The algorithm has been applied to invert the lunar gravity data over the entire globe. The approach and algorithm are equally applicable to regional scale on Earth, such as the 1/3 of the area on the Earth’s surface centered over Australia, which is of current interest to Geoscience Australia (Richard Lane, personal communication).

CONCLUDING REMARKS

Collectively, potential-field data including gravity, magnetic, and their gradients continue to be one of the richest data types available to mineral exploration. We are continuing to find better and faster ways to extract the wealth of information embedded in these data, and we have seen a wide variety of advances in the recent years. For practicing geophysicists, utilizing these data may have the tremendous potential of leading to the next major discovery. For researchers, inversion of potential-field data is an enjoyable and rewarding field to work in. For students entering into exploration geophysics, taking on the challenges of potential-field interpretation can be a promising career path.

ACKNOWLEDGMENTS

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REFERENCES

Advances in 3D potential-field inversion


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Inversion of Magnetic Data from Remanent and Induced Sources
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Summary
Magnetic field data are of fundamental importance in many areas of geophysical exploration with 3D voxel inversion being a common aid to their interpretation. In the majority of voxel based inversions it is assumed that the magnetic response arises entirely from magnetic induction, and that demagnetization and anisotropy can be ignored. Effectively, the magnetization is assumed to be in the same direction as the earth’s magnetic field. However, in the last decade, several studies have found that remanent magnetization is far more prevalent than previously thought. Further, it is known that demagnetization and anisotropy are important for several mineral deposit types. Our experience with numerous minerals exploration projects confirms that magnetization deviating from the earth’s field direction is the rule rather than the exception in minerals exploration.

In this presentation we show that failure to accommodate for demagnetization, anisotropy, and remanent magnetization in 3D voxel-based inversion can lead to misleading interpretations. We present a technique we call Magnetization Vector Inversion (MVI), which incorporates both remanent and induced magnetization without prior knowledge of the direction of the magnetization. We demonstrate our inversion using model studies and field data. Successful application to numerous minerals exploration surveys confirms that incorporating remanent magnetization, demagnetization, and anisotropy is essential for the correct interpretation of magnetic field data.

Introduction
The utility of magnetic field data in many areas of geophysical exploration is well-known as is the application of 3D voxel inversion to aid in magnetic data interpretation (for example, Li and Oldenburg 1996, Pilkington, M., 1997, Silva et al. 2000, Zhdanov and Portniaguine 2002, to cite just a few). In the majority of voxel based inversions it is assumed that the magnetic response arises entirely from magnetic induction, and demagnetization and anisotropy are ignored. In these inversions the magnetization is forced to be in the same direction as the earth’s magnetic field. However, it is known that demagnetization can give rise to magnetic anisotropy in mineralized targets, and further, in the last decade, studies have found that remanent magnetization is more prevalent than previously considered (McEnroe et al. 2009) and affects crustal rocks as well as zones of mineralization. Unfortunately, remanent magnetization, anisotropy, and demagnetization can seriously distort inversion based on the assumptions that the source is only induced magnetization, and that the induced magnetization direction is in the inducing field direction. The severity of the distortion is due to the highly non-unique nature of potential field inversion making it extraordinarily easy for a potential field inversion to produce a seemingly plausible model which agrees satisfactorily with the observed data, even when a fundamental assumption in the inversion is flawed.

Several authors have reported progress toward magnetic data inversions including remanent effects (for example, Shearer and Li 2004, Kubota and Uchiyama 2005, Lelièvre and Oldenburg 2009). In this work we report further progress in this direction with a technique we call Magnetization Vector Inversion (MVI), which incorporates both remanent and induced magnetization without prior knowledge of the direction or strength of the magnetization. In the following sections, we extend conventional scalar susceptibility inversion to a magnetization vector inversion, that is, we allow the inversion to solve for the source magnetization amplitude and direction. While this increases the number of variables in the inversion we will show by example that the same regularization principles that allow compact targets to be resolved in highly unconstrained scalar susceptibility inversion also apply in vector inversion.

Perhaps our most significant finding is that MVI, or more generally, inversion including all forms of magnetization, significantly improves the interpretation of the majority of minerals based magnetic field inversions. Unfortunately, the surprising degree of improvement in interpretability cannot be adequately presented in a paper and can only be verified by direct experience. Consequently, while we have applied MVI to a large number of magnetic field surveys and find the results to be significantly superior to conventional scalar based inversion, in this paper we are forced to limit our attention to a synthetic case and field data from the Cu-Au Osborne deposit located approximately 195km SE of Mount Isa, in Western Queensland, Australia.

Method and Results
Let us begin with the very general assumption that the magnetic properties of the earth can be represented by a volume magnetization, \( \mathbf{M}(r) \). We make no assumptions about whether source of the magnetization is induced, remanent, or otherwise. From magnetostatics, the magnetic field \( \mathbf{B} \) at point \( \mathbf{r}_j \) resulting from a volume \( V \) containing magnetization, \( \mathbf{M}(r) \), is given by

\[
\mathbf{B}(\mathbf{r}_j) = \nabla \int_V \mathbf{M}(r) \cdot \nabla \frac{1}{|\mathbf{r} - \mathbf{r}_j|} d\mathbf{r}^3
\]  

(1)
Magnetization Vector Inversion

This expression shows directly that the magnetization vector $M(\mathbf{r})$ is the natural parameter for inversion. This is an important observation.

If the volume $V$ consists of a collection of $N$ sub-volumes $V_k$ each of constant magnetization $\mathbf{m}_k$, then

\[
B_{\beta}(\mathbf{r}_j) = \frac{1}{\left| \mathbf{r} - \mathbf{r}_j \right|} \int_{V_k} \partial_\alpha \partial_\beta \frac{1}{\left| \mathbf{r} - \mathbf{r}_j \right|} d\mathbf{r}^3 \tag{2}
\]

This defines the forward problem: given a set of sources $\mathbf{m}_k (k = 1, \ldots, N)$ then $B_j$ is the predicted magnetic field anomaly at points, $\mathbf{r}_j (j = 1, \ldots, M)$. Note that the coordinate index $\alpha$ is summed over indicating that we are free to choose the most computationally convenient internal coordinate system. It also suggests that a coordinate invariant quantity, such as the amplitude, $M(\mathbf{r}) = |M(\mathbf{r})|$, will be most robustly determined from the data.

For conciseness, we will represent Eq (2) simply as

\[
\mathbf{B} = \mathbf{G} \mathbf{m} \tag{3}
\]

The vector magnetization inverse problem is defined as solving for $\mathbf{m}$ given $\mathbf{B}$ subject to an appropriate regularization condition. Although there are many choices for the regularization (see for example, Zhdanov 2002), we choose without loss of generality, the familiar Tikhonov minimum gradient regularizer. The inverse problem becomes solving for $\mathbf{m}$ in,

\[
\begin{align*}
\text{Min} & \quad \phi(\mathbf{m}) = \phi_D(\mathbf{m}) + \lambda \phi_M(\mathbf{m}) \\
\phi_D(\mathbf{m}) & = \sum_j \left| \frac{G_j \mathbf{m} - B_j}{e_j} \right|^2 \\
\phi_M(\mathbf{m}) & = \sum_y \left| w_y \partial_y \mathbf{m} \right|^2 + |w_0 \mathbf{m}|^2 \\
\lambda : \phi_D(\mathbf{m}) & = \chi^2
\end{align*} \tag{4}
\]

where in the first line, the total objective function $\phi$ is the sum of a data term $\phi_D$ and a model term $\phi_M$ with a Tikhonov regularization parameter, $\lambda$. The second line defines the data objective function in terms of the data equation (3) and the error associated with each data point, $e_j$. The third line gives the model objective function in terms of the gradient of the model $\partial_y \mathbf{m}$ and the amplitude of the model, with weighting terms as required, $w_y, w_0$. The fourth line indicates that the Tikhonov regularization parameter $\lambda$ is chosen based on a satisfactory fit to the data in a chi-squared sense, $\chi^2$. In addition, other constraints, such as upper and lower bounds, can be placed on $\mathbf{m}$ as appropriate to the specific exploration problem.

**Example – Buried Prism**

Although the buried prism model is far too simplistic to have exploration significance, it does make an excellent pedagogical example, so we follow tradition and begin by considering the inversion of simulated TMI data over a buried prism with magnetization vector $\mathbf{M}$ perpendicular to the earth field. The model consists of a cube with side length 40m buried with a depth to top of 20m and a magnetization vector in the EW direction, $(M_y = 0, M_z = 0)$ as shown in Figure 1.

Figure 1: The buried prism model with magnetization vector orientation (Easterly) shown by the green cones. Side=100m

Figure 2: The TMI data simulated over the magnetization vector model shown in Figure 1. The axes are in metres.

Figure 3: The MVI recovered model for comparison with Figure 1. The magnetization vector orientation is shown by the green cones.

Simulated TMI data are shown in Figure 2 for Earth field with inclination $90^\circ$ and amplitude 24000 nT. Cardinal directions have been chosen only for simplicity of explanation; any directions could be chosen with equivalent results. Also for simplicity, the data were simulated at 20m constant clearance and on a regular 8m grid.
**Magnetization Vector Inversion**

Inverting the TMI data in Figure 2 yields the model shown in Figure 3 which should be compared to the true model shown in Figure 1. There is some variability in the magnetization direction but the predominant direction is clearly EW, in agreement with the true model.

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. As suggested by Eq(1), the most robust and meaningful scalar is the amplitude of the vector magnetization and this should be the primary quantity used in interpretation. However, since the magnetization vector direction is the earth field direction for induced sources, it is tempting to attempt to use the directional information recovered in MVI to generate scalars related to the earth field direction. 

There are many possibilities but we have found that three useful derived scalars for exploration are: the amplitude of the magnetization, the earth field projection of the magnetization, and the amplitude of the perpendicular-to-earth-field components of the magnetization. In exploration problems, the amplitude is robust by being independent on of any assumptions regarding the earth field, while the amplitude perpendicular is an approximate indicator of non-induced magnetization. To support our findings, these three derived scalars are shown in Figure 4b, c, d for an East-West slice through the model volume bisecting the target in the true model. 

In exploration situations it is convenient to present MVI output $\mathbf{M}$ normalized by the amplitude of the earth's magnetic intensity in the area of interest. That is, our results are displayed as $\mathbf{M}/H_0$ where $H_0$ is the amplitude of the earth's magnetic intensity in the area of interest. By using this normalization in an area of purely induced magnetization, the numerical values returned by MVI inversion will be directly comparable to those of scalar susceptibility inversion, in our case in SI. 

For completeness, and to show the contrast between MVI and conventional scalar inversion, Figure 5b shows the equivalent section through a model produced by an inversion which assumes only induced magnetization. As should be expected, the recovered model using scalar inversion is a very poor representation of the true model, which in real-world exploration ultimately adds significant confusion to the interpretation process. 

This simple prism example demonstrates the power of magnetization vector inversion and its advantage over scalar susceptibility inversion in cases where the magnetization vector direction deviates from the earth field direction. We argue that this situation predominates in real-world exploration environments based on experience from many magnetic surveys, however this cannot be shown here.

**Example - Osborne**

The preceding pedagogical study of MVI on simulated data over a prism provides a solid basis for the much more important application of MVI to field data. As mentioned in the Introduction, it is hard to appreciate fully the impact on magnetic data interpretation by including non-induced magnetic sources. However, to motivate our assertion, we present typical results taken from TMI data collected over the Osborne deposit.

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. Exploration since 1995 has delineated high-grade primary mineralization dipping steeply East to some 1100 m vertical depth. 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.

Magnetization Vector Inversion of the Osborne TMI data yields the magnetization vector amplitude earth model...
Magnetization Vector Inversion

shown in Figure 7. Superimposed (in black) is the subsequently discovered mineralization from extensive drilling and underground mining. For comparison, Figure 8 shows the corresponding scalar susceptibility inversion.

Figure 6: The observed TMI data acquired over the Osborne property. The axes are in metres. The color scale shows the TMI amplitude in nT.

Figure 7: An EW section through the recovered MVI model amplitude at the Osborne property with the now known mineralization shown in black. The colour bar gives the normalized amplitude in SI. The axes are in metres.

Figure 8: The same section as in Figure 7 for the scalar model with drilling and mineralization in black.

Comparing Figure 7 and Figure 8 shows that inverting for the magnetization vector provides a much better model for interpretation. The scalar inversion fails to represent reality in this case suggesting, most likely, that the scalar assumption is violated: a common occurrence in mineral exploration in our experience. In contrast the MVI model is consistent with the drilling results, and furthermore, indicates a steeply dipping volume on the Eastern flank. The strong near surface anomaly to the west of the dipping zone is known banded ironstone.

Conclusions

We have argued that remanent magnetization, demagnetization, and anisotropy must be included in magnetic field data inversion in order to avoid seriously misleading interpretations. These affects all cause the magnetization direction to deviate from the inducing field direction: a problematic assumption made in conventional susceptibility inversion. To support this argument we demonstrated the value of Magnetization Vector Inversion using model studies, and field data from the Osborne property. Successful application to numerous minerals exploration surveys confirms that incorporating remanent magnetization is recommended for the correct interpretation of the majority of magnetic field data.

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Over the past 5-10 years and in parallel with the advent of faster and more powerful computers and 3D inversion algorithms, 3D inversion of geophysical data has recently become the ultimate modelling and interpretation target tool for many exploration mining companies. The same applies to semi-automatic interpretation routines: we have many new tools that provide the user with various different views or different aspects of the data. Thus, while we are able to generate many different views of the data, not enough time is spent thinking on which information is of interest to the exploration program. Do we just drill on the “big purple anomaly”? Or should we rather stop and think about the mineralization-rich alteration zone that has destroyed magnetite and therefore is situated next to the big mag anomaly? What is the nature of the exploration target being sought, and which aspect of that target is amenable to geophysical detection and modeling?

Based on the scale of the problem and the availability of a-priori geological information, 3D inversion might not be the more efficient way to model the data. Instead, the combined use of simple tools like 3-point solutions of topographic data combined with edge detection routines from geophysical data (SED, CET) can provide with a wealth of strike and dip information that can be used in the construction of a preliminary geological model. Similarly, simple single-anomaly inversion algorithms can provide with first order estimates of depth to top and dip of the magnetic/gravimetric sources. This preliminary geological model can further be incorporated as first-order information into the input mesh for a 3D constrained inversion scenario.

“Old” tools like 2D/2.5D modelling of profile-based data and the inversion of single-anomalies using simple geometries are not so interesting anymore and they are often disregarded as unexciting, or dull when compared to 3D cubes of data. Yet 2D tools impose parameters that have more geological meaning; for example a dipping slab must have parallel sides just like a lithological unit. For more regional problems, 2D-2.5D sections have the advantage of being easier to handle and giving the user full control of the modelled geology. This contribution presents two case studies: a) integrated 2D-3D geological modelling in the Bathurst Mining Camp, NB; and b) an hematite-rich iron exploration project in NWT where the target was not the major magnetic anomaly, but the unit underneath the magnetite-rich sedimentary sequence above the non-magnetic iron formation. This example, which did not target the major magnetic anomaly directly, emphasizes the importance of building a complete geological model from geophysical data.
Better geological rock properties lead to better mineral exploration - a case study from the Mt Isa Inlier

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SUMMARY
A large scale three-dimensional (3D) geology model using all current observations has been created as part of an effort to improve the geological understanding of the Mt Isa Inlier. The new geological model constructed from geological datasets is being tested using the regional geophysics as independent validation. Decisions must be made about selecting appropriate density and susceptibility rock properties before the model can be subjected to potential field geophysical processing. The initial rock property values are derived from boreholes, rock outcrops and prior studies. The southern part of this region has previously defied most attempts at explaining the geology as interpreted from the geophysics. To address this problem, a deterministic method to find the optimum rock properties that correlate to the geology and explain most of the first order features in the gravity and magnetics has been developed. It involves the Levenberg-Marquardt approach: a bounded, non-linear least-squares solver that allows optimisation of the rock property values. To test the geology model further, a Monte Carlo Markov Chain joint inversion of Mag/Gravity at high resolution on a super computer was then performed.

INTRODUCTION
All geological models require validation to ensure that hypotheses are supported by available data. This study aims to test whether the hypothetical 3D geological architecture can be validated against potential field geophysical datasets. A typical method to validate geology models is to subject a voxel representation of the geology to geophysical forward modelling and inversion. An inversion of the Mt Isa Inlier block could assist in the resolution of different geological elements to increase understanding of the study area. The ultimate aim of this study is to subject a high-resolution (570 x 650 x 195 voxels) 3D geological voxel model, constructed by the Geological Survey of Queensland (GSQ), to inversion. The high spatial resolution of this model requires the use of a multi-threaded calculations of the inversion on a supercomputer (‘Savannah’) located at the University of Queensland (UQ), St Lucia campus.

The first objective is to determine whether the voxel model, fields and initial rock property values were consistent and reasonable. This process was performed on low resolution voxels (57 x 65 x 195 voxels) on a high-end computer. Upon discovering large misfits between the calculated and measured field, a rock property optimisation and literature workflow was adopted. This produced a suite of geologically reconcilable rock properties that produced lower misfits for both the magnetic and gravity responses, providing a better input data set for the full resolution model inversion with the aim of reducing the amount of supercomputing time required.

METHODOLOGY

Initial modelling and observations
The first objective was to validate the calculation and test the misfit between the geological model and the geophysical grids. The first set of modelling was performed using the GeoModeller forward modelling process on both the magnetic and gravity grids. The aim was to achieve best fitting results with a geophysical (and geophysical) justification without adjusting the initial geological geometry. The geometry of the model was set up with the best geological knowledge of the GSQ. The magnetic forward models showed high degrees of misfit, both in comparing the measured and dynamic ranges of the histograms. Figure 1 shows the initial misfit of the magnetic field, where the magnetic response is worse in the southern region than the northern region. The misfit of the initial gravity forward model is also substantial and perhaps worse in the northern than the southern regions (Figure 2). That indicates the impossibility of a homogeneous density/susceptibility distribution in each layer. Furthermore both results were not suitable for an inversion because of the large misfit of the initial models, as seen in Figures 1 and 2.

Correlation to geology
Several different sets of susceptibility values were applied to the magnetic forward modelling and inversion processes. The obtained results were generally unsatisfactory with respect to histogram dynamic range or grid response comparison. In all cases the calculated response was lower than and could not account for the measured response.

The literature suggests that an occurrence of a highly magnetic geological formation known as the Eastern Creek Volcanics (Wilson, 1985; Betts, 1997; Betts et al., 1999; Meixner, 2009) (susceptibility values between 5000x10^-5 and 10000x10^-5) may explain the relatively high response of the calculated field. The susceptibility also exhibits a bi-modal distribution (Betts, 1997), possibly caused by isochemical alteration (Wilson, 1985), which was accommodated in the magnetic inversion processing.

Rock property optimisation
An optimisation process was applied to susceptibility and density rock properties to aid appropriate assignment of values and to lessen the misfit between the calculated and measured geophysical responses. The optimisation problem was solved using a non-linear least-squares Levenberg-Marquardt...
approach (Coleman and Li, 1985) which allows the definition of lower and upper bounds to the values that act as geological constraints. The density values were entirely optimised using bounds obtained from the literature to ensure that the results were geologically acceptable for the Mt Isa Inlier. Acknowledgement has been made of the hypothesis that the Eastern Creek Volcanics (ECV) is a thin layer and therefore likely to have less influence on the bulk geology density values than it did with susceptibility values. All optimised results have been cross-checked with the literature as a second pass to ensure geological acceptability. The rock property values determined from this process are shown in Table 1.

If the same directory structure and filename conventions are kept consistent between PC-based and supercomputing modelling environments, directory paths and input data (voxet and geophysical grids) need not be changed when moving from low-resolution modelling to full resolution environments. Generation of new projects can be conducted in the PC environment in the same way that any other GeoModeller project is created. Rock properties and inversion parameters can be set in the familiar GeoModeller GUI, without the need to become an expert within the supercomputing environment. The project can be saved into the PC environment and transferred to the supercomputer as a single entity. The need to copy individual files and creating a different, supercomputer-specific directory structure is therefore unnecessary. Workflow efficiency is improved by reducing the need to parameterisation procedures and avoiding easy mis-translation of model inputs. This is further streamlined by clever API to package up information about the ‘cloud’.

HIGH RESOLUTION STOCHASTIC INVERSION

The Monte Carlo Markov Chain (MCMC) approach needs a ‘close’ starting geology model to show you things you did not know about your project (Guillen, 2008). The full resolution inversion with XY resolution of 250m requires 7 days of computing, using 64 nodes, each node comprising 8 processors and 24 gigabytes of memory on the UQ supercomputer. Initial calculations predicted that the inversion would require 60 million iterations to minimise misfits and explore probability space. This number has now been reduced to 10 million iterations since adopting a rock property optimisation workflow. Following this about 360 million iterations are required to obtain the 7 days elapsed exploration of stochastic space. This is to ensure that every voxel of the full resolution voxel (590 x 650 x 195, or just under 75 million voxels) had to be visited at least five times. The inversion perturbs the properties and the geometry.

Fixing Cells

A cell in your model might have fixed lithologies as you are very confident of the geology at that point. Typical reasons and ways to control this are -

- Good surface geology map – hold this constant
- Borehole logged geology observation at depth
- Seismic pick on a section – an interpreted point

Of course, the fact that a cell has a fixed geology does not preclude its properties from changing, within the constraints of its property law.

Model Change Scenarios

Case MCMC

For MCMC, the natural case is to allow for a 50/50 split between changing the model at the lithology boundaries, and changing the properties within a unit at any one iteration.

Case Property Only

When you feel very confident about your geology model and you already may have bulk physical properties that do a good job of reproducing the observed geophysical response from that model, more subtle features may emerge in pockets, if you allow a 100% property change only run. The reason for this is that a non-deterministic exploration of probability space will show you the probability of coherent property anomalies at depth, within various units. You may also restrict which units to explore this way, by setting the Standard Deviation to zero for those units you want to exclude from the study.

Case Geology Only

The other extreme is similar to the algorithms used in more traditional gravity inversions for “depth to basement”. You hold all the properties constant and force boundary changes as the only way to reduce the misfit in the study.

RESULTS

Part A

The results for the magnetic and gravity property determination used a combination of the bi-modal susceptibility distribution and optimised susceptibility values. The improvement of the response misfit and dynamic range comparison can be seen for both magnetic and gravity field inversion in Figures 3 and 4. A number of scenarios have been tested and the best have been obtained using the parameters listed in Table 1 for geophysical inversion. It appears that a bi-modal susceptibility distribution is required to explain the ECV and to obtain a better fit between the calculated and measured fields. This may indicate a missing geology unit in the sequence.

Part B

The results obtained from stochastic inversion also highlights the importance of (1) using appropriate rock properties and (2) voxel size. The magnetic modelling provides clear examples illustrating this point. The initial forward modelling did not provide a low misfit between the calculated and observed grids. The cause was identified to be input susceptibility values originally assigned to the geological model. Low-resolution inversion provided further improvement. The same degree of improvement has not been observed in the full resolution magnetic modelling process. The only difference between these two processes is the resolution of the input voxel but low resolution provides faster convergence. The low-resolution voxel inversion has less voxels. Each iteration of the inversion iteration changes the rock property value of one voxel. If the change results in improved misfit, the change is accepted. The number of visits per 100 million iterations for the low-resolution voxel is less by a factor of ten, resulting in faster convergence of the misfit. Our recommendation is to use lower resolution voxels to produce even closer initial starting models, before doing higher
resolution work. Changes in geometry can improve misfit and allow significant increase in convergence rates (Figure 5). Allowing geometrical changes can produce different geological architecture that better represents the geophysics and provide insights into where model adjustments can be made to improve the representation of geology. Due care must be taken when using geometrical inversion, as the available geology rules for change are one step away from the original observations and pile constraints. Tests and rejection criteria are implemented using the Commonality Volume, Volume Ratio, Commonality and Shape Ratio tests. Stratigraphic relationships can be kept static using the vertical relationship function, ensuring the younger units always overlay older units. The vertical relationship function is therefore more appropriate for use in basin terranes rather than polydeformed, cratonic terranes where overturned geology is common.

CONCLUSIONS

The optimisation process described here presents an efficient workflow to present a geologically constrained suite of input data for fine-resolution geophysical inversions requiring supercomputing. It is important that the initial rock properties of the inversion are close to a geologically feasible solution. This process avoids the situation where initial inversion stages operate inefficiently and can lead toward shorter computation times and improved results. The project has evolved from a technical exercise in executing geophysical processes on a supercomputer into an effective modelling workflow. It is adaptable for use in many geological terranes and geoscientific applications. The number of deliverables that this workflow generates exemplifies this effectiveness. Not only is large-scale, high-resolution inversion now possible but the rock property optimisation procedure also supplies the operator with a dataset that may be used for other geological applications such as data validation, survey calibration and geophysical interpretation procedures. The process is scalable according to requirements as it can be executed on relatively low-powered personal computers such as laptops, to mid-level high-performance desktops and servers, to specialised platforms such as the UQ Savanna supercomputer and also the cloud.

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Figure 1: Comparison of calculated (left) and measured response of magnetic forward modelling using pre-optimised susceptibility values. The dynamic range histograms are shown underneath the corresponding image. Note the lack of similarity between each image and histogram range.

Figure 2: Comparison of calculated (left) and measured response of gravity forward modelling using pre-optimised density values. The dynamic range histograms are shown underneath the corresponding image. Note the lack of similarity between each image and histogram range.
Table 1: Rock properties applied to inversion processes shown in Figures 3 and 4. The 'Unit' column defines the stratigraphic column. The Eastern Creek Volcanics (ECV) are the equivalent of the Base Leichhardt Layer. Note the Yeldham and Webbera granites are both intrusives and their position within the column is not indicative.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Optimised Magnetics (Log-normal distributions)</th>
<th>Optimised Density (Normal distribution)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yeldham Granite</td>
<td>0.01</td>
<td>2.65</td>
</tr>
<tr>
<td>Webbera Granite</td>
<td>0.00001</td>
<td>2.553</td>
</tr>
<tr>
<td>Cambrian</td>
<td>0.00019</td>
<td>2.5</td>
</tr>
<tr>
<td>South Nicholson Group</td>
<td>0.0019</td>
<td>2.65</td>
</tr>
<tr>
<td>Base Termite</td>
<td>0.004</td>
<td>2.65</td>
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<tr>
<td>Base Riversleigh</td>
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<td>2.8118</td>
</tr>
<tr>
<td>Base Isa Superbasin</td>
<td>0.005</td>
<td>2.6935</td>
</tr>
<tr>
<td>Calvert Superbasin</td>
<td>0.0002</td>
<td>2.5971</td>
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<tr>
<td>Base Leichhardt Superbasin (equiv.ECV)</td>
<td>Bimodal (66% 0.05 and 34% 0.08)</td>
<td>2.6647</td>
</tr>
<tr>
<td>Basement</td>
<td>0.00001</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Figure 3: Comparison of calculated (left) and measured response of magnetic inversion modelling using the susceptibility values shown in Table 1. The dynamic range histograms are shown underneath the corresponding image. Note the improvement of response similarity and histogram range from Figure 1.
Figure 4: Comparison of calculated (left) and measured response of gravity inversion modelling using the density values shown in Table 1. The dynamic range histograms are shown underneath the corresponding image. Note the improvement between each image and histogram range.

Figure 5. Comparison of misfit curves obtained from low-resolution magnetic inversion. Each curve represents an inversion that allowed geometry to vary according to different thresholds. The lowest rate of convergence is seen in the ‘100 percent’ curve, meaning that there is a 100 percent chance that the attribute change will be property only. The study area was the Lawn Hill platform.
The needs of deep, undercover, and brownfields mineral exploration continue to demand ever-greater interpretational value from expensively-acquired data. The past five years has seen systematic progress in our ability to quantitatively interpret and integrate geoscience data for 3D exploration targeting at regional, prospect, and mine scales. Interpretational advances have occurred individually in each of the sub-disciplines of geology, geophysics, and geochemistry. Our ability to integrate these interpretations into practical targeting models, approximately consistent with both geological reasoning and data, has similarly advanced and delivered success at the drillbit.

The past 5 years has seen the truly mainstream adoption of 3D geophysical inversion, particularly for potential field and DC/IP data. There is now a wide variety of inversion technologies, service companies, and in-house practitioners broadly available across the exploration industry. Although most inversion work is still geologically unconstrained, there is a growing demand for the adding value by integrating geological data and insight directly into the geophysical inversion process. Constrained structural geometry inversion is now reasonably common for potential field data, is becoming available in 1D for airborne EM data, and is expected to be available in 3D within the next few years. Large scale, 3D constrained inversions of EM data (for MT, ZTEM, and controlled-source ground EM) are similarly becoming reasonably commonplace.

3D geological modelling has advanced significantly in the past 5 years with progress in rapid, implicit modelling methods from several technology providers. New developments such as 3D structural field interpolation are having an impact on both rapid structural modelling and the direct computation of structural constraints as controls on 3D geophysical inversions. Capturing both 3D structural boundaries and structural vector fields as inversion constraints is currently the strongest quantitative link integrating geological and geophysical data. The weak link remains physical property understanding, particularly hampering the development of joint or cooperative inversion strategies. However, recent work in petrophysical analysis has indicated some promising directions for characterizing rock property data directly in terms of alteration, typically the primary physical property control in ore-hosting environments.

Geochemistry interpretation has also seen notable advances in the past 5 years through technology development. Software systems directly integrating 3D lithgeochemistry data with 3D geological models in a spatial query environment are now available. These provide a basis for direct targeting, and further lay the foundation for quantitative understanding of alteration-physical property relationships, thus completing the circle back to geophysical interpretation.

Finally, 3D targeting processes and formulations have advanced significantly, building a significant track record. Quantification of multi-disciplinary exploration criteria, capturing of the criteria in a modelling process, and statistically combining them into drillable targets is still an area requiring significant R&D, but the progress made in the past 5 years is substantial and encouraging.

This review and survey of recent advances and future directions in 3D multi-disciplinary interpretation will feature specific technology and case study examples throughout.
Refining 3D Earth models through constrained joint inversion on flexible unstructured meshes

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Summary

We are using unstructured tetrahedral meshes to create 3D geophysical Earth models. We have developed forward modelling methods for gravity, magnetics, first-arrival seismic travel-times, DC and EM surveys on unstructured grids. We have built an inversion package that can invert on unstructured grids or standard rectilinear grids in 2D or 3D, and the inversion code can jointly invert multiple types of data simultaneously using various coupling approaches. We have also created a suite of utility tools to help us work with unstructured representations of the Earth, including a graphical user interface for building 3D wireframe models. In this manuscript we present our utility tools and modelling methods and apply them to examples from the Voisey's Bay massive sulfide deposit in Labrador.

Geological and geophysical models

3D geological ore deposit models are commonly created during delineation drilling. Geological structures may be known at points from down-hole intersections and outcrop mapping. The contacts can be interpolated between boreholes and extrapolated outwards to produce a 3D geological model. Contacts may also be interpreted from seismic sections. Rudimentary 3D geological models are important for visualization purposes during exploration and delineation stages. More sophisticated models can be used to calculate volumes of ore reserves and other information ultimately important for mine planning. The accuracy of these models is crucial when used to determine if a deposit is economic.

These 3D Earth models typically comprise wireframe surfaces that represent the geological contacts between different rock units. Wireframe surfaces (tessellated surfaces comprising connecting triangles) are appropriate for representing geological contacts as they are sufficiently general and flexible that they can be made to represent arbitrarily complicated geological structures and topography.

In contrast, most current 3D geophysical modelling is performed on rectilinear grids because they simplify the development of numerical methods. Algorithms can be made more computationally efficient by exploiting the underlying mesh structure. However, it can be impossible to adequately model complicated geology using rectilinear meshes, which produce pixellated representations of the Earth no matter how fine the discretization. Such a mesh is always incompatible with geological models comprising wireframe surfaces.

To address this incompatibility, we are using unstructured tetrahedral meshes to specify 3D geophysical Earth models. Unstructured meshes can be used to discretize the volumes between general wireframe surfaces while honouring exactly those surfaces within the volumetric discretization. It is therefore possible to have geological and geophysical models that are, in essence, the same Earth model.

The Voisey’s Bay deposit

The Voisey’s Bay nickel-copper-cobalt deposit, located on the north-east coast of Labrador, is considered to be one of the most significant mineral discoveries made in Canada in the past few decades. The main ore body, which is currently being mined, is the "ovoid". It is a massive sulfide lens roughly ellipsoidal in shape. An extensive drilling campaign, including over 500 boreholes, has provided an extensive collection of core samples. Detailed geological models have been built from this information.

Figure 1 shows parts of the geological model from the Voisey’s Bay site, including three tessellated wireframe surfaces. The topography surface was generated from point data using a 2D meshing program to generate a triangular mesh to connect the points. The two geological contact surfaces were constructed by first joining together the relevant down-hole contacts on vertical cross sections to give a sequence of horizontally stacked 2D outlines of the respective geological unit. Those outlines were then joined together between sections to create the wireframe contact surfaces.

Discretizing the Earth on rectilinear and unstructured meshes

As we have mentioned, it can be difficult to represent complicated geology on rectilinear grids. Some intermediary process is always required to convert from a geophysical model to a geological one, or the reverse. As an example, take the geology and discretization in Figure 1. A rectilinear mesh has been chosen and its cells segregated according to the known contacts between the main rock units. The rectilinear mesh has 87 × 61 × 54 = 286,578 cells, a reasonably fine discretization, but “stair-casing” of the contacts and topography is still evident. Finer discretization is possible, but computation times and memory requirements quickly become inconvenient or unfeasible.
Refining Earth models through inversion on unstructured meshes

The power of unstructured meshes is that they provide the ability to intelligently mesh the subsurface for modelling purposes. They can capture fine-scale structure without greatly increasing memory requirements by placing smaller cells where required and larger cells elsewhere. The generation of quality unstructured meshes is a topic of ongoing research in the computer science community. Interested readers can find more information in Owen (1998). We do not intend to make any form of endorsement for a particular package but we currently make use of TetGen (Si, 2008) to generate 3D tetrahedral meshes.

TetGen generates tetrahedral meshes from piecewise polygonal complexes (PPCs). A PPC comprises interconnected planar polygonal facets. In an exploration context, a PPC would contain the boundary of the modelling volume, the topography surface, any subsurface geological contacts that are known a priori, and any further facets required to separate the modelling volume into different regions. The meshing algorithm discretizes the volume between the tessellated surfaces while maintaining those surfaces exactly. As such, geological and geophysical models can share the same modelling mesh; they can be the same model, with no intermediary process required to convert from one to the other.

For TetGen and many other meshing packages there are many possible options that allow the user to control the characteristics of the final mesh. This makes for a suite of flexible options for generating volumetric tetrahedral meshes from the wireframe surfaces in a geological model.

Working with wireframe models

The amount of drilling necessary to define an ore body before the advanced exploration or development stage is often substantial. The drilling can provide a large amount of point-based data on the location of geological contacts. In such a situation, as is the case for the Voisey's Bay site, algorithms for automated wireframe surface construction from point clouds (e.g., Amenta at al., 2001) can be used to generate surfaces. Automatic surface construction methods are designed for relatively dense point sampling compared to what is likely available from drilling. Hence, the surfaces constructed may require further hand-guided improvements.

Earlier in the exploration and delineation stages there may not be enough drilling data to obtain a sensible surface from an automated surface construction approach. Even if enough data points exist, complicated scenarios involving multiple surfaces (e.g., the case where one unit cross-cuts the contact between two others) may confuse matters and lead to problematic surface constructions. Although some software packages provide methods for generating surfaces

Figure 1: Discretization of the Voisey's Bay ovoid ore body and surrounding rock units. At top, the ovoid ore body (red), troctolite (yellow) and topography surface (grey) are represented by transparent wireframe surfaces comprising tessellated triangles. At middle, the boundary of a rectilinear mesh is indicated in black and we have included the mesh cells that are inside the ovoid (red) and troctolite (yellow). At bottom we have added the surrounding gneiss (green), removed the wireframe surfaces and added black edges to the rectilinear cells to delineate them more clearly.
Refining Earth models through inversion on unstructured meshes

from sparse point data, it is often the case that the resulting geologic models cannot be used directly by a volumetric meshing algorithm. The only alternative is then to be able to create or manipulate the wireframe surfaces by hand.

Regardless of the approach taken to generate an unstructured mesh Earth model, at some point we need to be able to create and manipulate wireframe surfaces and volumetric unstructured mesh models. Creating a PPC to define a simple model, such as a block in a half space, is a simple process. However, if a more complicated, geologically realistic model is being considered then the situation becomes more difficult. In more complicated cases, stitching of triangular facets between vertical cross sections may be necessary. This task can be long and frustrating if 3D visualization capabilities are not available. To this end, we have developed a graphical user interface for creating and editing PPCs which we call FacetModeller. A screen-capture of the program is in Figure 2. The platform consists of both a 2D working window (left in Figure 2) and a 3D viewer window (right in Figure 2). The 2D working window allows for the creation and editing of nodes and facets on georeferenced cross sections. The 3D viewer window allows the user to see all or part of the model being manipulated.

Forward modelling and inversion on unstructured meshes

Although unstructured meshes provide utilitarian advantages over structured rectilinear meshes, there are some significant challenges involved in using unstructured meshes for the purposes of geophysical forward and inverse modelling. As we have mentioned, we no longer can benefit from the same numerical advantages presented by rectilinear meshes. Despite these challenges, we have developed methods for forward modelling gravity (Jahandari and Farquharson, 2011), magnetic, seismic (Lelièvre et al., 2011a, 2011b), DC/IP, and EM data (Ansari and Farquharson, 2011) on unstructured tetrahedral meshes. Here we show an example of modelling first-arrival seismic travel-times. The wave-fronts are marched outwards from the source using the Fast Marching Method. Figure 3 shows a solution for the Voisey’s Bay ovoid model.

In Figure 4 we show the results of inverting synthetic gravity data and first-arrival seismic travel-times for the Voisey’s Bay ovoid scenario. Only the ovoid is included in this model. Our joint inversion methods (Lelièvre et al., 2012) allow us to couple the two physical property models (in this case, density and seismic slowness) in various ways. The choice of which coupling approach to take is guided by the geological and petrophysical information available.
Refining Earth models through inversion on unstructured meshes

Figure 4: A joint inversion example from Voisey's bay. The outline of the inversion mesh is indicated in black. The mesh and local coordinate system are different from those used in previous figures (the ovoid has been rotated slightly to align its long axis east-west). The ovoid surface is transparent red. In (a) and (b) the topography surface is transparent grey. In (a) the ground-based gravity data are coloured by their data values as indicated on the colour-bar. In (b) the ground-based seismic sources are green and the down-hole receivers are blue. In (c) and (d) we show inversion results with vertical slices through the recovered density models, green density isosurfaces at 0.5 g/cc for those models, and the ovoid surface. The density colour-scale range for the slices is set to that for the true model. The isosurfaces and ovoid have been clipped in (c) and (d) to allow better viewing of the slices. For the inversion in (c) the density and slowness models are linked through a linear relationship. In (d) they are linked using clustering methods. Hence, the slowness models are practically identical to the density models shown.

Conclusion

Geophysical inversion provides the means to unite geophysical survey data with the geological information contained in ore deposit models. Incorporation of geological information into inversions is always an iterative process. One begins with the geologists' best guess about the Earth (i.e., the geological model) and the models recovered from geophysical inversion may indicate that the geological model should be changed slightly prior to the next iteration of the procedure. In this way, geological and geophysical data can be combined through inversion and we can move towards the creation of a common Earth model consistent with all data available.

Unstructured tetrahedral meshes can honour geological contacts, can represent fine-scale structure, and yet are efficient discretizations of the modelling domain when compared to the less flexible yet commonly used rectilinear mesh alternative. Hence, working on unstructured meshes provides advantages when one wishes to incorporate prior information associated with structurally complicated subsurface geometries, which may be difficult or impossible to represent adequately on rectilinear meshes. We are developing computational methods and utility tools to allow us to seamlessly work with geological and geophysical data within the framework of common Earth models built on flexible unstructured meshes.

Acknowledgements

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Refining Earth models through inversion on unstructured meshes

References


The Z-axis Tipper Electromagnetic (ZTEM) airborne AFMAG EM system has established itself as a valuable exploration tool with the ability to map geology to a greater depth and detect lower conductivity anomalies than active-source airborne EM systems. It is sensitive to channelling of natural magnetotelluric (MT) currents in the subsurface (Vozoff, 1972). ZTEM measures both the along-line (X) and cross-line (Y) polarizations of the MT tipper at frequencies from 30 Hz to 720 Hz. With each polarization having both real and quadrature components, a typical 6 frequency ZTEM survey will generate 24 channels of data. An interpretation that considers all of the ZTEM data acquired in a survey is not straightforward. The problem is naturally suited to inversion using the UBC-GIF MT3Dinv code. The 3D conductivity model produced by inversion of ZTEM data is useful for focussing exploration into an area of interest within the larger survey area.

In June 2011, a ZTEM survey, commissioned by New Nadina Explorations Ltd, was flown over the Silver Queen project area, British Columbia. Mira Geoscience inverted the ZTEM data. An integrated interpretation of the ZTEM, magnetic and ground based Titan24 data was done. Subsequent drill testing of the identified targets intersected a previously unknown buried molybdenum porphyry deposit. The airborne survey, ground geophysics, geophysical data inversion, and drilling were completed in one field season.

The ZTEM data and magnetic data acquired at the Silver Queen Project were inverted to produce a 3D conductivity model and 3D magnetic susceptibility model. These were visualized in Gocad along with the known vein-type mineralization and previous drilling. Using these results traverse lines for a Titan24 electrical survey were selected over a favourable area. This targeted a structurally favourable yet undrilled location proximal to the known mineralization. The Titan24 survey work was followed by drilling.

The approach used to process, analyze and invert the ZTEM data is presented below. This includes general considerations as well as practical considerations from our own inversion processes. We use the Silver Queen case study to illustrate how a focussed exploration program that integrates geology and geophysics can assist in the discovery of new prospects.

**INTRODUCTION**

The Silver Queen polymetallic vein system is a high grade past producer south of Houston, British Columbia. There are abundant small veins and showings around the old underground mine, but the source of the mineralizing fluids was not known. Current exploration around the old Silver Queen mine by New Nadina Explorations Ltd has been driven by a conceptual model, targeting a blind, buried bulk tonnage deposit near the old mine and deeper in the mineralized system.

In the 2011 field season, New Nadina Explorations Ltd completed an airborne ZTEM and magnetic survey, inversion of this data, a Titan24 ground geophysical program, inversion of this data and a drilling program to discover a new zone of porphyry-style mineralization. The Advanced Geophysical Interpretation Centre (AGIC) of Mira Geoscience provided data analysis, 3D inversion, modeling, visualization, and interpretation services.

ZTEM data require careful inspection prior to use in an inversion. ZTEM data along flight lines can be interpolated onto regular grids to visualize the data and to identify regions of poor data. Care needs to be taken to avoid spatial aliasing. Bad data needs to flagged or removed prior to inversion. Particular attention is paid to ensure consistent coordinate systems are being used. An appropriate error is assigned for each component of the data at this stage.

The inversion modelling process uses the UBC-GIF MT3Dinv code. This code derives from the UBC-GIF EH3Dinv code modified to consider the plane wave source field assumption for MT data. The inversion process is iterative and begins with one or more single frequency inversions that are used to assess the quality of the data and appropriateness of the errors assigned. The resultant conductivity models from the single frequency inversions provide a starting model for the multifrequency inversion(s) which are done using all frequencies or a user defined subset thereof. Although the exact approach taken needs to be flexible and is often adapted to best suit a particular project, the generalized workflow, shown in Figure 1, represents the major steps in the process.
Particular attention must be paid to the datums and coordinate systems of the project data. Inconsistencies can cause considerable trouble if not addressed at the earliest stages of the project work. ZTEM survey data are usually supplied in WGS84 UTM, with latitude and longitude as well as X, Y and Z for the ZTEM receiver coil. Data has been encountered that has latitude, longitude and elevation referenced to the WGS84 ellipsoid while X and Y are referenced to some other datum (e.g., NAD27). Other such permutations may exist and the user is advised to exercise considerable caution.

Elevation data are a potential source of confusion. The elevation of the ZTEM receiver coil is usually referenced to the WGS84 ellipsoid, while the topographic elevations are usually referenced to the geoid (i.e., meters above mean sea level). Ellipsoid heights above the geoid vary considerably around the world; in some areas the height of the ellipsoid from the geoid can be in excess of 100 m. If the receiver coil and the topography are mistakenly assumed to be measured from the same reference surface, spatial inaccuracies will propagate into the inversions and resultant models will be suspect. When building a digital elevation model using the altitude of the coil (or aircraft) from the GPS record and corresponding laser/radar altimetry, it is vital that the reference surface of the coil be checked, and if necessary, adjusted such that coil elevations are referenced to the geoid and not the ellipsoid.

In some cases when ZTEM surveys are flown over rough terrain the radar altimetry and thus the survey topographic model may be unreliable as a result of radar dropouts and positional artifacts. In such cases interpolated public digital elevation data or third party data may be the best available to define the inversion topography. This data is usually referenced to the geoid.

Having defined an acceptable topographic surface, problems can occur representing this surface within the inversion mesh. In steep terrain the use of large blocks to approximate the surface can result in a suboptimal topographic model. Figure 2 and Figure 3 show that the actual ground surface elevation and the top of the earth model used by the inversion algorithm can differ significantly. AGIC has developed a number of techniques to minimize such differences.

Figure 1: Generalized ZTEM inversion process workflow. Note that this is an iterative process and that several runs of both single frequency and multi-frequency inversions may required to achieve satisfactory results.
As part of a detailed QA/QC process, the ZTEM data at all frequencies and both polarizations are carefully reviewed. One approach is to grid the data and then to inspect each ZTEM data channel along with the power-line monitor (PLM) map in order to identify data that are geologically unreasonable. Most commonly, these are high amplitude short spotty anomalies or anomalies that are correlated with the anomalous PLM values and that break up the trends of the ZTEM data map. When bad data are identified, they are flagged as such or deleted at the users' discretion. Although somewhat qualitative, this approach has produced the best results to date.

Bad data can also be identified later in the workflow if the inversion routine is unable to achieve a good fit. This requires an understanding of tilt-angle anomalies in ZTEM data and how they are generated by geological features at the frequencies used by the ZTEM system. It is helpful to understand the historical interpretation of tilt-angle anomalies measured with VLF EM receivers such as an EM 16. Those interested in inverting ZTEM data are recommended to the well-established literature describing VLF EM theory and interpretation (e.g., Wright, 1988; McNeil and Labson, 1992). Tilt-angle EM anomalies are typically of the form shown in Figure 4. Sample ZTEM survey data, both prior to and after removal of bad data is shown in Figure 5.

Figure 5: Sample plots illustrating the method used to identity and remove bad ZTEM data. Bad data is removed by visual inspection of gridded data fields, in this case the X polarization 45 Hz in-phase and the X polarization 720Hz in-phase data. Generally, noisy data are associated with elevated power line response or other cultural feature. It is difficult to remove bad data automatically using an algorithm. Note the region of bad data at 720Hz is considerably larger than the region of 45Hz bad data. Deletion of bad data needs to be done separately for all four parameters of each frequency for best results.

**Silver Queen Case Study**

The Silver Queen project area of New Nadina Exploration Ltd has recorded production of copper, lead, zinc and gold from a past producing underground mine. Considerable drilling, including some deep holes, has been done around the old mine. Although the potential for buried porphyry-style mineralization was recognized, before 2011 no porphyry-style mineralization had been found.

Both ZTEM and magnetic data were inverted and visualized in 3D. These results located the limits of an intrusive stock below the Silver Queen mine and a large regional structure close to the old mine was mapped (Figure 6 and Figure 7). The interpretation of these results identified a favourable structural setting for porphyry style mineralization and helped locate a Titan24 ground based IP and MT electrical survey to identify drill targets.

The favourable area for detailed ground based geophysics was identified based on criteria shown in Table 1. These criteria served to focus attention on the area subsequently covered by a ground-based Titan24 electrical survey. This Titan24 induced polarization (IP) and resistivity data was inverted and drill targets identified. Thirteen holes were drilled. The first drillhole encountered quartz vein stockwork alteration with copper and molybdenum mineralization (Figure 8). Hole 11-S 13 ended in good porphyry style molybdenum mineralization at 777 m. The ZTEM, Titan24 work and drilling were completed in one northern Canadian field season.
3D ZTEM inversion, interpretation and integrated exploration at the Silver Queen project, British Columbia

Table 1: Criteria used to identify an area for detailed ground based follow-up using the ZTEM and Magnetic survey inversion results.

<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 in the boundary of intrusive body</td>
<td>Intrusive boundaries were interpreted using ZTEM inversion conductivity isosurfaces and MAG3DINV 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 higher conductivity associated in ZTEM inversion with linear features 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>

Figure 7: Magnetic susceptibility isosurfaces from the magnetic inversion model. The 0.002 SI isosurface (green) identifies a stock-like body interpreted as a magnetic phase of the intrusive below the Silver Queen vein system. The interpreted intrusive body is marked with a yellow arrow (1). The differing shapes of the inferred intrusives from the ZTEM inversion and the magnetic inversion suggest multiple phases; both magnetic and non-magnetic intrusive phases are present. The NE-SW structural trend corresponds to a magnetic low. In the SE corner of the project area, magnetic and conductive units exist (green in Figure 7 and brown in Figure 6); this is a region of basalts. The different magnetic and electrical character of this region can be recognized in the ZTEM and magnetic inverted models.

Figure 8: Core photographs showing molybdenum mineralization and stock-work veining.

CONCLUSIONS

ZTEM data from the New Nadina Ltd, Silver Queen project were successfully inverted in 3D using the UBC-GIF MT3Dinv code package. ZTEM and magnetic inversions yielded conductivity and magnetic susceptibility models. These were interpreted in a 3D model that included geology and past drilling to provide guidance situating a deeply penetrating Titan24 electrical survey. Subsequent drilling of the IP anomalies identified by the Titan24 survey data intersected a significant, previously unknown, porphyry style molybdenum deposit. The success of the drilling program can be attributed to the application of well-chosen geophysical methods, and to the integrated interpretation of geophysical and geological data. The use of ZTEM data as part of this process proved to be cost effective; the ZTEM results were used to focus follow-up ground exploration to a smaller area and shortened the time necessary to explore the project area.

ACKNOWLEDGEMENTS

The authors wish to thank New Nadina Explorations Ltd for granting permission to show select results from their Silver Queen project.


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Ten years of passive airborne EM system development for mineral exploration
Jean M. Legault and Paolo Berardelli - Geotech Ltd.

Summary
Geotech’s 10 year development in airborne passive EM technology originally started in 2000, with a receiver design that combined the earlier Hawk broadband frequency domain acquisition system, and the new VTEM 24-bit digital acquisition module, as well as advanced digital signal processing similar to those used in modern MT. This culminated in a lightweight digital AFMAG towed-bird receiver in 2001 whose sensor proved too small and prone to vibrational noise. Subsequent improvements led to a relatively successful prototype, in 2002, with improved damping and attitude sensors. But in spite of these advancements, the noise levels were unacceptably large until the addition of a base-station in 2004 whose ten-fold improvement in signal-to-noise and reduced receiver weight, spurred the development of the ZTEM system, in 2005, that became the first successful and commercially available AFMAG system of its kind in 30 years. Since then the AirMt system helped improved mobility in the base-station design, and has led to the Fixed-wing ZTEM system in late 2010-11.

Introduction
It has been over 10 years since Geotech first revisited airborne AFMAG (Audio Frequency Magnetics) in 2000, using digital technology and modern signal processing tools (Kuzmin et al., 2005), and more than five years since introducing the first passive airborne EM (AEM) survey results at AESC in Melbourne AU in 2006 (Lo et al., 2006). In the period since then, Geotech developed its ZTEM (Z-axis Tipper Electromagnetic) system in 2006 the first and only successful, commercially available passive airborne AFMAG EM system of its kind in mineral exploration in more than 30 years. Since then, Geotech has remained the lone industry leader in airborne AFMAG instrumentation, surveying, processing and interpretation, with significant advances being made to its systems for improved electrical imaging for regional reconnaissance resistivity mapping in mineral exploration - notably the inception of the AirMt (Airborne Magnetic Tensor) system in 2009 and, most recently, its Fixed Wing ZTEM system in 2011.

Passive AEM System Development
AFMAG (Ward, 1959; Labson et al., 1985) systems all measure the anomalous vertical secondary magnetic fields that are created by the interaction between electrical heterogeneities in the earth and naturally occurring, plane wave audio frequency EM fields that are from worldwide thunderstorm activity – the same as those used in audio-magnetotellurics (AMT), known for its great depth of penetration, up to several km (Strangway et al., 1973). Airborne AFMAG is therefore a unique airborne deep resistivity mapping tool capable of exceeding the depth penetration limits typically expected from traditional AEM.

The early airborne AFMAG development in 2000 by Geotech focused on a towed-bird, lightweight digital receiver (Figure 1), whose acquisition system was based on the earlier Hawk broadband fixed-wing-tip frequency-domain and new VTEM 24-bit time-domain digital acquisition systems (Kuzmin et al., 2005). By 2001, it had been determined that sensor size and vibrational motion noise were significant factors. Subsequent designs used a slightly larger, more sensitive multi-coil receiver (Figure 2a and 3a) with damping mechanisms and attitude sensors (Figure 2b), operating in the 20-6000Hz frequency band. A base-reference station (Figure 3b) was also included to record individual fields for remote-referencing and also to permit the use of single coil to measure the vertical Z-field on the aircraft (Lo and Kuzmin, 2004).

In addition to hardware development and field testing, this OMET sponsored project also included software development for advanced digital signal processing of time-series, similar to that used in ground magnetotelluric soundings (Anav et al., 1976;) and ground tippers, as proposed by Labson et al. (1985); as well as attitude corrections and noise rejection (Kuzmin et al., 2005).

Figure 1. Airborne AFMAG prototype, in early 2001, with nose-cone removed, showing Geotech system designer Petr Kuzmin (after Kuzmin et al., 2005).

The AFMAG system development culminated in relatively successful field trials in 2002 at the Reid Mahaffy test site (Witherly et al., 2004) and in 2002 and 2004 in the Sudbury area in northern Ontario, Canada, as well as fixed-wing tests, in 2002, that were described by Kuzmin et al. (2005),
Lo et al. (2005) and Lo et al., (2006). The studies revealed that the helicopter AFMAG system was workable and the data were repeatable and responded to known conductors. But the tipper data were also noisy and the system required improvements in suspension, better motion noise rejection and larger coils. Tests also showed that a fixed base-station could be used in place of horizontal coils on the receiver, offering a 10x improvement in signal to noise and reducing the weight of the system (Lo and Kuzmin, 2005; Lo et al., 2006). The lessons learned from the AFMAG system testing spawned the ZTEM (Z-axis tipper electromagnetic) helicopter system (Figures 4 and 6).

The ZTEM development, that started in 2005, led to field testing in 2006 (Thompson et al., 2007) and eventually it was fully commercial by 2007 (Lo and Zang, 2008). In ZTEM, only the vertical (Hz) component data are acquired at the receiver, with the horizontal fields (Hx, Hy) obtained at a fixed, stable base-station – the assumption being that the AFMAG primary fields are relatively homogeneous over the survey area and below the base station. The ZTEM receiver is a 7.4 diameter single-axis air-coil that is towed as a sling-load 90m below the aircraft and flown 50-100m nominally above the ground. Built of fibreglass and isolated from vibrational noise using a patented suspension system, the airborne coil is designed to fly horizontally. The attitude positioning of the receiver is enabled by 3 GPS on the receiver as well as GPS and radar on-board the helicopter, as shown in Figure 6). From the attitude information the horizontal field detected by the airborne receiver is removed (Lo and Zang, 2008).

In 2006, the ZTEM base station coils were initially identical to the airborne sensors (Figures 4 & 5a) but their size proved impractical and were replaced by smaller (3.2m) perpendicular coils in 2007 (Figure 5b). A 3-axis AirMt sensor coil (3.04m) has also been alternately used as a ZTEM base station since 2009 (Figure 8).
The ZTEM data are sampled at 2 kHz and the vertical component data (Hz) are then synchronously merged with the base station data to produce the appropriate real and imaginary tipper transfer functions using standard magnetotelluric digital signal processing. The in-line (Tzx) and cross-line (Tzy) tipper data are then output at 2.5Hz or approximately 10m interval sampling. Attitude corrections and filtering are performed in a post-acquisition processing step. Initially, 25 to 2800Hz bandwidth signals were analyzed (Lo and Kuzmin, 2008) but now 5-6 frequencies of data, in the 30-360Hz ± 720Hz or 25-300Hz ± 600Hz band, are derived, based on signal strength (Lo et al., 2009ab).

In 2009, the next generation AFMAG system, AirMt (Figure 7), was introduced (Kaminski et al., 2010; Kuzmin et al, 2010). In AirMt all three orthogonal components of primary and secondary magnetic field (Hx, Hy and Hz) are measured at the receiver (Figure 8), as opposed to a single vertical component measurement in ZTEM. The three measured components are further converted into an attitude-invariant tensor amplitude parameter “AP” that effectively eliminates the need for tilt-compensation and therefore significantly improves the signal to noise (and potential better depth of penetration) over a standard ZTEM tipper measurement. In-phase and quadrature transfer functions are derived at 4-5 frequencies in the 45-360Hz +/- 720Hz band (or alternatively 37-300Hz +/- 600Hz). AirMt is designed to be the next step in Geotech’s AFMAG technology for higher resolution mapping of even deeper geological formations, as well as shallower structures.
rently AirMt is still at an R&D and field testing stage (cf. Legault et al., 2012) and is not yet fully available for commercial use.

The Fixed-Wing (FW) ZTEM system (Legault and Fisk, 2012) is the newest airborne AFMAG development in 2011 and is intended for improved efficiency in more regional geologic mapping applications. Deployed from a Cessna Grand Caravan, the FW-ZTEM uses an identical data acquisition system as the helicopter version but obtains vertical (Hz) component data using a redesigned (3x4m) aircoil receiver, suspended below the fixed-wing aircraft, using a retractable cable, winch and cradle system (Figure 9). The vertical component data (Hz) are also ratioed to fixed horizontal field measurements (Hx-Hy) using smaller, more mobile base-station reference coils. In-phase and quadrature transfer functions are derived for the In-line and cross-line tipper at 5-6 frequencies in the 30-360Hz +/- 720Hz band (or alternatively 25-300Hz +/- 600Hz).

Currently aeromagnetic data are collected using a tail stinger sensor on the aircraft, but future plans are to place it in the EM receiver assembly. In addition to magnetics and ZTEM, the increased payload in the fixed-wing aircraft would permit adding other sensors, such as gravity/gradientometry and spectrometry, to the airframe, thereby allowing for the widest possible range of physical property measurements in reconnaissance geologic mapping surveys. Field surveys with the FW-ZTEM system are planned for 2012.
Conclusions

It has now been more than ten years since Geotech embarked on the development of airborne AFMAG technology, starting with a lightweight prototype in 2001, then a fully damped and attitude-corrected receiver as well as modern digital signal acquisition & processing in 2002, followed by successful field trials that proved the merits of a fixed base-station in 2004, that eventually led to the successful ZTEM concept in 2005, and which later became commercially viable in 2007. This steady progression in pioneering technology has subsequently led to the highly innovative AirMt system in 2009 and continues with the more recent development of the Fixed-wing ZTEM system in 2011 – all with the design goal of creating deeper penetrating airborne EM platforms for mineral exploration.

Acknowledgments

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Broadband Airborne Electromagnetics: An update

James Macnae

Summary

During my presentation on Airborne Electromagnetics at Exploration ’07, I outlined five important challenges for the next decade, specifically 1) conductive cover penetration 2) better 2D/3D target detection and interpretation 3) improved AEM system calibration and stability 4) noise reduction through referencing 5) system cost reductions. Items 2, 3 and 4 on the list have seen very significant progress, with 3D inversion becoming common, significant improvements to Helicopter AEM systems and the development of ZTEM. Items 1 and 5 have seen some developments, but significant challenges remain.

AEM system principles

An AEM system is used to measure ground conductivity through the remote detection of induced currents in conductive regions of the earth. It creates a primary signal (magnetic field) through passing a time-varying current through a transmitter (Figure 1). Changes in this primary magnetic field induce currents into the ground, and when the surface is conductive as is usually the case geologically, the initial induced currents flow in a diffuse horizontal vortex, whose radius is approximately the sum of Tx loop altitude plus the radius of the Tx loop. The magnetic field of these induced currents are picked up in a nearby receiver. The ground currents diffuse downwards and outwards, and decay as energy is converted to heat. As a result, the receiver will tend to see a decaying magnetic field. In quasi-layered environments, the objective of AEM is sounding, which provides useful geological mapping information from images of conductivity-depth structure. A second objective of AEM is the detection of anomalies from discrete targets, which responses can then be modelled or inverted to find those whose conductivity and geometrical characteristics are consistent with expectations for targets of interest.

The 5 challenges

During my presentation on Airborne Electromagnetics at Exploration ’07, I outlined five important challenges for the next decade, specifically 1) conductive cover penetration 2) better 2D/3D target detection and interpretation 3) improved AEM system calibration and stability 4) noise reduction through referencing 5) system cost reductions. At the half-way point, it is clear that steady progress has occurred as described below, but that the challenges remain.

1) Conductive Cover Penetration

The main limitation on working in conductive areas is that AEM systems cannot collect good data at base frequencies less than about 25 Hz. To map features below conductive cover requires that sufficient delay range be samples for the magnetic field to penetrate the cover. At 25 Hz with a 50% duty cycle, only 10 ms delays are sampled. Targets under a few tens of Siemens of cover are then invisible to AEM, but may be detected by ground systems operating at low base-frequencies, typically a few Hertz. Lower base frequency AEM research is underway in at least three separate projects, two of which are confidential: I am fairly confident that improvements will be achieved within the next 5 years. It is easy to build a low-frequency AEM transmitter. The main challenge to be addressed is the removal of motion noise, where the magnetic response effects of receiver coils rotating in the earth’s field dominates any secondary field signals.

2) Better 2D/3D target detection and interpretation

At the end of 2011, there were at least 5 service providers offering 3D AEM inversion, and just prior to this KEGS event, several workshops at the ASEG conference in Brisbane have looked at electromagnetic inversion developments. 3D inversion is here, but the jury may still be out on whether it is providing the best answers in the tradeoff between resolution, accuracy and computer
time. In the talk, I will review the recent advances in AEM modelling, and discuss the current limitations based on the ASEG workshop two days before this presentation.

Since 2007, significant increases in dipole moment of Helicopter-borne systems (VTEM, Helitem and Aerotem) and reductions in system noise have provided some unprecedented examples of deep conductor detection. Figure 2 shows the predicted signal/noise ratio for the VTEM system, using an extensive horizontal conductor under resistive cover as the target (providing a calculated signal), and estimating noise from a snapshot of field data in Western Australia.

![Figure 2: Plot of S/N ratio for detection of a thin sheet conductor under resistive cover using the VTEM system. Noise levels were taken from a snapshot of data collected at Forrestania, WA in early 2011, using the n'th difference method. Signals were predicted from forward modelling of a large, horizontal thin-sheet conductor.](image)

Quite clear from Fig 2 is that the VTEM system could in theory detect a thin layer of conductance between 0.1 and 1 S at depths well over 1 or 2 km. In fact, this prediction was made following EMFlow processing of VTEM data from Kombolgie in the Northern Territory of Australia (Figure 3), where Brodie and Costelloe confirmed detection of thin layers to depths up to 2 km using inversion.

Several papers have recently been submitted or presented on Induced Polarization and SPM effects in AEM data. These effects complicate detailed modelling and interpretation, and will be illustrated in the talk.

3) Calibration and stability
Recent developments (eg Skytem, Helitem, Early time VTEM, to be described at the upcoming SAGEEP conference) show how system calibration
and stability improvements, together with bucking improvements and novel waveforms, can allow EM systems to improve their calibration and extend their useful bandwidth. Issues remain however, with models not always in agreement, particularly when signals are significantly smaller than levelling corrections.

One piece of experience that I have, which appears to be consistent with that of others, is that EM sounding is “easier” and more accurate with fixed wing (Spectrem and Tempest in particular with their ideal step-response waveforms) rather than Helicopter geometries (Fig. 5). This is surprising, given the larger signals from the Helicopter systems. I attribute this difficulty of obtaining “consistent and accurate” sounding from (nominally 40 m altitude) helicopter systems to the rapid falloff of signals with depth, with helicopter AEM sensitivities changing by a factor of 40 in the top 100 m (Figure 4). A fixed-wing system with its transmitter at say 100 m, and a receiver training 120 m behind has a far more uniform sensitivity to shallow conductivity (figure 4).

4) Noise reduction
In general, all the commercial helicopter EM systems have achieved much lower noise levels through conventional means in the past few years; through a combination of electronic, suspension of processing improvements. No reported progress has been made on the use of sferic noise referencing in controlled source EM, however, it is an absolutely essential part of ZTEM data acquisition, a development not predicted in my 2007 address.

5) Cost reduction
System cost reduction is most easily achieved through changes in aircraft, with the aim to mount systems or sensors on low-operating cost platforms, whether piloted or UAV’s. UAV operation is still far from simple, and regulation onerous in the extreme, although changes for the positive are underway in the USA with recent congressional pressure on the FAA. Fixed-wing operations tend to be more economic than helicopter surveys for large grids within range of an airstrip, and a couple of developments of AEM on inexpensive platforms are underway. Fugro’s introduction of Tempest Lite, a fixed-wing AEM system on a Caravan is an example of how cost reductions may be achieved.

Figure 4: Comparison of sensitivity of Helicopter (HEM) and Fixed Wing (FWx and FWz, x and z component) to near-surface conductivity. The z component of fixed-wing system changes by a factor of 4 for conductivity in the top 100 m, whereas HEM sensitivity drops by a factor of 40.

Figure 5: The transmitter (black polygon) on a fixed wing AEM system, shown with high- and low-drag birds flies higher than the transmitter on a helicopter system. The initial current vortex induced in the ground (orange) from the fixed-wing system is bigger than that from the helicopter system.
Conclusions

AEM continues to attract large R&D investments, and the technology will continue to improve. Hardware and interpretational developments will mean that many more changes can be expected in the next 5 years.
Recent advances in airborne gravity gradiometry:  
A case study from the Bathurst Mining Camp

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Gravity gradiometers directly measure the second order spatial derivatives of the gravity potential. During Exploration '07, Dransfield (2007) discussed how airborne gravity gradiometry had gained prevalence in mineral exploration since the first surveys were flown in 1999. Since 2007, advances in data acquisition and data processing have improved data quality. Simultaneously, various methods have been developed to aid interpretation of gravity gradiometry data. In addition to the regular use of rotational invariants and lineament analysis using horizontal tensor components, 3D regularized inversion methods have been developed to provide an estimate of the 3D density structures that produce the measured gradient responses. Rather than rely on ubiquitous smoothness constraints, it is possible to use focusing regularization to recover sharper density contrasts. Notably, 3D inversions for giga-cell earth models can recover deposit-scale resolution from regional scale surveys. Such developments have broadened the spectrum of applications from targeting to regional reconnaissance. Full tensor gravity data that had been acquired over the Bathurst Mining Camp in 2004 provides an excellent example of these improvements.

On behalf of Nordanda (now Xstrata Zinc Canada Corporation), SLAM Exploration Ltd., and the Government of New Brunswick, Bell Geospace acquired approximately 15,500 line km of full tensor gravity gradiometry data that covered more than 2,755 square km of the Bathurst Mining Camp. The survey was flown at 200 m line spacing with 2000 m tie lines using a gentle drape with nominal clearance of 80 m above the terrain. Overall, the survey conditions were marginal, and the data delivered in 2004 contained significant noise. In May 2010, Bell Geospace reprocessed the data using updated processing procedures including improved acceleration compensation methods, improved leveling techniques, and full tensor noise reduction (FTNR). In October 2011, TechnoImaging inverted all 15,500 line km of 2.70 g/cc terrain corrected full tensor gravity gradiometry data (approximately 1.4 million independent data points) to a 3D density model of the entire camp with over 85 million cells of 50 m x 50 m x 25 m resolution. Examples will be shown how the aforementioned recent developments in data processing have improved the overall quality of full tensor gravity surveys, and how regional scale surveys can be inverted to a 3D deposit-scale resolution.

Introduction

During Exploration 2007, Dransfield (2007) discussed the advances and acceptance of airborne gravity gradiometry in mineral exploration since its introduction in 1999. Using data that had been acquired prior to 2007, we present a case study that demonstrates the advances in data processing methods and interpretation tools for gravity gradiometry data that have developed since 2007.

Background

Whereas a gravimeter directly measures the acceleration of gravity, a gradiometer measures how the gravity acceleration changes in three-dimensional (3D) space. Since the acceleration of gravity is directional in three-dimensions, the change in gravity contains nine components that make up the gravity tensor:

\[
\begin{bmatrix}
\frac{\partial g(x)}{\partial x} & \frac{\partial g(x)}{\partial y} & \frac{\partial g(x)}{\partial z} \\
\frac{\partial g(y)}{\partial x} & \frac{\partial g(y)}{\partial y} & \frac{\partial g(y)}{\partial z} \\
\frac{\partial g(z)}{\partial x} & \frac{\partial g(z)}{\partial y} & \frac{\partial g(z)}{\partial z}
\end{bmatrix}
= \begin{bmatrix}
T_{xx} & T_{xy} & T_{xz} \\
T_{yx} & T_{yy} & T_{yz} \\
T_{zx} & T_{zy} & T_{zz}
\end{bmatrix}
\]

Since the gravity tensor is Laplacian and symmetric, only five of the nine components define the entire array:
Figure 1 shows the response of each of the independent gradient components and the vertical component (Tzz) for an isolated mass.

As in 2007, the only gravity gradiometers currently available for commercial surveys are those manufactured by Lockheed Martin in Niagara Falls, New York. These rotating accelerometer gravity gradiometer systems employ pairs of opposing accelerometers mounted orthogonally on a continuously rotating platen (Figure 2). This configuration solves the two most important gravity gradient measurement problems. First, in order to not be influenced by the vehicle accelerations, the response of the opposing accelerometers must be precisely matched. Second, to eliminate the low frequency noise of the individual accelerometers, the measured gradient signal must be shifted to a higher frequency. The rotating accelerometer scheme resolves both of these issues. Scale factor differences are modulated by the rotation frequency, which can be separated from the gradient measurement and used to adjust the scale factor of each pair. The gradient measurement is also modulated but by twice the rotation frequency, which can be separated from the low frequency noise. The tangential orientation of the accelerometers serves to isolate the measurement from changes in the rotation rate. While the concept is relatively simple, the engineering problems associated with making the instrument accurate to one part in $10^{11}$ are quite formidable. For the full tensor system, three gradiometers, each with two pair of match accelerometers, are mounted on an inertially stabilized platform.

Brunswick Mining Camp survey

In 2004, airborne full tensor gravity gradiometry (FTG) data had been acquired over the Bathurst Mining Camp (BMC) in northern New Brunswick for a joint venture that consisted of Noranda (now Xstrata Zinc Canada Corporation), SLAM Exploration, and the Government of New Brunswick (Figure 3). Since the large known deposits in the camp were nearing depletion, the goal of this survey, along with other camp-wide surveys acquired at the time, was to provide data that might lead to the discovery of a new world-class mineral deposit within this very mature mining camp. This survey was the first regional scale full tensor gradiometry survey acquired.

The survey covered more than 2,755 square kilometers and acquired approximately 15,500 line-km of full tensor gravity data. The survey lines were flown north-south at 200 m line spacing with east-west tie lines spaced at 2 km. The data was acquired with a nominal ground...
clearance of 80 m using a gentle drape. Since survey conditions were difficult, much of the data was acquired at higher vertical acceleration levels (stronger air turbulence) than what was typically preferred, adding noise to the data. With the poor survey conditions acquisition of repeat lines was eventually ended prior to all lines meeting the quality specifications by mutual consent of the contractor and the client representative. Since the survey ended prior to acquisition of all necessary repeat lines, the overall data quality was considered to be noisier than most other surveys acquired at the time.

Data processing: 2004 vs. 2010

In 2004 the data was processed using the sequence shown in Figure 6. Immediately after acquisition the data is processed using an automatic high rate processing that de-multiplexes and reformatsthe data and applies a compensation to remove measured accelerations that the platform has experienced during acquisition. Each tensor component was then leveled using standard gravity leveling methods. Finally, a terrain correction was applied using the calculated response from a digital terrain model. Figure 7 shows the final processed free air data that was delivered in June 2004. Note that since the largest density contrast and the closes source is from the terrain, the free-air data detects the major terrain features, as expected. After applying the terrain correction, however, noise becomes obvious (Figure 8), especially when comparing the data response to the geologic map in Figure 5.
Since 2004, the data processing sequence has undergone several revisions and several additional processing steps have been added and modified (Figure 9). One of the early changes was to move the terrain correction from the last step to one of the earlier steps. This allows the data processor to identify noise that might not be as obvious when riding on top of the large amplitude terrain signal. Another addition is an automatic leveling to account for major trends in the data. After this step, although the data is not in its final form, it can be used by a client to determine whether or not they might wish to make any adjustments to the survey plan.

One of the major improvements in FTG data processing is the development of several full tensor noise reduction (FTNR) methods. The first FTNR technique, Multi-Channel Processing (MCP), was developed at Conoco (Jorgensen and Kisabeth, 2000, Jorgensen, et al., 2001). Since then, other FTNR methods have been published (e.g., Murphy et al., 2006). FTNR methods operate on the basis that although the full tensor system measures independent tensor components, the expected response from each component can be estimated from the other tensor components. Any non-Laplacian signal within a channel can be identified and removed (Figure 10). The final enhancement was an improved acceleration compensation to remove aircraft induced noise.

Because the BMC survey data was known to be noisy, it underwent several iterations of processing as new techniques developed. In 2010, the data was reprocessed using the latest processing methods. As seen in Figures 10 and 11, the data processing methods applied in 2010 significantly improved the overall quality compared to the 2004 deliverables.
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Figure 9. FTG data processing flow in 2010.

Figure 10. Example of full tensor noise reduction (FTNR).

Although the free-air data using the 2004 processing compared to the terrain quite well, the 2010 data appears less noisy. The improvement is most dramatic in the terrain corrected data, where the 2010 data processing shows subtle features and faults that were buried in noise after the 2004 data processing.

Figure 11. Free-air Tzz using 2010 processing methods (compare to DEM in Figure 5).

Figure 12. Terrain corrected Tzz using 2010 processing methods (compare to the geologic map in Figure 5).

Note that the terrain correction density is chosen to minimize the terrain signal after the correction has been applied. In 2004, the correction density was determined to be 2.82 g/cc, whereas in 2010 the most appropriate density was 2.70 g/cc.

Full tensor interpretation tools

Pedersen and Rasmussen (1990) discussed methods to enhance resolution from full tensor data. At the time, their discussion was theoretical because little if any full tensor data was acquired. Since then, full tensor gravity data has been acquired on a regular basis, and their rotational invariants have become valuable interpretation tools. For example, Mataragio and Kieley, (2009) enhance high frequency
information using the second rotational invariant:

\[ I_2 = [Txx(TyyTzz - Tyz^2) + Txy(TyzTxz - TxyTzz) + Txz(TxyTyz - TxzTyy)]^{1/3} \]

In the BMC data, the deposit associated with the Brunswick 12 Mine was located on the edge of a mafic intrusion. The mafic body has a higher density (~3.2 g/cc) than the host (~2.67 g/cc), and the sulfide body has even higher density (~4.37 g/cc). Ideally, the response would be a high gravity response with a high frequency bump of higher gravity. However, a simple forward model study suggests that using the survey specifications the sulfide body would merely increase the overall slope of the mafic intrusion response. Although the signal from the sulfide body theoretically would be detectible, practically, its response would be hidden within the response from the mafic intrusion (Figure 13). \( I_2 \), however, tends to enhance individual high frequency bodies and attenuates lower frequency responses.

![Figure 13. Tzz and Txz component response from VMS deposit model.](image1)

Zooming into Brunswick-12 in the Tzz data, it is obvious that the model prediction that the sulfide body is obscured by the mafic intrusion is accurate (Figure 14). However, \( I_2 \) attenuates the response from the large mafic body allowing an image of the mine. The low gravity in this image might suggest that much of the ore deposit has been mined out with remnant gravity anomalies to the north and to the south. At the time of survey acquisition in 2004, the Brunswick-12 mine was near depletion.

![Figure 14. Tzz over the Brunswick-12 mine.](image2)

![Figure 15. I_2 over the Brunswick-12 mine.](image3)

**Full tensor gravity inversion**

Since 2007, several companies and organizations have developed inversion programs for full tensor gravity data. The first published inversion was by Jorgensen and Kisabeth (2000) for the specific case of estimating the base of deep salt structure in the offshore Gulf of Mexico. Variants of voxel-based inversion have been developed by Li (2001) and Zhdanov et al. (2004). In this paper, we report of results using a massively parallel inversion program described by Čuma et al. (2012), which was developed specifically to quickly invert large (regional) data volumes such as the BMC FTG survey. This program uses focusing regularization to allow recovery of 3D density models with sharp boundaries and contrasts. (Portniaguine and Zhdanov, 1999).

In 2011, all 15,500 line-km of the BMC FTG data were inverted to a topographically conforming 3D density model with over 85 million cells of 50 m x 50 m x 25 m discretization. The inversion was unconstrained. Figure 16 is an example of the observed and predicted data. Figure 17 shows a series of depth slices through the final 3D density model.
Figure 16. Observed response (upper panel) and predicted model response (lower panel) for the terrain corrected $T_{zz}$ data.

(a) 37 meters above sea level (ASL).

(b) -63 meters ASL

(c) -363 meters ASL

(d) -663 meters ASL

(e) -1063 meters ASL

Figures 17 (a)-(e). Horizontal depth slices through the 3D density contrast model obtained from the simultaneous inversion of all gravity tensor components from the BMC survey.

(e) -1063 meters ASL
Conclusion

In the 5 years since Exploration '07, processing and interpretation methods for airborne gravity gradiometry have significantly improved. After applying current processing methods to a 2004 survey that was known to contain high levels of noise, the data better matches the known geology, and provides a much better product for future exploration. During this period, interpretation methods have evolved that make better use of the measured tensor data, and truly large-scale 3D inversion has been developed that, when used appropriately, can provide three dimensional density models that better represent the actual geology.

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References


Exploration Geochemistry – Recent Developments and an Uncertain Future.
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Over the last five years the science of exploration geochemistry has seen many significant developments that have had a direct impact on the exploration geologist’s capabilities to detect the signals of mineralization in the environment. These advances have come in a variety of disciplines, including: conceptual models, analytical methods and data processing. This paper highlights some of the key developments and looks forward to some of the future developments and challenges facing Exploration Geochemistry as a discipline.

In the field of conceptual models, Stew Hamilton introduced the concept of Redox Induced Spontaneous Potential or (RSIP) as a mechanism to explain observed surface geochemical patterns over blind sulphide mineralization. This model helps us understand the significance of ‘Deep Penetrating’ geochemical anomalies and improves our ability to plan and execute geochemical surveys in transported cover. In the commercial laboratories, detection limits continue to go ever lower. In the last 5 years detection limits for standard ICP-MS packages have dropped by an order of magnitude or more for some elements. The commercial availability of High resolution ICP-MS and the introduction of stable isotope packages have given the explorationist new tools to detect ever more subtle signals of blind mineralization. Quemscan technology, now available through several commercial laboratories, provides SEM-EDS based automatic mineral identification capability. This has potentially huge applications for indicator mineral surveys. Field based analyzers have also made great inroads into the mineral exploration industry. Portable XRF analyzers now give the geologist the capability to carry out semi quantitative and quantitative analyses for many elements right in the field. These units are now widely used on overburden, core and RC drilling programs and are finding ever growing roles in sediment and soil geochemistry programs as well. Nevertheless there are limitations to the technology such as relatively high detection limits for many important elements as well as drift, interference and calibration issues.

New software applications that help us to manage and interpret large multi-element datasets have made great inroads into the industry over the last five years. Some, like ioGAS, are becoming a key tool for geologists and geochemists alike. Programs like Geosoft’s Target® and Encom’s Discover® are now highly integrated with common GIS packages and empower the user to make more robust interpretations of geochemical datasets thereby adding value to a company’s investment in sampling and analysis.

Great challenges lie ahead for exploration geochemistry. Perhaps the biggest is the aging population of industry geochemists, many of whom are at or approaching retirement age. This combined with the paucity of formal tuition in applied geochemistry at Canadian Universities is resulting in few and fewer trained geochemists working in the industry; a situation that can only get worse without drastic measures.
Advances in seismic exploration for VMS deposits: Current results and future directions

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Summary

Seismic mineral exploration studies conducted under the TGI-3 program are summarized for the Flin Flon and Halfmile Lake mining camps. Research directions in seismic exploration being pursued under TGI-4 are outlined.

Introduction

Seismic methods have been used primarily as a means of exploration in the immediate vicinity of existing VMS mining camps. Research in this area has been conducted under the Geological Survey of Canada’s Targetted Geoscience Initiative-3 (TGI-3) and is continuing under TGI-4. Conventional P-wave and converted-wave (PS) imaging have proven to be effective in the Flin Flon and Halfmile Lake camps. Research directions being pursued under the auspices of TGI-4 focus on the use of vector-seismic data, high density sensor acquisition and ambient-noise imaging.

TGI-3: Seismic studies in the Flin Flon and Halfmile Lake mining camps

A 17 km² 3D-3C seismic survey was conducted within the active Flin Flon mining camp. As described in White et al. (2012), the resultant 3D images show strong reflectivity associated with the ore-hosting mine horizon and prominent reflections attributed to the known ore zones. Structural repetition of the mine horizon is clearly identified in the seismic images with at least 3 levels identified. The 3D seismic images have been used in conjunction with detailed geological and geophysical drillhole logs to identify new exploration drill targets. The first three seismic-based exploration drillholes encountered reflective geological contacts at depths within 3-8% of those predicted from the 3D seismic images. In the first case, a gabbro of no economic significance was encountered at the target depth. In the second case, a highly altered mafic volcanic panel with stringer mineralization was identified sitting blind beneath surface exposures of sandstone. In the third case, the target turned out to be an additional structural level of the mine rhyolite which provides a new horizon for further exploration. A small massive sulfide ore lens was discovered during follow-up drilling around this third target.

Malehmir and Bellefleur (2009) present the results of reprocessing an 18 km² 3D seismic data volume from the Halfmile Lake area of New Brunswick. The focus of the study was to improve the observed seismic response from a 5 Mtonne VHMS deposit located at a depth of ~1200 m as well as enhancing images of the key geological structures. Prestack dip-moveout (DMO) processing combined with post-stack time migration proved effective in improving the 3D images in spite of the large static issues and high levels of source-generated coherent noise. A high amplitude reflection at ~800 m depth observed in the unmigrated data was interpreted to be caused by a small part of the lower ore zone. Also, a high amplitude asymmetric diffraction response originating from the deep VHMS deposit was observed which had not been preserved in the original approach to data processing which utilized prestack migration.

TGI-4: Deep Mineral Exploration Methodology Development at the Lalor Deposit Test Site

A key research objective in TGI-4 is to develop and test new and innovative geophysical methods for deep mineral exploration. Chosen methods (described below) will be evaluated as stand-alone technologies and as elements of an integrated methodology. In particular, innovative 3D vector seismic imaging techniques (active and passive) will be tested and integrated with 3D geological modelling and potential field inversion for physical properties to produce a well characterized 3D knowledge cube. This methodology will be tested at the Lalor deposit in the Snow Lake camp in Manitoba, where it is anticipated that a 3D vector seismic survey will be conducted in 2012. This vector data set will form the central framework for the project where several novel methodologies will be developed and tested with a focus on deep ore deposits. The methodologies to be considered include 3D converted-wave (PS) seismic imaging and modelling, 3D seismic interferometry or ambient-noise imaging, and high-density data recording. These methodologies are described further below.

The proposed test site is the Lalor deposit in Manitoba which was discovered in 2007 by Hudson Bay Mining and Smelting. It is a 17 Mtonne deposit located at ~800m depth with metal contents of 9% Zn, 0.6% Cu, 1.4 g/t gold and 25.5 g/t silver. Infrastructure for mining the deposit is currently being put in place, but otherwise the deposit is
Converted wave processing using vector seismic data is commonly applied in oil and gas exploration (Stewart et al., 1999; Hardage et al., 2011) but has only rarely been used in hardrock seismic exploration (e.g., Snyder et al., 2009; Malinowski and White, 2011). Seismic exploration for ore deposits has relied primarily on subsurface images obtained using reflected P-wave energy (e.g., Milkereit et al., 2000; Adam et al., 2003; Malehmir and Bellefleur, 2009). However, the elastic properties of the host rock - ore deposit system (Salisbury et al., 2003) should generally produce a complex, multimode reflected and scattered wave field. Bohlen et al. (2003) concluded that the energy scattered from an orebody in the form of PP and P-to-S converted waves (PS waves) commonly exceeds 25% of the incident P-wave energy. The coda of the scattering response of small and large ore bodies embedded in a homogeneous background will be dominated by the shear wave energy. The shorter wavelength associated with S-waves suggests that migration of high-amplitude scattered S-waves may improve imaging of small ore inclusions. Multimode converted waves originating from a sulphide lens were reported earlier for VSP data (Bellefleur et al., 2004).

The objective of this study is to acquire and process a state-of-the-art vector (3-component) 3D seismic survey over a well-defined existing orebody. This will provide the opportunity to directly calibrate converted-wave images against a 3D P-wave image and 3D geological model. Detailed knowledge of the subsurface geology will allow the results to be critically assessed and form the basis for benchmarking new developments in the methodology. The 3D seismic volumes in conjunction with existing drillhole data will provide a framework for constrained inversions and a basis for evaluating seismic interferometric imaging results.

Mineral Exploration with Seismic Interferometry

Mineral exploration using seismic reflection methods is complex, both practically and theoretically. Practically, the technique is often burdened with expensive deployments of large receiver and source arrays. These limitations coupled with the data processing challenge in a hard-rock environment hamper the adoption of this technique for greenfield and brownfield exploration. Development of a seismic technique that does away with the source may increase the effectiveness of this tool in an exploration context.

Wapenaar (2004) demonstrated that, in theory, a full reconstruction of the seismic impulse in three dimensions can be recovered using noise correlations. No seismic source, dynamite or vibroseis, is required. Ambient noise imaging methods have been applied to the retrieval of surface wave information in the past, largely because of the stronger signals involved. The technique is also related to the transformation to crustal-scale reflection images based on information in teleseismic coda. Recent papers (Draganov et al., 2007, 2009; Hohl and Mateeva, 2006; and Torri et al., 2007) suggest it is feasible to recover the reflected wave-response with interferometry.

Whereas there has been considerable success with the technique, there have not been many reports of the technique in use for resource exploration. Within TGI we seek to reproduce the methodologies outlined in Wapenaar et al. (2010) and apply them in a mineral exploration context. We seek to develop tools that when combined with rock property information will enable the discrimination at the surface of reflections originating at key metallogenic interfaces without using active sources. At no extra cost, the new tools will be able to derive subsurface images of seismic velocity useful in highlighting lithological features related to the ore-bearing host rocks.

Seismic exploration using dense receiver coverage

The widespread application of 3D seismic methods for mineral exploration has been limited largely because seismic surveys are relatively expensive to conduct as noted in the previous section. A cursory analysis of the costs associated with 3D seismic acquisition in crystalline terrains shows that the largest cost is that associated with implementing the seismic source; in particular, the cost of drilling shot holes. In contrast, the cost of seismic recording systems has decreased substantially in the past 10-15 years while at the same time providing an order of magnitude increase in the number of data recording channels that can be deployed. Furthermore, vector sensors are commonly available. Systems of 10,000-20,000 channels have been deployed. This suggests that some of the expensive source effort could be replaced by compensating with the use of kilo-channel systems to achieve comparable imaging results. 3D modelling and data processing will be conducted to test alternative seismic acquisition protocols toward improving the overall cost efficiency of seismic mineral exploration. This study will numerically model a variety of seismic acquisition scenarios that will be evaluated for optimum balance between minimum
acquisition effort and high quality geological imaging. This will be accomplished by conducting 3D forward modelling for an existing realistic mining-camp scale model to generate synthetic shot gathers. The 3D seismic survey parameters will be based on acquisition parameters that were used in a recent 3D survey conducted in the TGI-3 Flin Flon project. Data will be generated for a number of shots that is comparable to the original survey (~1000), but with the number of receivers increased by a factor of up to 10 to allow data decimation testing. The “phase screen” method will be utilized as it is capable of simulating diffracted modes which are likely an important component of the ore body response while at the same time being computationally feasible. Synthetic “raw” shot-gathers shall be processed including stacking, DMO and post-stack migration.

References


Virtual seismic sources and combined surface and borehole seismic imaging: Seismic imaging tuned for hard rock terrains, an introduction and field test

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Summary

The imaging response of the seismic reflection method is strongly biased by the orientation of the source and receiver arrays. For example, surface seismic data are inherently tuned to imaging targets that are oriented within ~45° of horizontal. In this presentation we discuss a novel seismic data acquisition and processing approach that combines collocated surface and borehole seismic data to provide more complete imaging of geometrically complex targets such as those typically encountered in hard rock minerals exploration. The method uses seismic interferometry to transform walk-away vertical seismic profile data acquired with surface sources and borehole receivers into a virtual seismic profile with sources and receivers in the borehole. The virtual seismic profile is then processed using standard CMP processing and is subsequently combined with surface seismic data to mitigate acquisition bias. Combination of the two data sets results in more complete imaging of the target. We present synthetic examples to illustrate the methodology, a discussion of the design of field experiments and an example of a field test of the technique at Vale’s Voisey’s Bay mine site.

Introduction

There is significant interest in applying seismic techniques for delineation and evaluation of hard rock mineral deposits because of the inherent high resolution of seismic techniques compared to more traditional geophysical methods. However, there are some challenges that have inhibited the adoption of seismic techniques by the minerals exploration industry. In general, the geology of hard rock mineral deposits tends to be complex and discontinuous with dips ranging from horizontal to vertical, resulting in wave fields dominated by scattering rather than specular reflection. Alternative approaches to data acquisition and processing that are specifically designed to detect or image geometrically complex hard rock targets have the potential to bring seismic techniques into the realm of importance of the other geophysical techniques typically applied in hard rock exploration and particularly in the realm of deposit delineation and resource evaluation.

The response of seismic reflection techniques are biased by the orientation of the acquisition plane. That is, reflection data acquired on the surface are biased toward detecting and imaging sub-horizontal geologic features. This is particularly true when limited offset ranges and profile lengths inhibit recovery of information from steep dips as is often the case in the hard rock environment. This inherent bias is generally not a major issue for imaging sedimentary basins with predominantly sub-horizontal targets but can be a significant problem in the hard rock environment where imaging targets can have any orientation. One approach to mitigating imaging bias is to combine surface and borehole data in a fashion that provides a larger range of illumination angles than is available from either data set on its own. Such a combined data set has the potential to produce a seismic reflection image that better represents complex geology in the hard rock environment.

The combined seismic image is formed by combining conventional surface seismic data with borehole data in the form of a walk-away vertical seismic profile (VSP). The VSP data are transformed into a standard CMP profile with sources and receivers in the borehole. Mapping of the VSP data into the borehole frame is carried out using seismic interferometry to form virtual sources in the borehole which are then processed with a standard CMP processing flow. The surface and borehole CMP profiles are then combined to form a seismic image with less directional bias and better imaging than the individual profiles.

Method

While surface seismic methods are well known, seismic interferometry and virtual source profiling are emerging technologies. Seismic interferometry is developing in a variety of different forms for different applications. The basis for the method investigated in this paper is the idea that the direct wave arriving at a borehole receiver from a surface source effectively represents a virtual source in the borehole. The problem then is to recover both the kinematic and dynamics aspects of the virtual source and the associated forward and back propagating wave field associated with the virtual source. The virtual source wave field is constructed by the process of cross-correlating the seismic data from the receiver to be converted to a virtual source with all of the receivers associated with a particular surface shot to form a correlation gather, carrying out the same process for all of the surface shots associated with the walk-away VSP and then summation of all of the correlation gathers to construct the virtual shot. This process is illustrated in Table one for a walk-away VSP with 240 borehole channels and 20 surface shots.
Example of the Virtual Source method

The advantage of using borehole seismic data in combination with surface seismic data is that while surface profiling is inherently biased toward imaging subhorizontal features, the virtual source profile in the borehole is biased toward imaging subvertical (with respect to the surface) features. Combination of the two data sets results in significantly less orientation bias in the seismic image. As an illustration of the effectiveness of virtual source profiling for imaging sub-vertical features we present a test using synthetic seismic data derived from a geologically realistic model. The model (Figure 1) represents a dyke with an average dip of 70° and thickness varying between 30 and 60 m. The synthetic seismic data were acquired using a 4 m receiver spacing in the borehole and an 8 m surface shot spacing.

Figure 2 shows a time migration of the results of the synthetic experiment. The synthetic example confirms the effectiveness of the virtual source profile for imaging subvertical targets but does not explore limitations on the method that arise from realistic field conditions that often occur in a mining camp such as limited access, extreme and variable topography and environmental restrictions as well as economics that may lead to a field experiment that occurs in less than ideal conditions for creation of virtual sources.

Field experiment and data processing

A combined imaging experiment was carried out as a collaborative project of Memorial University and Vale at Vale’s Voisey’s Bay mine site in northern Labrador, Canada. The Voisey’s Bay site hosts extensive nickel-copper-cobalt mineralization associated with a magmatic event that is locally characterized by intrusion of a sulphide bearing troctolitic magma. Massive sulphide concentrations are associated with both the large troctolite bodies and the system of dikes that fed the troctolite bodies. Within the feeder system, massive sulphides are concentrated at kinks in the feeder dikes making the mapping of the generally steeply dipping dikes and particularly the kinks in the dikes an important exploration objective.

The field experiment was carried out in the Reid Brook zone of the Voisey’s Bay deposit. The main target of the experiment is a mineralized troctolite dike that is intruded into gneisses and has a general dip of approximately 60 degrees to the south. The detailed geometry of the dike is relatively complex with segments of variable dip either associated with exploitation of pre-existing fracture zones during intrusion and/or post-intrusion brittle deformation.
Combined surface and borehole seismic imaging

The thickness of the dike varies from 20 to 50 m in the area of the experiment. Physical properties data indicate an average reflection coefficient of +0.07 between the troctolite and the gneisses. However, the contrast between the gneiss and troctolite is only moderately higher than that between the felsic and mafic components of the gneiss (+0.05).

The field experiment consisted of a walk-away VSP and a surface seismic profile that is centered on the borehole used for the VSP. The receivers for the VSP comprised a 60 m hydrophone cable with 2 m hydrophone spacing. The borehole was surveyed over the depth range of 750 m to 272 m so the VSP was constructed from eight passes over the source locations, raising the hydrophone cable for each pass to provide continuous two m sampling over the surveyed depth range. The source was a swept impact source (MUNSIST) mounted on a medium sized excavator. The source spacing was 20 m with five sweeps of the MUNSIST source at each shot point for a total of 20 shot points and maximum offset from the borehole of 400 m. The walk-away experiment resulted in 20 individual VSP panels each of which record the full depth range of the in the borehole.

The surface data were acquired using a fixed receiver spread of 150 stations with a 10 m geophone spacing and shot spacing of 20 m. The data were acquired by shooting through the entire spread. This acquisition geometry resulted in a five m CMP spacing. Processing of the surface data followed a standard processing sequence resulting in CMP fold varying between eight at the ends of the spread to 69 in the center of the spread. The data were imaged with a post-stack Kirchhoff depth migration.

The virtual source data were processed using the process outlined above resulting in 240 virtual source gathers, one for each receiver location in the borehole. The resulting virtual sources were then processed using a standard CMP processing flow resulting in a borehole based CMP profile with fold varying from 1 at the ends of the profile to 236 in the middle of the profile and imaged using post-stack Kirchhoff depth migration.

Results of the field experiment

Surface data
The post-stack depth migrated data from the surface profile are shown in Figure 3. The reflection wave field is complex with event coherence limited to 100-200 m, a response that is typical of polydeformed gneissic sequences. Correlation with lithologic and televiewer logs indicate that the reflections predominantly originate from fluctuations between the mafic and felsic components of the gneiss. However, despite the limited length of the profile, the surface data were quite successful in imaging the target dike in the (450-650 m range) where the dip of the dike shallows to about 45 degrees.

Virtual Source profile
Although a surprising variety of dips are apparent in the surface data, there is a clear bias toward imaging of sub-horizontal features. The virtual source profile was designed to mitigate some of this bias by imaging from a datum that is approximately orthogonal to the surface datum. The Kirchhoff depth migrated virtual source profile is shown in Figure 4. As expected, reflections in the virtual source data show a clear orientation bias toward sub-vertical events (with respect to the surface). The lower part of the dike is clearly imaged but the upper part of the dike is not and in that area the predominant reflection fabric dips toward the north rather than the south. Modeling of the virtual source profile demonstrates that the uphole coverage of the virtual source profile was not sufficient to allow imaging of the upper part of the dyke.

Combined Profiles
The combined surface and virtual source profiles are shown in Figure 5. The combined data are complex but are less biased by the acquisition datum and more representative of the subsurface geology although it is unclear how much directional bias remains in the image. The combined data emphasizes event truncations and the cross-cutting nature of the dike with respect to gneissic foliation. The data also confirms the partitioning of the dike by fracture zones with modest offsets and a variety of orientations.

Summary
This paper reports a first field test of the use of combined surface and borehole seismic imaging in a hard rock environment. The borehole imaging is accomplished by using walk-away VSP data to create virtual shot gathers with sources and receivers in the borehole and then processing the virtual shots as a standard CMP profile. The field test demonstrates the effectiveness of the borehole data for imaging sub-vertical interfaces and additionally that the surface and borehole data can be combined into a single image that mitigates some of the directional bias inherent in the seismic system. This approach to combined surface and borehole imaging has significant potential for imaging in complex polydeformed hard rock terrains and the results of the initial test were encouraging enough that a follow up was conducted in fall 2011.

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Combined surface and borehole seismic imaging

Figure 3. Surface seismic data. The troctolite dike is indicated by the dashed line.

Figure 4. Virtual source seismic profile in the borehole. The troctolite dike is indicated by the dashed line.

Figure 5. Combined surface and virtual source seismic profile. The dashed square represents the zone of overlap between the two data sets.
Summary

Remote sensing technologies are increasingly breaking out of their “synoptic view” regional study function and playing a significant role in exploration, mine development, and operations. Production scale hyperspectral core imaging is poised to provide highly detailed three dimensional mineral maps that contribute to discovery and geo-metallurgy. The widening recognition that geologic spectroscopy can benefit from tools used for chemical and biological spectroscopy is driving the adoption of chemometric analysis by multiple mining companies. The baseline for airborne thermal infrared hyperspectral imaging was established over the last few years with multiple test and production surveys utilizing the effective but expensive to operate SEBASS instrument. The technology is on the verge of a breakout with the availability of field thermal spectrometers and cost effective airborne thermal hyperspectral imaging systems. The technology for high spatial and spectral resolution satellite hyperspectral imaging has been demonstrated by the US Air Force and the countdown to the launch of a moderate resolution hyperspectral satellite by Germany (EnMap) appears to be on track.

Introduction

Remote sensing is the science of collecting passive or active measurements of reflected or emitted electromagnetic radiation from the surface of natural or man-made materials. From a geophysical perspective the property we would like to measure is the vector of the spectral reflectance or emission response of materials. The more accurately we measure the spectral response, the more accurately we can identify the constituents of the material. It is important to differentiate between the two fundamental different types of remote sensing data. Data that convey spatial information with minimal spectral resolution (e.g. Landsat, Quickbird, et al,) are primarily visualization tools whereas imagery that lends itself to qualitative or quantitative analysis of material properties (e.g., hyperspectral imagery or field spectrometers) are primarily analytical tools. Some systems such as ASTER and Worldview II (8 band data) lean toward being analytical but provide only moderately accurate material identification capabilities. The majority of these measurements are made from satellite or airborne platforms but the utilization of portable terrestrial instruments has seen rapid growth in the last decade. Historically the rate of advancement in remote sensing has been relatively slow due to the data sources being tied largely to satellite systems with their inherent high cost and long development lead-time. In the last five years we have seen remote sensing technologies break out of the satellite focused approach. Airborne hyperspectral imagery (HSI) has been around since the mid 1980’s and commercial surveys have been flying since the mid 1990’s. By the early 2000’s lowering of costs and increased competition had made acquisition of airborne hyperspectral data more routine. More recently, four important remote sensing technologies are poised to significantly change the impact remote sensing has in the mining industry: core imaging technologies of the visible to shortwave infrared range (VIS-SWIR), chemometric analysis methods, thermal infrared (TIR) imaging technologies, and satellite based hyperspectral imagery. These are the focus of this discussion.

Hyperspectral Core Imaging

Hyperspectral core logging has been around for many years, first as manual measurements made with a handheld spectrometer which naturally progressed to robotic measurements with modified versions of handheld spectrometers. Methods for acquiring high resolution hyperspectral imagery of core and cuttings have seen significant development in the past five years. Two of the major players in the field are Corescan Pty Ltd which produces the Corescan system and Spectral Imaging Ltd (SPECIM) produces the SISU Rock system. Corescan

Figure 1  Corescan system (Source: Corescan Pty Ltd)
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utilizes an in-house developed hyperspectral camera designed specifically for core imaging (Figure 1). SPECIM utilizes a modified version of their AISA airborne camera system (Figure 2). Both systems collect high spatial resolution visible imagery in addition to the hyperspectral imagery. In addition, since measurements are made at close proximity, atmospheric interference is non-existent.

Ultimately, hyperspectral core imagery allows a high resolution 3D geo-located mineral map of core or cuttings to be generated. The impact of this for exploration, development, and operations is significant and has the potential of being a game changing technology. In the past visual alteration mineral logging, supplemented by handheld spectroscopy, and verified by limited XRD, provided the only 3D mineral mapping. This approach grossly undersamples the core and is often subjective and qualitative. The result was highly subjective alteration models for exploration and a lack of adequate identification and mapping of confounding minerals for production. Core imaging provides highly accurate, semi-quantitative mineral models that provide useful information for the entire life of the exploration-design-development-production-closure cycle. In addition, the clay minerals that often present problems for production are mapped with the highest degree of accuracy. An example of the information generated by core imaging is shown in Figure 3.

Chemometric Analysis

Spectroscopy is a mature technology that has been used for material identification in many different scientific and engineering fields. In exploration and mining we have generally relied on qualitative analytical methods for extracting mineralogical information from the spectral measurements. In other fields, scientists have used chemometric methods to extract semi-quantitative information from the spectral measurements. The approach involves making coordinated quantitative measurements (typically with XRD but CEC, Qemscan, and ICP have been used in some cases) and spectroscopic measurements. The spectroscopic measurements are then regressed to predict the XRD defined mineralogy. Because of the high dimensionality of the spectral data, partial least squares regression is utilized. Two software packages dominate the field: Grams Suite and Unscrambler. The initial model data set of coordinated samples typically consists of 100-200 samples but will grow over time. As more samples are added the accuracy of the analysis improves. The method inherently allows samples that don’t fit a model to be identified.

Chemometrics work best on spatially constrained problems such as a single geological environment since the spectroscopy and XRD are more likely to be correlated. As such it is currently used primarily for production rather than exploration. Ultimately chemometric analysis will be used on spectroscopy from core images allowing highly accurate semi-quantitative mineral models to be constructed of entire deposits.

Thermal Spectroscopy

Conventional reflected light remote sensing methods operate in the visible to shortwave infrared (VIS-SWIR) regions of the electromagnetic spectrum (approximately 350 nanometers to 2500 nanometers). A variety of minerals can be identified in this range but phyllosilicates are mapped most accurately. The tectosilicate family including feldspars and quartz are largely invisible in the reflected light range. Most of the tectosilicate spectral fingerprints are located in the thermal infrared range of the

Figure 2 SISU Rock system (Source: Specim)

Figure 3 Core mineral map (Source: Specim)
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EMS. The measured phenomenon is emitted energy rather than reflected energy and possesses a much lower signal. Thus thermal hyperspectral imagery has lagged behind imagery in the VIS-SWIR range. An additional dilemma for explorationists has been the lack of a reliable field portable TIR spectrometer. The level of confidence that geologists have in airborne and core scanning technologies in the VIS-SWIR was driven by the ubiquitous field spectrometers used in the industry. The lack of a TIR spectrometer has hampered enthusiasm for airborne TIR hyperspectral imagery since we effectively have had no way to verify the imagery on the ground; a particular problem when working with noisy TIR imagery. Recently a portable TIR spectrometer has been adapted to geologic use. The A2 Technologies (now Agilent) ExoScan spectrometer (Figure 4) holds promise for field data validation and acquisition of exploration related mineral libraries but has not yet caught hold in the mining industry.

Airborne TIR hyperspectral has relied on a single instrument called SEBASS to provide data to date. In 2008 this was paired with a SPECIM AISA dual hyperspectral camera by Spectir LLC to provide simultaneous collection of VIS-TIR data. The system was flown by a number of mining companies, primarily to test the technology. The SEBASS instrument, while very capable, has a narrow swath width and expensive operating costs. While excellent for acquiring benchmark data it does not have simplicity and low operating costs needed to fly large commercial surveys for mining applications. Commercial instrument companies ITRES and SPECIM (Figure 5) have developed airborne TIR hyperspectral cameras. Widespread adoption of this technology depends on the development of mineral libraries for ore deposits and greater usage of field TIR spectrometers.

Satellite Hyperspectral Imagery

The concept of collecting hyperspectral data from a satellite platform seems like a logical next step in remote sensing. The implementation of this has posed significant challenges. A single full range (VIS-SWIR) hyperspectral satellite system with openly available data called Hyperion is operating. This system provides 30m resolution data but has a relatively poor SNR. It also has a narrow swath width and very limited acquisition capacity per orbit resulting in very little of the Earth being mapped after 10 years in orbit. Several full range, moderate resolution (20-30m) satellite hyperspectral systems have been proposed to succeed Hyperion but none have been funded and launched. The model for the next generation of HSI satellite systems is focused toward on-demand task directed data acquisition. Global mapping ala Landsat or ASTER are impractical with current technologies.

The single most encouraging recent development in satellite HSI has come from a US military experimental program. The Advanced Responsive Tactics Effective Imaging Spectrometer (ARTEMIS) sensor was developed the Air Force Research Laboratory. It was deemed to be so useful that it was converted from a test platform to operational status. It is believed to have a spatial resolution of 3-5m (the official numbers are classified but estimates have been made by people familiar with the unclassified aspects of the design). The importance of ARTEMIS is that it shows that high spatial resolution satellite hyperspectral data with “good” SNR can be collected. Whether the technology can be commercialized or data made available to general users remain to be seen.
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The most likely hyperspectral satellite system to achieve orbit and operational status in the near term is EnMap, a German system anticipated to launch in 2015. EnMap will have a reasonable swath width of 30Km (compared to 7Km for Hyperion) and ground resolution of 30m. With the relatively coarse ground resolution EnMap is likely to be primarily used for district to regional scale studies. It will also be useful for general geologic mapping in remote areas such as the Canadian north.

Conclusions

Remote sensing methods are progressing toward providing quantitative results and 3D data sets that will impact exploration, mine planning, and mine operations. The drivers behind this are hyperspectral core imaging and the use of chemometric analyses. In addition, advances in thermal spectroscopy are allowing minerals invisible to visible to shortwave infrared wavelengths to be resolved. Although lagging behind airborne and ground methods, satellite hyperspectral imagery shows more promise than ever.

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POSTER PRESENTATIONS
High Precision Early Time Airborne EM Data

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Introduction

In the last 10 years airborne time-domain electromagnetic (TDEM) systems have been deployed as a sling load beneath helicopters. This configuration offers advantages over fixed wing systems including elimination of noise from the aircraft, the ability to drape terrain at low altitudes and opportunities to improve transmitter-receiver geometry.

In 1998 at Aarhus University a group of researchers with a need for an airborne method to map subtle contrasts with a high degree of accuracy set out to develop a high precision TDEM helicopter-borne system. Early in the design and engineering phase several elements were identified as being crucial to building a high precision system. Some of the key factors were:

- Rapid turn off of current in the transmitter loop
- Collection of data as close to turn off as possible
- Low noise
- A high degree of repeatability

It was also recognized early on that to increase the accuracy and resolution of the final results the TEM data would need to be accompanied by certain types of auxiliary data. This supplementary data was required to provide information about system altitude variations, inclination of the transmitter and receiver coils, precise GPS location and variations in waveforms.

The system resulting from this work is the SkyTEM TDEM method. During the last five years one of the primary focus points for the R&D team has been on accurately measuring the secondary signal in the receiver at very early time gates by turning off the current in the transmitter as rapidly as possible. This paper will present and discuss some of the elements identified as crucial for obtaining high resolution TDEM data.

Theory

The shape of the transmitter waveform is a key parameter. The waveform must be accurately defined and highly stable in order to reduce uncertainties in the forward model. Furthermore, the shape of the applied waveform determines the properties of the measured response. Considering that an impulse response contains more information about the near surface resistivity structure than the step response, when recorded over the same time interval (Raiche, 1983, “Discussion”), it is preferable to record impulse responses as compared to step responses when the purpose of the survey is to map both the near surface and the more resistive geology.

Due to the non-negligible transmitter coil self-inductance, airborne TEM systems cannot transmit a perfect square waveform, and the current turn-off is instead typically designed to closely approximate a linear ramp-down (as shown in Fig 1).

![Figure 1: Idealized current waveforms for step, impulse and pulse type transient recordings in the case of an induction coil receiver. (from Ravenhurst (2001))](image)

The resulting response is referred to as a pulse response (Ravenhurst, 2001). The off-time pulse response is characterized by having the properties of a step response at early times and an impulse response at late times (relative to the width of the turn-off ramp). Considering the following convolution identity, it is clear that the off-time pulse response is indeed the difference between two ideal step responses separated in time by the width of the turn-off ramp.

\[ V_{\text{obs}}(t) = V_{\text{step}}(t) \times \frac{d^2v(t)}{dt^2} \]

(Nyboe et al., 2011, in review)
A short linear turn-off ramp therefore yields a more rapid transition to the desirable impulse response type signal properties as compared to the long linear turn-off ramp.

For a linear turn-off ramp, the definition of a zero-time relative to the transmitter turn-off and positioning of the gates can naturally be chosen as the end of the linear part of the turn-off ramp, as this is the exact time where the second step response is generated. See Figure 2.

![Figure 2: Sketch of short and long turn-off ramps and relative positioning of early time gates. The proximity of the first gate to the end of the linear part of the turn-off ramp is mainly limited by the unavoidable exponential current-decay.](image)

It is well established that the primary factor determining the near-surface resolution is the ability to measure the earth response at very early times (Spies, 1989 & Fig. 3).

![Figure 3: Difference in response for two-layer 1D models with different first layer resistivities. Information about the upper layer is contained mainly in the early time gates.](image)

The recording of very early time gates is challenging for several reasons. First, the very last part of the current turn-off cannot be maintained as a perfectly linear ramp, which results in a lingering exponential current decay with a duration determined by the combination of the transmitter coil damping resistor and self-inductance. During this time, a primary field contribution is superimposed on the secondary field, which complicates the estimation of the secondary field decay. Secondly, the recording of very early time transient behavior requires a very large bandwidth of the applied receiver coil and recording equipment in order to reduce the distortion of the transient response.

![Figure 4: Panel a) shows the distorting effect on an off-time earth response of applying 1st order low-pass filtering with different cut-off frequencies (receiver coil in central loop position). Panel b) shows the effect of low-pass filtering with a 15 kHz filter for different levels of primary field coupling (from Christiansen et al., 2011)](image)

An insufficient bandwidth likewise introduces the problem of low pass filtered response from the primary field extending well into the off-time and obscuring the earth response as demonstrated in Fig. 4b.

A rigid platform
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The SkyTEM system is configured with all sensors mounted on a rigid carrier frame as shown in Figure 5. In order to obtain high lateral and vertical resolution the carrier frame is drape flown over the surface as close, and as safely, as possible.

![Figure 5 The rigid carrier frame showing the position of sensors.](image)

The system can be configured with wide band receiver system of up to 300 kHz that enhances resolution in the nearer surface. Alternatively a low band pass filter can be employed when near surface resolution is less important and deeper targets are mapped by late time gates after 1 ms.

By measuring and ascertaining the position and the inclination of the all sensors the data can be corrected accordingly during the processing and inversion of the data.

There is no drift or need for high altitude corrections and the waveform and auxiliary data are collected together making data collected by the SkyTEM method repeatable. This is particularly relevant when two or more contiguous areas are flown at separate times as data from the two areas can be stitched together seamlessly. It is also important in base line studies as change-over-time comparisons are reliable and potentially more revealing. Economic benefits are realized as well since elimination of high altitude calibration flights means helicopter time, fuel, wages and available daylight are not negatively impacted when low ceiling or bad weather restricts calibration flights and survey productivity.

Conclusions

In the last five years there have been significant improvements in airborne TDEM transmitter turn off times and receiver early time measurements. When used in combination with accurate system positioning information and wideband receivers that minimize distortion from the primary, data resolution and accuracy are greatly enhanced.

These are important factors when, in addition to identifying distinct strong conductors, there is a need to map subtle changes, such as weak resistivity contrasts between earth layers. Mapping laterally as well as to depth in high resolution makes the creation of reliable 3D data presentations. Noise free highly accurate data is a perfect input for calibrating and constraining numerical geological models.

The collection of ultra high resolution TDEM data allows for more confidence in analysis, interpretation and decision making that all play a significant role in the financial implications of any resource exploration program.

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Typically the system is configured with four plus one transmitter turns. The single turn, with a thin wire and less self-inductance, transmits less current and permits a very rapid turn off (4-5 usecs). The four turns are used to transmit a high current that is turned off less abruptly. The two decays are combined providing concurrent soundings based on very early time gates as well as late times.

The rigid frame allows for a well defined geometrical configuration. This makes it possible to position the EM receiver coils so that it is close to zero coupled to the primary field in the transmitter loop. This damping-effect is important as it allows for recording data very soon after turn off. Furthermore the rigid configuration makes it possible to know the relative position of the transmitter and receivers. This serves to enhance data reliability.

By measuring and ascertaining the position and the inclination of the all sensors the data can be corrected accordingly during the processing and inversion of the data.
High Precision Early Time Airborne EM Data


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Capacitive electric field sensors for electromagnetic geophysics

Summary

Over the last ten years, GroundMetrics, Inc., and QUASAR Federal Systems, Inc. (QFS) have developed the first commercial range of next generation electric (E-) field sensors that employ a chemically inert electrode and couples to the E-field via capacitive coupling. The new type of sensor, known as the eQube™, can easily function in historically challenging, high resistance terrains including desert, frozen ground, gravel and caliche without the need for burial of the electrodes or modification of the ground while still offering performance equivalent to that of conventional porous pot technology. The eQube’s capabilities allow electromagnetic (EM) surveys to be conducted in terrains for which such measurements were previously difficult or not possible, and can simplify and expedite E-field surveys in all terrain types. Telluric cancellation via remote reference further improves E-field data quality. Examples will be shown for comparisons of E-fields measured with our sensors and with extant sensors.

Introduction

Electromagnetic (EM) geophysical methods require accurate and reliable measurement of the electric (E-) fields in order to characterize the subsurface from the near surface down to several kilometers depth. To date, porous pot or metal electrodes used to measure the E-field have had significant measurement and operational limitations that have prevented reliable E-field data collection in very resistive terrains, such as those covered by ice, tundra, sand, gravel and caliche (e.g., Thiel, 2000). Yet, many such terrains are very prospective, so the ability to accurately and reliably measure the E-fields in land and yet-to-be-developed airborne EM systems opens up new opportunities for EM-led mineral exploration in prospective regions of Australia, Africa, Canada, Chile, Mongolia, Peru, Russia, and the US.

Over the last ten years, GroundMetrics, Inc., and QUASAR Federal Systems, Inc. (QFS) have developed a new type of E-field sensor that employs a chemically inert electrode and directly couples to the electric field via capacitive coupling (Matthews et al., 2005). Unlike other capacitive sensors (e.g., Kuras et al., 2006), our sensors are broadband, and have been deployed in a variety of land, airborne and marine EM geophysical systems. Our sensor employs ultra-high impedance feedback techniques to provide unprecedented accuracy in measuring the electric field from 0.1 Hz to 100 kHz. The sensors contact their surrounding medium via an insulated metal surface, which under normal atmospheric or marine conditions forms a protective and self-healing oxide. Airborne, these sensors have enabled the first tri-axial measurement of the E-field in air at the μV/m level. In all land and marine tests to date, our capacitive sensors have exceeded the performance of Ag/AgCl galvanic electrodes, and no measurable electrochemical reaction in any of the deployed sensors have been observed since initial tests began in 2006.

Theory for capacitive E-field sensors

Capacitive coupling is a purely EM phenomenon, which, to first order, has no temperature, ionic concentration or corrosion effects, and thus provides unprecedented measurement fidelity. The absence of an electrochemical reaction with the ground can potentially provide an operational lifetime of tens of years, even when exposed to extreme environmental conditions. In addition, ultra-high impedance feedback techniques can be implemented in a capacitive sensor to enhance measurement fidelity even further. The general measurement circuit architecture for capacitive sensing is shown in Figure 1. The potential of the earth is represented by the voltage $V_{source}$. The sensor couples to this potential via the resistance of the earth, $R_e$, and the electrode coupling impedance represented by $C_{couple}$ and $R_{couple}$. $R_e$ is dominated by the ground in the immediate vicinity of the electrode while $C_{couple}$ and $R_{couple}$ are set by the protective oxide layer on the electrode. The goal is to make the sensor output as independent as possible of changes in the $R_e$, while operating in the regime of zero electrochemical coupling ($R_{couple} = \infty$). The key issue with designing such a sensor is there is no resistive path to...
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ground at the input to carry the amplifier input bias current. As a result, the current flows onto the electrode capacitance \( C_{\text{couple}} \), increasing the voltage at the amplifier input until it saturates. The challenge is to provide a resistive path at the amplifier input (not shown) without essentially shorting the signal into the amplifier. This has been addressed by utilizing a novel patented feedback scheme (Krupka, 2004). The result of aiming to operate in the fully capacitive regime over a wide range of \( R_e \) is that \( R_{\text{in}} \) must be very large (> 100 GΩ). However, making \( R_{\text{in}} \) so large means that the sensor upper frequency response becomes dominated by \( C_{\text{in}} \). For example, a typical value of \( C_{\text{in}} \) for a well-designed amplifier circuit connected to a capacitive plate is 10 pF to 20 pF. For \( C_{\text{in}} = 10 \) pF, a ground impedance of 1 MΩ will result in an upper frequency 3 dB point of 16 kHz. Thus, if the ground impedance were to change from 1 MΩ to 100 kΩ due to rainfall, such a sensor could produce gain and phase errors. To address this, GMI has incorporated negative feedback methods that reduce the effective value of \( C_{\text{in}} \) from ~ 10 pF to less than 0.3 pF.

Example

Figure 2 shows the measured amplitude and phase response of a prototype sensor to a known applied potential in \( R_e \) ranging from 100 Ω to 4 MΩ over frequencies from 0.1 Hz to 100 Hz. The average difference in gain is within 0.2% to 100 Hz while the phase difference is less than 1 mrad to 100 Hz except for very dry sand, for which it is still less than 5 mrad. This property opens the door to E-field sensors that can be permanently installed in very harsh environments and accurately record data even when the ground conditions vary widely, for example due to rainfall, temperature (e.g. ice or snow), ground compaction, and ground fissuring.

Geophysical applications

The Qmax EM3 marine sensors developed by QFS have been in commercial use for marine magnetotelluric (MT) and controlled-source EM (CSEM) surveys for oil and gas exploration. Numerous side-by-side tests have been performed with marine EM contractors and research providers, to which the Qmax EM3 has demonstrated superior performance. The eQube land sensors developed by GMI are being used for a variety of EM geophysical methods, including magnetotellurics (MT), audiomagnetotellurics (AMT), induced polarization (IP), and controlled-source EM (CSEM). Professor Frank Morrison of the University of California at Berkeley recently led an industry consortium for the side-by-side testing of GMI’s eQube sensors with porous pots in a semi-arid environment. This consortium was sponsored by Barrick Gold, Cameco, Newmont, and Vale. The results are currently embargoed to consortium sponsors only.

Figure 2. Experimental data for a pair of eQube™ sensors measuring the E-field in earth varying from 100 Ω to ~ 4 MΩ. The average difference in gain over the 4 x 10^4 range of resistance is within 0.2% to 100 Hz while the phase difference is less than 1 mrad to 100 Hz except for very dry sand, for which it is still less than 5 mrad.

Conclusions

GMI and QFS have developed innovative capacitive E-field sensors that, for the first time, enable accurate EM surveys in historically challenging terrains. The ability to accurately and reliably measure the E-fields in land and yet-to-be-developed airborne EM systems opens up new opportunities for EM-led mineral exploration in prospective regions of Australia, Africa, Canada, Chile, Mongolia, Peru, Russia, and the US. The sensors also enable long term, permanent E-field monitoring for acid mine drainage, contaminant mapping, enhanced oil recovery (EOR), carbon sequestration, hydraulic fracturing, and infrastructure integrity.
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Capacitive electric field sensors for electromagnetic geophysics
Surface distribution of uranium using geophysical results in the asfar thwelil, northern arabian shield

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Recent field geologic mapping supported by magnetic and radioactive surveys provide a new view on uranium distribution in the Asfar Thwelil area. Geologically, the Asfar Thwelil belongs to the Shammar Group, and consists of a rhyolite dome dissected by several faults with different trends. Most prominent of these transgresses the dome at N120° strike, 81° dip and N60°E dip direction. In addition, another major fault trend found in the area has N155° strike, 77° dip and N50°E dip direction. Two groups of uranium veins intrude the dome: (a) the veins rich in fluorite are associated with the main faults which trend N120. This group consists of black uranium oxides representing gummite and uraninite and constitutes by far the most important uranium source, while (b) the second group is associated with the faults that trend N155°, and is represented by uranium oxides such as uraninite and uranophane together with purple fluorite. It can be clearly seen from this study that the Najd Fault System is controlling the main radioactive minerals in the Asfar Thwelil area.
Innovations in Cross-hole Borehole DCIP Visualization
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Summary
In recent years significant advancements have been made in the development of borehole technologies to image off-hole resistivity and chargeability. These technologies aim to improve the understanding of the off-hole extent or presence of disseminated mineralization, in much the same way as borehole electromagnetic methods have been used over the past few decades. Despite the technological advances in data acquisition, data processing methods that enable the geologist to easily visualize the spatial location of borehole profiling and cross-hole tomography results continue to remain a challenge within the industry.

This paper presents the results of an Occam-type 2D inversion innovations that has been applied to high resolution EarthProbe cross-hole DCIP tomography data. The inversion algorithm is based on complex algebra to invert the resistivity and chargeability simultaneously. In undertaking 2D tomographic inversion in a mining scenario, where borehole configurations are typically 3D, consideration is given to the applicability of the 2D inversion algorithm. Enhanced spatial visualization and correlation with geologic information is achieved by subsequently presenting inversion results using a 3D platform, thus providing a product that can be readily used by geologists to guide exploration activities.

Introduction
Borehole resistivity and chargeability (DCIP) imaging can provide valuable assistance to mining exploration programs. In-hole data can provide information on the DCIP signatures of key lithologies and mineralization, thus enabling improved understanding of which geophysical signatures reflect geologic features of interest. Off-hole data provides information on the spatial extent and orientation of in-hole features, as well as identifies off-hole targets.

Spatial resolution is most effectively achieved through electrical DCIP tomography between boreholes. Cross-hole tomography is achieved through quadrupole measurements using many combinations of current (AB) and potential (MN) electrode positions to provide a very high resolution image.

Multi-electrode data acquisition system and adequate 2D/3D inversion algorithms have been developed and increasingly applied in resistivity/IP surveys over the past two decades in the environmental and geo-engineering field. In contrast, 2D and 3D inversion applications for mineral exploration has been limited due to challenges posed by non-planar borehole geometries and necessarily large mesh sizes which significantly complicate the inversion process. The adaptation of an Occam-type 2D inversion algorithm is tested on high-resolution EarthProbe cross-hole data to assess its ability provide geologically representative information in the mining/exploration field.

EarthProbe Borehole DCIP Technology
The EarthProbe DCIP system has emerged from a resistivity technology developed by Geoserve in Germany for geotechnical and hydrogeologic applications. The University of Toronto, through CAMIRO funding, and Caracle Creek, with the assistance of IRAP funding, tested and adapted the system for mining applications (Qian et al, 2007; Palich and Qian, 2011). The resultant EarthProbe DCIP system is successfully enabling geophysicists to adjust their scale of surveying to the scale of geologic features applicable to modern exploration projects. EarthProbe’s narrow electrode spacing and ability to operate in multiple surface and borehole configurations facilitates both improved target delineation and characterization of host rock and mineralization signatures.

EarthProbe uses borehole cables with up to 24 electrodes spaced at either 4 m or 16 m with the capacity to profile boreholes up to 250 m or 400 m, respectively. Data are collected with the electrode array in a single borehole in which the current and potential electrode setup is the same as for a surface Schlumberger survey (Figure 1).

Vertical profiles provide information regarding in-hole features and can detect off-hole features up to 100 m from the borehole. The resistivity and chargeability information collected at the borehole can also be used to provide realistic bulk rock properties of the host rock and mineralized zones for improved characterization.

The EarthProbe system can also be configured to collect tomographic images. Cross-hole tomography, in which both current electrodes and potential electrodes are placed in two boreholes, can provide detailed information about resistivity distribution between the boreholes and assist in determining the orientation and connectivity of in-hole features between boreholes (Daniels 1977; Daniels
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Challenges in Off-hole Visualization

Figure 3 presents “pseudosections” of the vertical profiling and cross-hole tomographic imaging results collected from two boreholes with a surface separation of 123 m. The two boreholes are non-planar with Borehole 1 oriented at an azimuth of 104° and a dip of 67° and Borehole 2 oriented at an azimuth of 95° and dip of 71°.

Vertical profiling identifies a low resistivity, high chargeability in-hole response in Borehole 1 associated with known gold mineralization and a predominantly off-hole response in association with narrow, low grade mineralization in Borehole 2. A second off-hole response is partially imaged below the in-hole anomaly in Borehole 1 and above the aforementioned feature in Borehole 2. The “bullseye” response in the tomography suggests a weak electrical and chargeable connectivity between the mineralized zones.

While pseudosection presentation provides some indication of the features present in association with the boreholes, two inherent challenges exist in visualising their spatial orientation:

- Single borehole vertical profiling does not confine the location of an anomaly within 3D space and therefore may represent the electrical response at that depth and distance from anywhere within a 360° radius of the bore.
- Cross-hole tomographic data is necessarily presented as the AM-midpoint (X-axis) and BN-midpoint (Y-axis) effectively causing one borehole to be plotted against the other, which is spatially counterintuitive.

While the simple solution to these issues may be to conduct a 3D inversion of the data, several limitations often exist that prohibit 3D inversion from representing a viable processing option in many situations:

- In the absence of a 3D representative distribution of boreholes (nominally five or more) inversion artifacts are commonly generated;
- The narrow electrode spacing used to achieve rock property characterization combined with wide borehole spacings necessitates very large mesh generation because vertical and lateral mesh proportions must be maintained for inversion stability. This results in long inversion run-times that may not be practical for the delivery of useful results to support exploration programs;
- Typical non-vertical, non-parallel borehole orientations further add complexity to mesh generation and size.
Rapid 2D inversion of the cross-hole tomography data was undertaken on the example data to test its ability to resolve some of the spatial visualization issues previously identified.

2D tomography inversion results were obtained using a complex resistivity inversion algorithm originally proposed by Kemna and Binley (1996) and discussed in detail in Kemna (2000). The algorithm directly solves for conductivity magnitude and phase by consequent adoption of complex calculus. Although the approach is analogously applicable to 3D imaging (Shi et al., 1998; Yang et al., 2000), we assume that the region of interest may be represented as a 2D distribution. This is considered a fair approximation for the data presented because it exhibits a layered sequence of sediments with predominantly vertical rather than lateral conductivity variations. Accordingly, 3D effects in impedance data collected in a vertical image plane at the site are expected to be insignificant.

The tomography algorithm was developed for geotechnical and environmental applications where boreholes are almost always vertical and therefore all electrodes between boreholes can be defined on a single plane. This assumption does not hold true for most mining scenarios, including our example data. To undertake the 2D inversion for our data, a vertical plan was specified and then all electrode positions were projected onto this plane. Ideally, the boreholes should be on or closely aligned to this plane for the inversion results to accurately honour the data.

Results of the 2D inversion are presented in Figure 4 for resistivity. The accuracy of the model can be evaluated from the data presented in Figure 5 where the value of the measured data is plotted on the X-axis and the value of the predicted data is plotted on the Y-axis. Here we can see that the data is fitted reasonably well and there is no statistical bias in the data fit. If all the data are fitted perfectly, the data point should all be on the 45° slope red line.

In support of the strong statistical correlation, the inversion results honour the features identified in both the single borehole vertical profiling and cross-hole tomography pseudosections. An in-hole feature is modelled in Borehole 1 at 80 m and a weaker in-hole feature is modelled at 140 m in Borehole 2. Additionally, an off-hole feature is imaged below the mineralized zone in Borehole 1 and above the mineralized zone in Borehole 2, consistent with the single borehole profiling results. This off-hole feature between the two mineralized zones appears to provide the source of electrical continuity between the boreholes that was identified by the cross-hole tomography.
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The final stage of the interpretation involves reconstructing the 3D orientation of the data to reflect the non-vertical plane from which the data were collected. The GoCAD platform was used for this purpose. Figure 6 presents the results of this process, with the 2D chargeability inversion results draped between the boreholes. The GoCAD platform further enables the geophysical inversion to be presented along with geological information including lithology and gold assay concentration. The result is an enhanced ability to spatially visualise the relationships between the DCIP data and key geologic exploration parameters, thus facilitating improved targeting using the borehole data.

Figure 4: Results of the 2D cross-hole tomography inversion for resistivity.

Figure 5: Scatterplot depicting the error between the measured and calculated data from the 2D resistivity inversion. The 45° sloped red line represents perfect agreement between the measured and calculated data.

Figure 6: 3D representation of the 2D cross-hole tomography chargeability inversion, presented with comparison lithology (along the boreholes), and gold concentration (projected outwards from the boreholes).

Conclusions

The EarthProbe high resolution DCIP system has been demonstrated to be able to collect and meaningfully invert cross-hole tomography data. Despite the necessity to extrapolate cross-hole data off-plane using 2D inversion algorithms, tomographic inversion results are demonstrated to provide accurate spatial reconciliation of the information gathered by both single borehole profiling and cross-hole tomography. The ability to subsequently project the inversion results in true 3D space facilitates the geologic interpretation and spatial visualization process necessary to make cross-hole tomography a valuable exploration tool for the exploration and mining industry.

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P- THEM response for geologically active and non-active areas
Anton Vetrov, Pico Envirotec Inc.

Summary

Time Domain Electromagnetic air-borne systems are widely used in geological exploration for minerals associated with conductive rocks, underground water resources and geological underground mapping.

The newly designed P- THEM system has been test-flown at the Reid Mahaffy geological test site in Northern Ontario, Canada; and then over an area near Newmarket, north of Toronto. While the flight in Reid Mahaffy was made to verify real characteristics of the system: stability and repeatability of results, the flight over the Newmarket area, represented with thick Quaternary sediments, was made to verify correct operation of the EM system with a magnetometer and gamma-ray spectrometer.

Interesting and significant response of the TDEM observations to agricultural and engineering objects were observed during the Newmarket test flight. These results demonstrate a possibility of TDEM method for environmental tasks, such as detection of surface and near surface pollution, grounding of metal constructions and other.

Introduction

While developing and adjusting the P- THEM system the author had the opportunity to perform research in the field of Time Domain Electromagnetic methods and its applicability to geological and non-geological tasks.

The results of the flight tests of the system performed in 2010 show the possibility of the TDEM to detect underground conductors, as well as an opportunity to use the method in environmental and engineering tasks.

System description

The P- THEM Time Domain Electromagnetic system developed by Pico Envirotec Inc. is based on technologies developed by THEM Geophysics Inc.

The P- THEM system consists of a loop-transmitter assembly, powered either by a motor generator (APU version) or a DC to DC converter, using DC power generated by the rectification of 400 Hz 125VAC helicopter generator.

The transmitting loop is designed as a 4 turn nonagon. The loop and the attached transmitter are designed to produce a peak magnetic moment of approximately 250,000 NIA requiring constant generator power of approximately 3.5kW at 18VDC. The pulsed current is a semi sinusoidal shape. The pulse length is generally adjusted to be close to the quarter wavelength of the chosen base frequency, which can be adjusted to 50 or 60 Hz environment.

The system is equipped with two different sensors:

- A gondola containing a three axis coil assembly mounted on the tethered mast in the mid-point of the tow-cable between the transmitter loop and helicopter.

- A dB/dt receiver (coil “A”) mounted above the rear section (apex) of the Transmitter loop on a composite frame which is attached directly to the loop “apex” segment. It allows mechanical adjustment of the “A” coil to back out most of the primary field.

In a typical geophysical survey the transmitter is elevated about 30 meters above the ground. The slight positional offset of the receiver and transmitter projected centers provides signal related to the orientation of the gondola against the main loop, which can be useful while processing and interpretation of data (Figure 1).

Figure 1: P- THEM geometry

The center gravity point of the attachment of the transmitter to the tow cable allows the system to remain horizontal for a very wide range of survey speed, though the standard survey speed is 55 to 60 knots.
Reid Mahaffy tests

The Reid Mahaffy Test Site is located in the Abitibi Subprovince, immediately east of the Mattagami River Fault. The area is underlain by Archean (~2.7 b.y.) mafic to intermediate metavolcanic rocks in the south, and felsic to intermediate metavolcanic rocks in the north, with roughly an east-west striking stratigraphy. The test site was created in 1999 by the Ontario Geological Survey, initially to enable various airborne geophysical systems to demonstrate their basic performance capabilities.

The general geology of the site contains known overburden thickness based on almost 50 diamond drill holes, with geological logs available for these. Each drill hole tested a conductive target, typically massive sulphides and graphite with minor copper and zinc mineralization.

The survey flights over Reid Mahaffy test site were performed in April 2010. The altitude and direction tests were flown on three lines over the test survey area. The lengths of test lines were approximately 5.3 km with a line spacing of 200 m. All test lines were flown with the transmitter elevation 30 meters above the ground and a survey speed of approximately 55 knots.

The conductive body under overburden can be seen on the grid of the observation results at different decay time channels (Figure 2). One can see that early time windows represent overburden which correlates with the known thickness. The conductive body appears on later time channels and remains detectable over noise level.

The electrical inversion of the results allows distinguishing a structure of several vertical conductor slices, forming the conductive body (Figure 3).

Newmarket test

The area selected for tests is a highly developed urban zone in the Greater Toronto Area, Ontario, Canada.

A large number of farms, private cottages and horse racetracks are presented in this area, as well as two railroads tracks traversing the test area in a N-S direction, a train yard, a small factory and a high voltage power line traversing the test area in a N-S direction at the east.

Geologically, the area is represented with Quadrennial sediments with underlying bedrocks of the Ordovician formation. The main area is represented with sand and gravel of Glacial lake deposits with River and Moraine deposits at the west end of the survey block.

The main purpose of the test flights was to check the functional integration of the P-THEM system with a Magnetometer and Gamma-Ray Spectrometer system.
P-THEM response for geologically active and non-active areas

The data indicated a very good agricultural response of the P-THEM system after the interpretation of the observed data (Figure 4).

A large amount of salt is being spread on the roads of Southern Ontario during the winter season. The salt floats to the sides of paved roads with melted snow and precipitation and starts diffusing into the soil around it. The conductivity of surrounding salted soil is higher, and we can see it on the observed data. Additionally, we can distinguish the grounded high voltage towers of the powerline in the east side of the observation area, the factory buildings in the middle of the block and other on-ground constructions in the west side of the block.

The achieved results of the survey show the possibility of the TDEM airborne system for applications in characterization of environmental and engineering properties over large areas of interest.

Conclusions

The results achieved after the test flights performed with the P- THEM system showed extended possibilities of the airborne time domain electromagnetic method for geological, environmental and engineering applications.

The P- THEM observations on the Reid Mahaffy geological test site allow distinguishing the overburden, conductive body and the structure of the conductive body.

The test flights in the “non-geological” area North of Toronto allow us to determine possibilities of the airborne Time Domain Electromagnetic method to application of geological, environmental and engineering tasks.

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Mega-cell 3D AEM inversion
Glenn A. Wilson*, Leif H. Cox, TechnoImaging, Michael S. Zhdanov, University of Utah and TechnoImaging, and Matthew Hope, Barrick Gold

Summary
At Exploration '07, Macnae (2007) reported that “while the formal inversion process is practical for targets already identified as being of interest, it [3D airborne electromagnetic (AEM) inversion] is unlikely to be routine in the near future as a means of processing complete surveys.” In the few short years since Exploration '07, mega-cell 3D AEM inversion of entire surveys with a moving sensitivity domain has emerged as the most significant innovation in AEM interpretation. Not only is 3D AEM inversion now a practical consideration for any scale of survey, but it has already invoked improved understandings of major mineralization systems and has challenged exploration strategies. Since August 2010, the lead authors have complex over sixty projects for Aerodat, AEROTEM, DIGHEM, GEOTEM, HELITEM, HoisTEM, MEGATEM, RepTEM, RESOLVE, SkyTEM, SPECTREM, TEMPEST, and VTEM surveys from Australia, Canada, Finland, Ghana, Peru, Tanzania, the US, and Zambia. At current trends, we expect to report of giga-cell 3D AEM inversions by Exploration '17.

Introduction
Geophysicists know and accept that geology is inherently 3D, and is resultant from complex, overlapping processes related to genesis, metamorphism, deformation, alteration and/or weathering. Yet, the AEM community to date has not fully accepted that geophysics should also be 3D, and has long relied on qualitative analysis, conductivity depth imaging (CDIs) and/or 1D inversion. There are many reasons for this unfortunate deficiency, not the least of which has been the lack of capacity of historic 3D AEM inversion algorithms. As eluded by Macnae (2007), these have not been able to invert entire surveys with sufficient resolution in sufficient time so as to practically affect exploration decisions. Figure 1 effectively summarizes the history of 3D AEM inversion. As our pragmatic metric of measuring 3D AEM inversion capacity, we define the AEM problem size as the product of the number of cells in the 3D earth model and the number of AEM stations modeled. While 3D modeling kernels have varied between authors, 3D AEM inversion has been limited to kilo-cell 3D models with tens to hundreds of stations. To be practical, it has been suggested that deposit-scale kilo-cell 3D inversions could be used for those parts of AEM surveys where 1D methods were deemed to have failed (e.g., Raiche et al, 2007).

At the 2007 SEG Annual Meeting in San Antonio, merely weeks after Exploration '07, Cox and Zhdanov (2007) introduced the concept of a moving sensitivity domain. According to this concept, one only needs to calculate the responses and sensitivities for that part of the 3D earth model that is within the AEM system’s sensitivity domain, and then superimpose the sensitivities for all footprints into a single, sparse sensitivity matrix for the entire 3D earth model. By doing so, Cox and Zhdanov (2007) were able to increase the AEM problem size by nearly five orders of magnitude without dividing the inversion domain into smaller subdomains. This clearly represented a paradigm change in 3D AEM inversion methodology. Using the same moving sensitivity domain methodology, Cox et al. (2010) used rigorous modeling for both the AEM responses and their sensitivities. This has also been extended to time-domain AEM (e.g., Cox et al., 2012). As shown by the black diamonds in Figure 1, this has made it practical for the authors to rigorously invert entire surveys with thousands of line kilometers of AEM data to mega-cell 3D models in hours using multi-processor workstations.

Figure 1. A plot illustrating progress in 3D AEM inversion from 1995 to the present, summarized in terms of AEM problem size, i.e., number of cells in the 3D model times the number of transmitters in the survey, as extracted from published papers. The introduction of a moving sensitivity domain by Cox and Zhdanov (2007) that has been fully realized by Cox et al. (2010, 2012) has resulted in the paradigm change from kilo-cell to mega-cell 3D inversion for all AEM systems. Examples of different 3D AEM inversions completed by the authors are shown by black diamonds.
Since August 2010, over sixty individual projects have been completed for Aerodat, AEROTEM, DIGHEM, GEOTEM, HELITEM, HoisTEM, MEGATEM, RepTEM, RESOLVE, SkyTEM, SPECTREM, TEMPEST, and VTEM data from Australia, Canada, Finland, Ghana, Peru, Tanzania, the US, and Zambia. Examples of 3D AEM inversion have been published for exploration under cover (e.g., Combrinck et al., 2012), gold (e.g., Combrinck et al., 2012), copper (e.g., Wijns, 2012), uranium (e.g., Fitzpatrick, 2012), porphyry copper (e.g., Pure et al., 2012), Pb-Zn (Jansen, 2012), Ni-Cu-PGE (Polomé, 2011), bathymetry (Vrbancich, 2012), and hydrogeology (e.g., Abraham et al., 2012). Numerous other examples remain unpublished. Rather than focus our case study on regional-scale surveys or any of those described above, we will present an example for a 3D AEM inversion for which there is ample geological control to verify the accuracy of the 3D inversion.

**Case study – Golden Ridge, Tanzania**

![Figure 2. Location map of the Lake Victoria Goldfields in Tanzania, with Golden Ridge marked by the red circle.](image)

The Lake Victoria Goldfields of Tanzania are one of the world’s most important gold provinces, estimated to represent more than 60 million ounces of gold in combined past production and known resources (Chamberlain et al., 2000). African Barrick Gold’s (ABG) Golden Ridge deposit is located between ABG’s Bulyanhulu mine, 30 km southeast and 55 km due north of ABG’s Buzwagi gold mine (Figure 2). Golden Ridge is situated in the Archaean Sukumaland greenstone belt which is part of the Tanzanian Craton and characterized by two sub-parallel arcs. The region’s topography is closely associated with geology, with low rolling hills largely comprised of erosionally resistant banded iron formation (BIF). Surrounding lowlands are dominated by Upper Nyanzian felsic volcanic, pyroclastics and sedimentary rocks. Due to the close proximity to Lake Victoria, black soils (mbuga) are a common surficial feature to lowland areas supporting farming and pastoral activities. Golden Ridge is a typical Archaean greenstone BIF-hosted deposit (after Robert et al., 2007). It is a sinuous BIF-supported ridge underlain by folded and thrusted (?) Upper Nyanzian sequence locally intruded by dikes and sills of quartz feldspar porphyry (QFP).

The focus of the following case study is the Golden Ridge Main Zone, also referred to as the Nyaligongo zone. Mineralization consists primarily of replacement style sulfidised BIFs, although a lesser but high grade quartz vein style of mineralization is superimposed on the auriferous BIFs. The sulfidised BIFs assume the tabular, stratiform character of the host rock, but in detail, the mineralized segments of the BIF ridges are characterized by structural complications and often by the presence of dikes and sills of quartz-feldspar porphyry. The deposit extends along a ridge-forming BIF unit for a strike length of over 2.5 km, although the Main Zone is best developed over a strike length of about 800 m. The BIF and its associated mineralisation dips about 60 degrees to the east with true thickness ranging between 15 and 30 m. The Main Zone is centred on a bend in the strike of the host BIF from a dominantly north-south orientation to a local N45E trend with mineralisation known to locally extend down-dip in excess of 300 m.

Sulfidation of magnetite bands by pyrite, pyrrhotite, and arsenopyrite are temporally and spatially associated with the precipitation of gold. Volumetrically, this mineralization is the dominant style of the Golden Ridge deposit and as a result, the deposit is broadly stratiform, following the host BIF. Total sulfide percentages vary significantly from < 2% to > 20% (and up to 50%) of the rock volume based on visual estimations, though no direct correlation can be drawn between total sulfide percentage and gold grade. The sulfide distribution is broadly zoned with pyrite dominant samples in the near surface environment giving way to increasing levels of pyrrhotite with depth. Arsenopyrite is a significant accessory sulfide throughout the deposit.

In 2006, 210 line km of VTEM data at 50 m line spacing were acquired perpendicular to the strike of mineralization at Golden Ridge to assess the conductive response of sulfides within the system for application to other exploration programs. The VTEM system was configured with a 35% duty cycle 25 Hz base frequency bipolar trapezoidal waveform of 187 A peak current. The transmitter loop was 26 m in diameter with four turns and the receiver coil was 1.2 m in diameter with 100 turns. Mean terrain clearance for the transmitter was 32 m. Data were processed to 5,500 stations, each containing 30 channels of dBz/dt measured from 60 ms to 9640 ms. The
Mega-cell 3D AEM inversion

observed data shows a discrete late time anomaly associated with the Main Zone with a decay constant up to 3 ms, confirming the conductive nature of sulfide replacement zones and a spatial association with gold. Other conductive features are noted throughout all time channels and are related to conductive cover soils infilling valley space between BIF ridges showing much lower time constant signatures.

Figure 3. Vertical cross-sections of the 3D conductivity model superimposed with gold grade and total sulphide (up to 25%) visual estimates. The conductivity values of the mineralization agree well with the measured 70 $\Omega$ m resistivity of mineralized drill core samples. An easterly dip is also recovered. Overlying conductive mbuga depths agree well with drilling data.

For 3D inversion (in August 2010), the earth model was discretized into 57,000 cells of 30 m by 60 m horizontal discretization that varied in thickness from 5 m near the surface to 30 m at 300 m depth. No geological constraints were applied a priori. The inversion required 4 hours to converge to a final misfit of 14% from an initial misfit of 63%. Figures 8 to 11 show examples of the observed and predicted data for the final model. As shown in Figure 3, our 3D VTEM inversion results successfully replicated the expected conductive response of the Golden Ridge system. The 3D model shows a shallow flat-lying conductive zone to a varying in depth from a few meters over ridges up to 40 m in lowlands areas and channels consistent with known mbuga depth from project drilling. Underlying this cover unit and coincident with pyrite dominant mineralization is a moderate-weak conductive zone which closely mirrors the gold mineralization envelope. Other moderate conductive zones such as seen to the west of the Main Zone are also confirmed to be sulfide-related by drilling. Deeper slices through inversion result show the coalescence of two main conductive zones slightly offset from shallow gold mineralization. Though these zones themselves do not appear to be strongly mineralized they are immediately beneath the most significantly mineralized parts of the system. The cause of this anomalous is believed to be abundant pyrrhotite and possible fold closure. However further testing is required to confirm this and assess untested potential related to deeper extensions of this anomalous zone.

The Main Zone reports with a moderately conductive feature from near surface with a prominent easterly dip. This easterly dip is supported by drilling as real and the conductive body agrees well with visual sulphide estimates where available. In Figure 4, we present an NNE looking perspective of the different conductivity iso-surfaces superimposed with the sulphide mineralization shells derived from drilling. A strong spatial relationship between the conductivity and sulfide mineralization is observed. To add confidence to the 3D inversion results, laboratory-based resistivity measurements were made on drill core samples. Mineralized samples had an average resistivity of approximately 70 $\Omega$ m, and these correlate very well with the conductivity values recovered from the 3D AEM inversion.

Figure 4. 3D view looking NNE of the 0.005 S/m (left) and 0.01 S/m (right) conductivity iso-surfaces and sulphide mineralization shells derived from visual estimates from drilling where available. A strong spatial relationship between the conductivity and sulphide mineralization is demonstrated.

Conclusions

In this paper, we have discussed the recent introduction of mega-cell 3D AEM inversion with a moving sensitivity domain, and its relevance to AEM-led mineral exploration. We can conclude that 3D AEM inversion is no longer an academic pursuit, but is a practical methodology that has made material contributions to exploration. At current trends, we expect to report of giga-cell 3D AEM inversions by Exploration ’17. With the emergence of multi-sensor airborne systems, the 3D inversion capabilities discussed in this paper provide the basis of multi-modal data mining (e.g., Fraser et al., 2012) and simultaneous 3D joint inversion (Zhdanov et al., 2012).
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