Paper 3

Ground Geophysics and Borehole Logging – A Decade of Improvements.

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ABSTRACT

The driving force in today's world is to do more, take less time and of course, do it cost effectively. This is while we try to discover the deeper, more subtle and more difficult ore deposits. This has encouraged different thoughts and processes in business which has changed the mindset of both the explorer and the miner. The challenges as stated in '97 which have been addressed during the last decade are: improved detectability, reduced noise levels, more resolution, improved success rate in discovery and improved delineation. The physical rock properties (measured from in-situ borehole techniques) are the quantitative link between the geology (rock type) and the high resolution geophysics (ground geophysics). This results in a single geological model (common earth model) which can be used for constrained inversion or true data integration and data interrogation in 3D with platforms like GOCAD. The process is now embedded in most exploration and delineation programs. New technologies developed from this quantifiable approach are squid technology, neutron activation, borehole gravity, array systems.

INTRODUCTION

Exploration has been directed at increasingly deeper and or more subtle targets. The paper will note some key improvements and new advances over the past decade. Key developments in ground geophysics over the past decade include:

- SQUID technology - ground EM provides a 4 fold increase in resolution
- Neutron activation - real time in-situ assays downhole
- Borehole gravity - true density values in hole and off hole
- Array systems such as Titan 24 (MT/IP/resistivity)

We believe the greatest improvement over the past decade has been the change of attitude within the industry to understand the need for full integration of geophysics into the common geological model. Ground geophysics survey data and in-situ borehole physical rock property data are fundamental tools needed to be truly integrated with other data into a common geological model and visualized in 3D. The mindset has changed as geophysical data inversion goes beyond producing geophysical maps. It provides the opportunity of defining a 3D litho-petrophysical earth model quantitatively consistent with the drilling, physical rock properties and measured geophysical data. The methodology is geared to getting results continuously from early exploration, discovery, delineation, evaluation and mining to create value. Geophysicists, geologists and engineers are working together on the same model in the same domain improving the single model able to handle all the complex datasets. Gocad (Geological object computer aided design) was developed from international research from a consortium of oil and gas companies. The platform is a true 3D GIS interpretive environment in which 3D spatial data, can be queried, manipulated and represented, so as to provide insight into geological problems (de Kemp 2004). The collaborative research undertaken by government, universities and industry have provided the funding, the thought processes, the data and case studies which prove the value of this approach in mineral exploration. Most companies are now routinely using this methodology. This paper will now outline how Rio Tinto has adopted this technology.

KEY IMPROVEMENTS

SQUID technology

The addition of the SQUID B field sensor to the standard time domain EM system appears to have been the logical progression of better quality EM data with improved S/N ratio and providing the conductance discrimination capabilities to detect long time constant (>>10ms) pyrrhotite hosted Ni, Cu sulphides at greater than 100m depths. The high temperature SQUIDS developed from the CSIRO and adapted to the Crone receiver have been in production for 6 years at Raglan and have discovered a number of new nickel deposits adding significant ore and value to Xstrata (Hughes 2006). (Figure 1)

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Anglo American plc proved low temperature SQUIDs (Super Conducting Quantum Interference Devices) have superior quality and sensitivity over high temperature squids. The LTS TEM SQUID system with a 4 fold increase in resolution over conventional systems detected the conductor controlling the mineralization of the Tropicana Au deposit in Australia.

Neutron activation

Many nuclear techniques commonly used in laboratories and the oil and gas industry have been successfully adopted to mineral exploration and mining applications. A review by Killeen (1997) summarizes the use of nuclear borehole logging methods for ore grade estimation and indicates that although the technology is suitable for mining applications it is not yet widely used.

Progress in the past decade on borehole neutron activation, specifically applied to hard rock environments, has been promising. Inco has invested in the development of the first pulsed neutron probe specifically for mining (King et al, 2006) reporting that preliminary modeling and tests suggest the possibility of quantitative in situ assays for elements such as Ni, Cu, Fe, S, Cr, Mn, and Al with accuracies ranging from 1% for major elements to 0.1% for minor elements such as Ni and Cu. As Killeen observed in '97 one of the disadvantages of borehole neutron activation is that the instrumentation is "rather bulky" thus limiting the use of the technology to large diameter boreholes, a fact that still holds true to this day. If or when a production mode neutron activation tool specifically designed for hard rock environments becomes available, it's most likely application would be grade control from large diameter blast holes (Figure 2). It is anticipated that the technology will improve over time leading to relatively slim in-situ assay probes that could be applied to mineral exploration.

According to King et al., (2006), cost savings could be achieved through improved grade control and also reduced delineation drilling cost through the use of non-cored drilling.

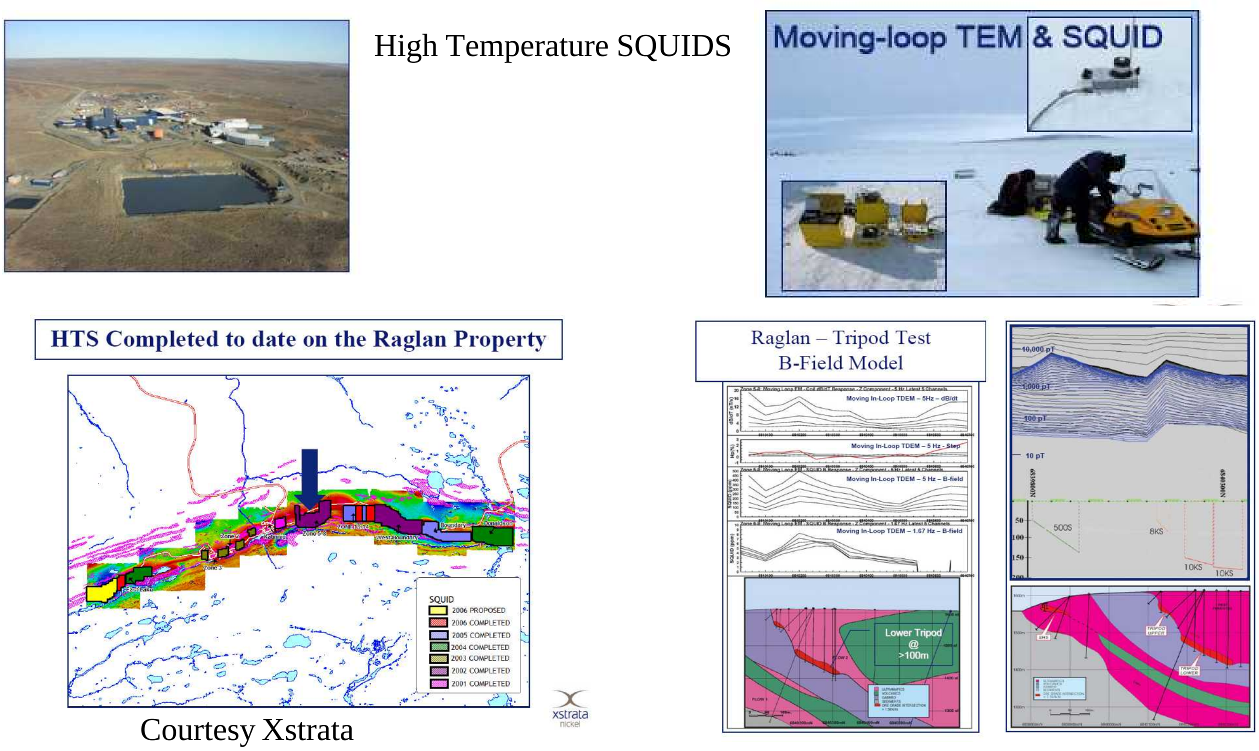


Figure 1: High Temperature SQUIDS

Figure 2: Neutron Activation. Prompt Gamma Neutron Activation multi-element assay system.

In addition to modeling geochemical processes, other applications are location of ore deposits and tracking of elements of environmental importance. This has been highlighted from collaborative research from universities, industries and government (such as predictive mineral discovery), to vastly improving the understanding of mineralized processes and providing a fourth dimensional approach of evolution of the geology. It is linking this type of information back to a common earth model that links geochemical processes to the physical rock properties and the measured geophysical data.

Borehole gravity

Borehole gravity measurements reflect the distribution of rock densities at depth with greater target sensitivity and resolution than surface measurements (Nind et al. (2007)). There are two types of basic information that can be obtained from borehole gravity measurements. Information concerning the distribution of densities, both the vicinity of the hole and remote from it, allows the explorationist to construct a three dimensional representation of the subsurface geology with improved spatial resolution and sensitivity for deeply buried structures. "Bulk density determination" of the rocks traversed by the borehole is a feature that is unique to borehole gravity. Knowledge of the bulk density of the ore and measured insitu provides a more accurate estimate of the tonnage improving grade control. It is very important to define accurate relative depths to determine accurate bulk density (Figure 3).

Array systems

Measuring the parameters DC(resistivity), IP(chargeability) and MT(magnetotelluric resistivity), Titan 24 measures to depths of 750 m with IP and to depths beyond 1.5 km with the MT data (Legault et al., 2002). These depths and multi-parameter data make this system the best option available for obtaining subsurface pre-drilling information related to geologic structure and for the direct detection of mineral deposits. Measuring multifold full waveform data and sophisticated digital signal processing, Titan 24 can highlight subtle features through thick cultural overburden making it ideal for mine site work and it provides a strategic advantage for grass roots projects. The application of the system over porphyry Cu deposits, Au deposits, massive sulphide deposits, uranium, Ni and diamond deposits. The current development of Titan 3D type acquisition systems will add a new dimension for the next decade (Figure 4 and 5).

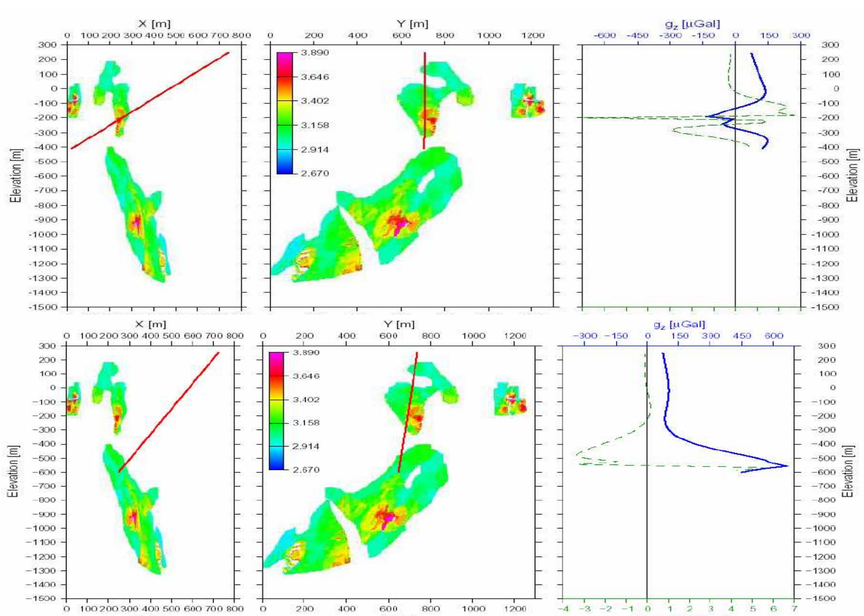
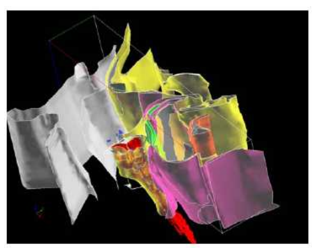


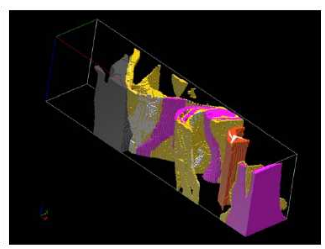
Figure 3: Scintrex Borehole Gravimeter. Scintrex: Borehole Gravity. Kelly Lake Ore Body. Courtesy of Scintrex and CVRDInco

Figure 4: Titan 24 Array Data Acquisition System

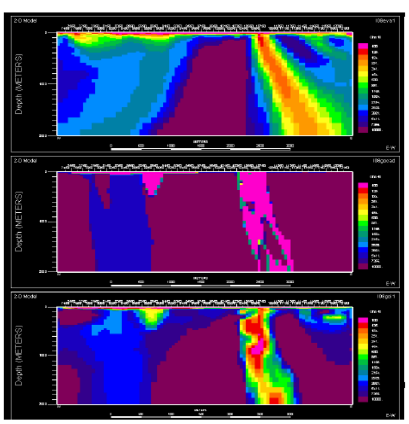
Courtesy of OMET, Quantec and Xstrata



Kidd Creek geological starting model



Physical property of the inferred resistivity at Kidd Creek



Unconstrained inversion

Constrains for inversion
Ground with applied resistivity information

Constrained inversion

Figure 5: Kidd Creek Constrained Resistivity Inversion of Titan 24 data

Seismic Tomography

Cross hole tomography is emerging as the most common technique for mapping sulphide distribution between drill holes. P wave velocity tomography was designed to outline the morphology and continuity of the massive sulphide zone since this zone contains a large portion of the metal in the deposit. This work was completed over the Voisey Bay deposit (Enescu et al., 2002).

Down hole Seismic Imaging

Downhole seismic surveys were undertaken at the Victor kimberlite as part of an Ontario Minerals Exploration Project (OMET). For a review of recent kimberlite exploration and delineation case histories use McMonnies (2005, 2006). The purpose of the project was to develop and demonstrate the effectiveness of down hole seismic imaging in mineral exploration. The specific objectives were to assess the potential of vertical seismic profiling (VSP) to complement information from boreholes to help define geometry and volume for evaluation purposes and to try to map the margin of the kimberlite. VSP data acquired from a borehole in the kimberlite with shot points located in the sediments are characterized by several reflections from sedimentary units and Precambrian basement. All VSP data were processed to extract the up going wave field from the direct arrivals. The VSP data provide an indirect method for determining the shape of the kimberlite by mapping truncations of the reflections from the sedimentary layers near the pipe. For a review of hardrock seismic VSP data acquisition and processing see Beatty et al. (2002), Bellefleur et al. (2000), Bellefleur et al. (2005), Cosma and Enescu (2002) and Cosma et al. (2005).

Change of attitude

The mineral exploration industry has traditionally searched for new ore deposits by using the geological, geochemical and geophysical characteristics of known ore deposits.

The challenge in ore body discovery is simply not to acquire information but to analyse, integrate and model it at all scales across the whole mineral exploration pipeline. Results show that it is proven methodology from the oil industry. The following picture shows this rather eloquently and they have built processes integrating drilling data in real time (Figure 6).

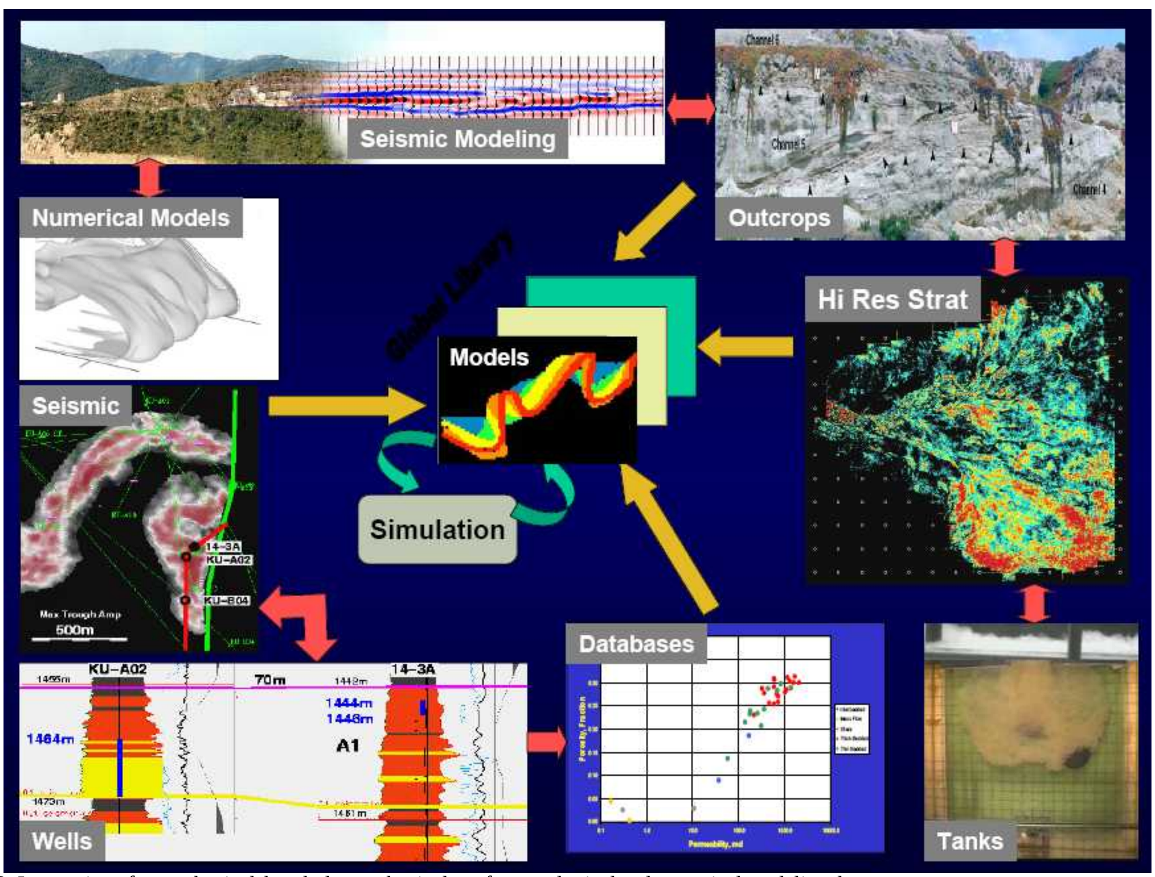


Figure 6: Integration of petrophysical, borehole geophysical, surface geological and numerical modeling data.

Collaborative research projects with people from government, universities and industry have created common goals and work flows to provide solutions and predictive capability of ore location. The key is to understand and model the process that give rise to ore deposition. The geological model can now be quantitatively linked to the physical rock properties which in turn link to the geophysical survey data (McGaughey and Morrison, 2001). It must be stated that the distinction between ground geophysical surveys and airborne geophysical surveys is increasingly blurred with the current influx of heli-borne systems delivering drill targets at the expense of ground surveys being completed. Ideally, the understanding of rock properties should be driving the exploration strategy rather than the exploration driving the understanding of rock properties. It is now much more common to perform a physical characterization study by logging holes with multiple parameters (such as resistivity, magnetic susceptibility, density, conductivity, acoustic velocity etc.) to provide quantitative values for each parameter per lithology. Forward modeling and inversion modeling of the geophysical data in constrained geological settings has changed the thought process from being an undefined or unreal solution to one that is providing a real and valid result. True integration of all data into one geological model that honors all the data has been accepted by all in the industry as it is the foundation of decision making and risk management, whether the decisions concern exploration drill hole targeting, resource estimation, or engineering analysis. For a review of integrated geophysical modeling studies see Ford et al. (2007), Garrett et al. (1997) and Gingerich (2003).

Inversion code

Great improvements have been made to inversion code. 3D inversion of EM and IP have been developed and implemented by UBC Geophysical Inversion facility (Li and Oldenburg (1996, 1998)). Developed through mining industry consortia, these programs have become the industry standard. Currently available are forward modeling and inversion 1D frequency domain EM data (EM1DFM), 2D and 3D resistivity and induced polarization data (DCIP2D and DCIP3D) and 3D magnetics and gravity (Mag3d) and (Grav3d). Importantly, inversion of geophysical information have facilitated the visualization of the earth in 3D, and have enabled more geologic information to be recovered about the subsurface. The aim of companies and research groups like the Mineral Deposit Research Unit (MRDU) and Geophysical Inversion Facility (GIF) at the University of British Columbia working in collaboration is enhancing the exploration process through the 3D integration of geologic, physical property and geophysical data. To create better models with a better understanding of different deposit types through constrained geophysical inversion from the initial to advanced stages of exploration. 3D earth models intend to honor all data sources. This includes an understanding of ore genesis, mineralogy, structural controls, alteration geochemistry, geophysical techniques and geophysical forward modeling and inversion. This also involves detailed analysis of rock properties, the mineralogic implications of physical rock properties and how to appropriately implement this data into the inversion process. All data is integrated in a virtual 3d environment using Gocad where earth models are built and iteratively improved upon using validation of geology and rock property models through forward modeling and inversion.

VPmg is a gravity, gravity gradient, and magnetic 3D modelling and inversion program developed by Fullagar Geophysics Pty Ltd (Fullagar et al 1999, Fullagar et al 2003). VPmg can forward model and invert any 3D block model geology. It was developed as it was necessary to geologically constrain potential field inversion. In VPmg, the shape and property (density or susceptibility) of each unit can change during inversion, but its geological (or topological) identity is preserved. Bounds can be imposed on the individual unit properties, and geological contacts can be fixed (where pierced by a drillhole), bounded, or free to move during inversion. Contacts below the reach of drilling can be bounded above (EOH constraints); those which occur within pre-collars can be bounded below. All contacts are bounded above by the ground surface. VPmg represents the sub-surface as a set of close-packed vertical rectangular prisms. Prism tops honour surface topography, and internal contacts divide each prism into cells. The vertical dimension of the cells is arbitrary (allow more accurate representation of geological contacts). Each geological unit can be homogeneous or heterogeneous in density or susceptibility. Thus the same property is assigned to each cell which belongs to a homogeneous unit. VPmg offers considerable flexibility during interpretation. The model complexity ranges from discrete bodies in uniform basement, or conventional terrain models, to complex 3D models. Regional effects can be handled by constructing a regional model, based on a relatively large rectangular mesh. The regional model is embedded in a uniform half-space. A local model, comprised of smaller prisms, can be embedded in a regional model. The local model parameters can be adjusted by inversion until the gravity, gravity gradient, or magnetic data within the local model area are satisfied. VPmg offers a variety of inversion styles: homogeneous unit property, contact geometry, and heterogeneous property. During property inversion, model contacts (geometry) are fixed. During contact inversion, model geometry is altered while physical properties remain fixed. The main advantages of this “sequential” strategy are enhanced flexibility and control for the operator, speed (since separate inversion runs involving fewer parameters are faster), and reduced demands on computer memory. In particular, homogeneous unit property inversion involves a small number of active parameters, even for complex 3D models. The user is able to easily switch from one inversion style to another. The main advantage over UBC code is that the edges of the bodies are clearly defined to a particular geological unit with the assigned physical properties. It simply fits how we understand the geology defining sharp boundaries. The boundaries can be easily changed or updated. Both codes were applied to FALC kimberlites with VPmg providing much better results (Figure 7).

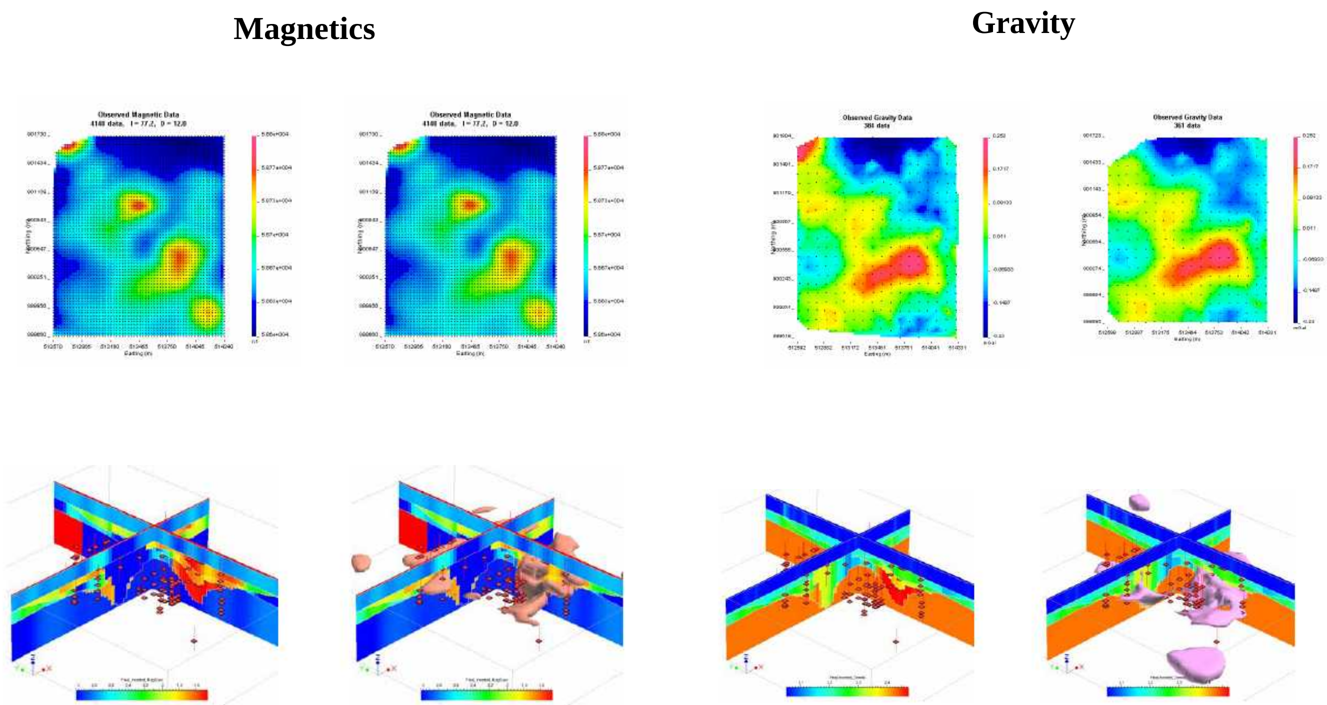


Figure 7: VPmg Constrained Inversion of Potential Field data at FALC

3D Geomodeller is a ‘geological editor’ where you can build a 3D coherent geometrical model that reflects your field data. Once the data is entered, you can examine it in 2D map view and cross sections, or in the 3D in the form of volumes. Using 3D Geomodeller you can combine field observations of various origins and type in the same 3D space and ensure geometrical coherence. Field observations supported are: strike and dip, contacts, faults, fold axes, erosion, on lap, series in a pile, unit relationship processing and lithological properties. A geologically constrained and coherent model is essential for reliably creating and exporting voxel representations.

Des Fitzgerald and Associates have developed new methods have been developed for processing of vector and tensor datasets supporting power spectra generation of quaternion and tensor data. For tensors just 4 spectra are generated using an amplitude/phase generation.

RIO TINTO’S EXPLORATION STRATEGY

The remainder of the paper outlines how Rio Tinto has embedded this philosophy into their strategy to improve exploration success. Various examples will be shown from exploration, ore body delineation and mine site development.

The strategy is based on establishing clear objectives, prioritizing, focusing on results (not process), collaborating with partners, using technology appropriately, selecting the best team, targeting quality, multi commodity footprinting, concentrating on greenfield and brownfield projects.

The key driver is to create value by providing ore resources to Rio Tinto.

Murray River Coal Project in British Columbia, Canada

The objective was to image 2 to 5 meter thick coal seams at depths from 300-1000 meters below the surface and to define geologic structures in the same depth range (Gochioco (2000)). A series of 1D synthetic seismograms were computed to estimate the minimal frequencies that can allow proper imaging of the coal seams and to determine which seismic source (vibroseis or explosives) would deliver the best result (Figure 8).

Eagle Nickel/Copper sulphide deposit located in the Baraga Basin on Michigan’s Upper Peninsula, USA.

Eagle was a pure geophysical discovery from drilling ground geophysical targets. The magnetic grid clearly shows two magnetic targets. The ground gravity shows two high density anomalies coincident with the magnetic anomalies. The first inversion clearly defines the targets for drilling. Eagle East was sub-cropping with no significant sulphide mineralization. Eagle West was drilled with a significant ore grade intersection. The rest is history. A Gocad model was compiled combining and integrating all the geophysical and geological data (Figure 9).

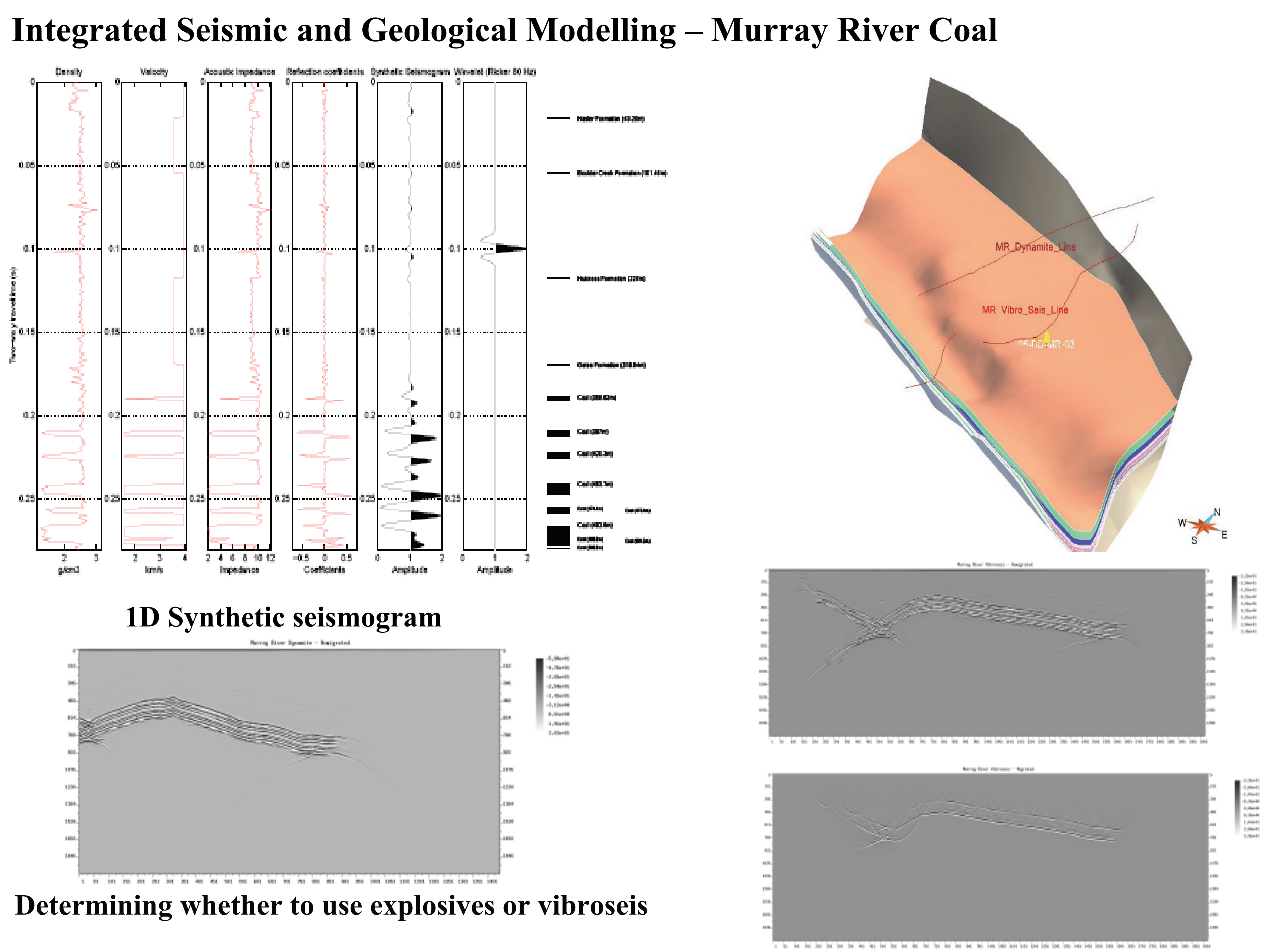


Figure 8: Murray River Coal. Seismic modeling study for project.

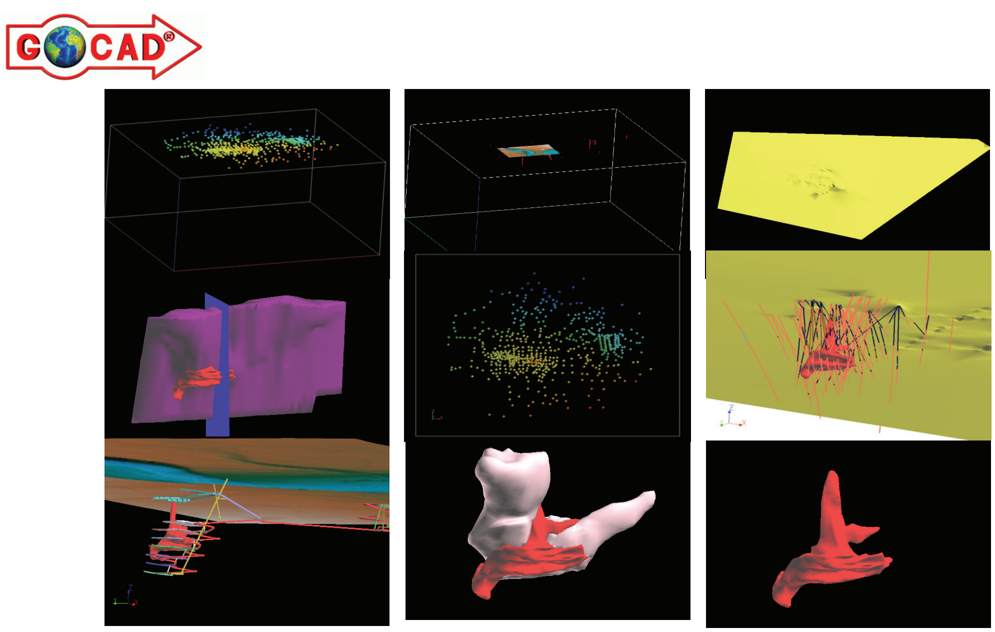


Figure 9: Eagle Gocad Gravity and Seismic Study – "Eagle Gocad Project – Gravity and Seismic Study"

The physical rock properties of the different lithologies are determined and the different reflective co-efficients are calculated. This information is used for determining the effectiveness of vertical seismic profiling. The VSP survey is conducted and the results are shown. The multi-azimuth, multi-offset VSP is considered an effective method for determining positions and orientations of fracture zones. Preliminary data conditioning sequence focuses on eliminating the direct P, the direct S, tube waves and ground roll, so that the weaker later events eg. reflections, become visible. Second stage processing includes Image Point (IP) processing aimed at enhancing the reflected wave fields and at separating reflection events originating at interfaces at different orientations. With the IP transform a reflective interface is divided into a series of planar elements, the mirror image of the source with respect to each element forming an image point. Stacking is performed along hyperbolic paths corresponding to time depth functions of possible reflectors. The coherency can be used to effectively to enhance weak reflections.

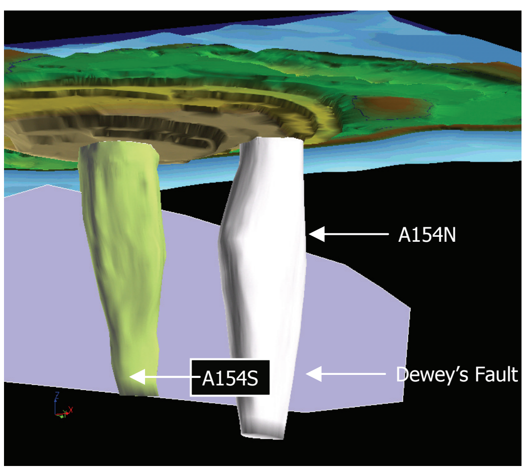
Example Delineation: Diavik delineation of A154S and A154N pipes in NWT, Canada.

The geological model was built in Gocad from all the known data such as the geology, bathymetry, drillhole information, topography etc. Dewey's Fault, the structure controlling the emplacement of the kimberlites, is added into the model (Figure 10).

Physical rock property measurements were made from two geotechnical boreholes that intersected kimberlite. Boreholes were logged with a full waveform sonic tool from which were extracted P wave velocities. Point bulk density measurements were made from core samples and then edited and re-sampled to match the velocity. Acoustic impedance is the physical rock property that controls how seismic waves behave at a contact between different rock types. Acoustic impedence is derived from the product of density and velocity. Significant seismic reflections occur at boundaries between lithologies characterized by a reflection co-efficient greater than 5%. The reflection co-efficient (R) is a function of the seismic impedance (Z) of each medium on each side of the boundary. Statistical analysis of velocity and acoustic impedances per lithology are computed with principal component analysis (PCA) and presented as cross plots of P wave velocity versus Density on a per lithology basis. The cross plots suggest a good contrast exists between the kimberlite and the granitoid, biotie schist and diabase country rocks. No impedance contrast is shown between the kimberlite and the mudstones.

1D synthetic seismograms with 9 different central frequencies were computed to determine which frequency best images the kimberlite contact. Lower frequencies ~75Hz will highlight impedance variations taking place at distance of 10-20m while higher frequencies >500 Hz will be at a distance of less than one meter. Therefore, the next part of the process was survey design. The seismic modelling maybe used for: a). the seismic expression of morphological complex, hypothetical structures b.) designing surveys across known structures and c). comparing modelling results with recorded seismic sections in order to interpret observed patterns of reflectivity.

A VSP survey was undertaken at Diavik and was successful in delineating the kimberlite and country rock contact. A new model has been created fitting all the data providing better delineation of pipe A154N. It was a cost effective way to increase the geological knowledge, raise the confidence of the geological model reducing risks in resource estimation (Figure 11).



DIAVIK™ DIAMOND MINES INC.

Figure 10: Diavik Geological Model. "Diavik Modelling – Dewey's Fault" A surface representing Dewey's Fault was imported from AutoCAD. It was extended vertically to the top and bottom of the model as well as horizontally.

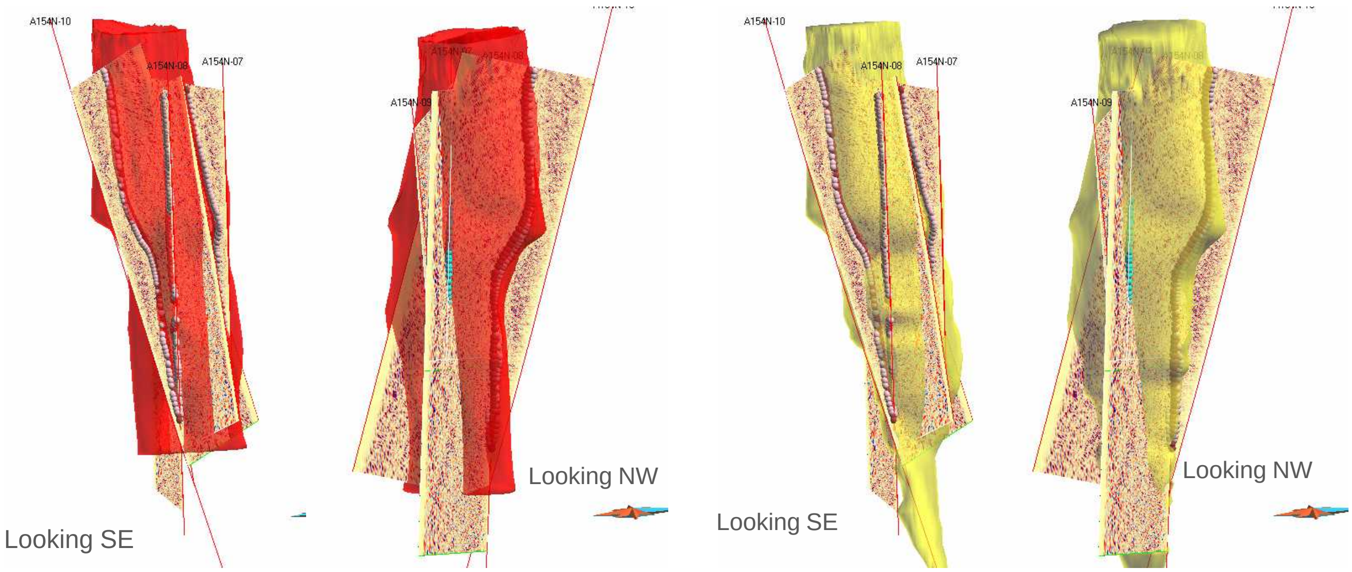


Figure 11: Improved delineation of A154N Pipe. 2 kimberlite models; best estimate it2 (red) Diavik Nov30_05 (yellow) + shown with best and worst case scenario interpretations from seismics

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Example Mine site - Kennecott Utah Copper Company Compiling Geometallurgy.

Kennecott Utah Copper Corporation and IPT team's (Improving Performance Together) exploration strategy at Bingham Canyon (Figure 12) was based on the following steps:

- Learning more about the ore body and understanding it.

New drilling, measurement of physical rock bodies, quality inversion and 3D integration and visualization provided:

- Strategic mine planning
- Optimized extraction.
- Detailed understanding of the complex ore body contains other important revenue streams such as Au, Ag and Mo
- Molybdenum second largest revenue and extraction optimised without effecting copper production
- Single continuous value stream from extraction to markets saving 10s of millions of dollars in NPV

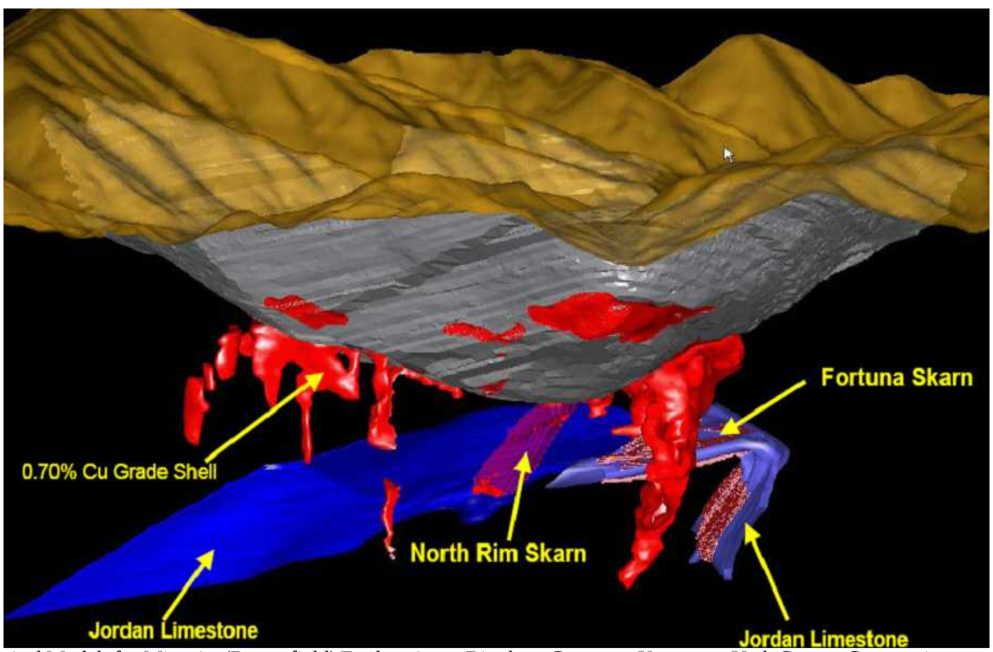

Figure 12: Geological Model. for Minesite (Brownfield) Exploration at Bingham Canyon – Kennecott Utah Copper Corporation

Rio Tinto Successes

Rio Tinto has demonstrated unprecedented success since 1995:

- For the period from '87 to '97, One success: Diavik
- For the period from '97 to '07, Seven successes: Murowa, Kazan, Potassio Rio Colorado, Resolution, Suri Gunay, Eagle and Simandou.
- The pipeline never looked better
- Distinction through exploration and excellent brownfields efforts
- Key driver to the business.

CONCLUSION

The physical rock properties (measured from borehole techniques) are the quantitative link between the geology (rock type) and the high resolution geophysics (ground geophysics). This results in a single geological model (common earth model) which can be used for constrained inversion or true data integration and data interrogation in 3D with software platforms like GOCAD. The process is now embedded in most mineral exploration and ore delineation programs.

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