An Integrated 3D Approach to Deep Search Exploration

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ABSTRACT

Advances in various technologies continue to contribute to our exploration efforts, specifically towards reducing the time to execute tasks. Several technologies have made their introductions within the last several years and despite generally slow uptake by the industry more and more groups are utilizing technology to achieve improved success through effective deep exploration. However, application of new technologies does not necessarily mean that new discoveries will immediately follow. As we try to sense deeper and find improved means of effectively drilling, we will, more often than not, uncover new information that was unexpected and this may require more thought and time than we had initially intended. This makes the use of technology by itself complicated and using it may require that we re-think the way we do things such as learning new concepts and scientific fundamentals.

Making a discovery is difficult and is arguably more difficult as undiscovered deposits today are more likely found at greater depths. In addition, the financial risk with deep drilling is hindering deep exploration. Technology advances have been hindered because the mining industry has been traditionally slow to embrace new technologies particularly if they are not easily understood or when the cost paradigm is out of sync with traditional spending habits regarding drilling versus other technologies. However, the dramatic change that has happened within the industry over these last ten years from low to high metal prices has contributed dramatically to the uptake of new technology. Recent advances in digital signal processing, and faster computers, coupled with the ability to collect very high resolution and deep geophysical data, resulting in physical property contrasts that can now be discriminated from the surface with accuracy and depth penetration that has not been seen before. This provides new opportunity to further geoscientific investigation at greater depths prior to drilling. Drill targeting can be more focused thereby providing better returns per metre drilled. In essence, high potential ground may not be under-explored. Economists have often said a critical failure in exploration is the inefficiencies of exploration while exploring highly prospective regions. Today, images to depths of over 1500 metres for key targeting parameters can assist with required deeper exploration within favourable land packages. Moreover, technology can now provide a means to revitalize exploration in mature mining camps. A "bottom-up" vs "top-down" exploration process begins to address economic concerns that face the industry such as drilling risk and discovery rates.

In order to take advantage of the newer deeper searching techniques, and the advances that have been made in the computing field regarding speed and inversion capability, it is essential that geologists, geochemists, and geophysicists stop working in silos and attempt to bridge the gap that continually exists between the disciplines. This paper will discuss the importance of deep exploration and the significance of 3D data integration at depth to the discovery process. A process for thorough deep search exploration will be highlighted through case examples.

INTRODUCTION

There are several purposes for exploration and mining throughout the world. Principally, the business provides many of the raw materials that we require in order to conduct our activities and evolutionary progress. The drivers for today's mining activities though are business related, with considerations for providing positive cash flow, ever increasing shareholder value, and improved return on investment. Prospectors, geologists, and exploration teams are tasked with bringing the most prospectively significant and highly potential geological environments in the world to the table. Through thorough and efficient exploration, these environments, which can be considered as key corporate assets, may then provide companies with immense wealth. A subsequent discovery can make a company, and provide substantial return for shareholders. Basically, the science of multi-disciplinary exploration is the foundation of the business of mining.

There are some corollaries and basic risk considerations that should be considered when discussing the business of mining in this simplified process mentioned above. What is the real cost of exploration, when properties are not efficiently explored and potential value is left in the ground, and how does this factor in the exploration risk profile of companies? Does it have a bearing on which company an investor backs? It is well known that ore deposits are found at a range of depths within the earth's crust. Today, a majority of exploration drilling and expense still occurs in the top 200 m of the earth. To date, surface studies and nearer surface surveys have been useful in providing reasonable discovery rates compared to overall global demands for more and more raw materials. However, many significant deposits have been subsequently discovered below 200 m and, statistically, many more must exist in the 200 m to 1000 m depth range. It is interesting to consider the total number of reported copper discoveries per year that have been made from 1998 (six) to 2004 (one), as shown in Figure 1 (Metals Economic Group, 2004). The decline in number of discoveries may be attributed to two key points: i) overall exploration expenditures have been less during the previous six years, and ii) new discoveries are going to be deeper than before, and our near-surface exploration programs are becoming less effective.

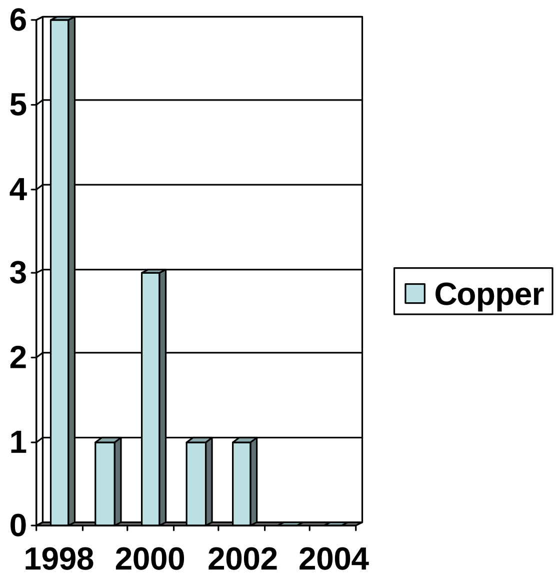

Figure 1. Global copper discoveries from 1998–2004 (Metals Economic Group, 2004).

More expenditure and more drilling should help contribute to more discoveries; however, if deposits are deeper, then expenditures will go up as drilling depth increases. The net effect of exploring with our current exploration processes will be that prospective ground in a 3D sense will not be thoroughly explored unless a means of saturation drilling is performed. Drilling, therefore, continues to be very high risk as the volume of ground sampled by the drillhole is very small and low exploration returns provide little value for shareholders.

In this sense, the most important exploration challenge is to be efficient at understanding the relative potential of an exploration prospect, evaluating it, and recognizing whether the program should move forward or on to other favorable ground as quickly as possible. The sooner a property can be effectively evaluated, even if there is no discovery, the less exposure to the lost time value of money, therefore the less overall cost. One way of looking at the process is that we must fail faster if we are ultimately going to contribute to the economics of any discovery.

WHY IS DEPTH IMPORTANT ?

The ability to thoroughly investigate a volume of the Earth's crust as quickly as possible should be the overall objective of any exploration team. Historically, partially due to technology limitations and partially due to economics, the approach that has prevailed follows a traditional means of surface exploration, referred to as "Top Down" exploration. This process includes the anaysis of vasts quantities of information that we can obtain relatively easily such as first pass airborne surveying, geological mapping, geochemical sampling, structural analysis and some depth-limited ground geophysical surveys followed by drilling, and repeating the process to investigate economic depths (Figure 2). However, this method may have some significant economic flaws, particularly when dealing with the concept of time. For an example a junior mining company based in eastern Canada had a large article published about it's activities over a three year period. (Northern Miner, 2006) In the article, it stated that over ten million dollars had been raised for exploration, two major airborne surveys covering vasts areas were flown, followed by ground geophysics and over 60 drill holes. After three years with the funds exhausted, the JV and shareholders said "enough". One might conclude that that was all that could have been done or all that should have been done. The program took three years and at the end of that time, the question remains. " Is there an orebody in this highly prospective ground?" Now, two years later, another junior is re-investigating the ground.

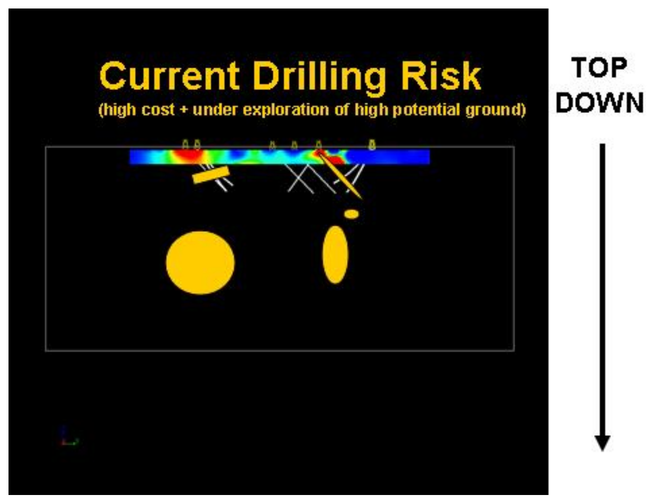

Figure 2. Traditional top down exploration, high drilling risk and non-thorough exploration.. The large objects in the subsurface represent potential missed orebodies.

Surficial mapping and depth-limited airborne data may direct exploration efforts in a proximal area, but the more prospective ground in a belt may be under cover (e.g., by till) and slightly beyond the limitations of geologic projection and first-pass geophysical surveys. The drilling efforts become biased to the locations where all the geoscientific data, such as extensive airborne surveys, provide anomalies, and yet still highly potential ground remains to be untested because the economics and time criteria do not allow saturation drilling. As more drilling is applied, more time goes by and associated costs remain high with, in many cases, no discovery.

MORE DATA = MORE KNOWLEDGE

Advances in various technologies continue to contribute to our exploration efforts and may help the industry achieve improved success through effective deep exploration and reducing the time to execute tasks such as essential data compilation and query in 3d based platforms. As depth becomes more important so does the use of deep geophysics, although geophysics alone will not be the solution that the industry will adapt. The key to success will be the relationships of the variety of disciplines that make up our exploration process.

In order to take advantage of the newer deeper searching techniques, and the advances that have been made in the computing field regarding speed and inversion capability, it is essential that geologists, geochemists, and geophysicists stop working in silos and attempt to bridge the gap that continually exists between the disciplines. The advances that are being made in nano-technology today and the revolutionary new developments in miniaturization are coming from the greater understanding of the interrelationships of our key sciences such as chemistry, physics and engineering, and biology, the same efforts need to be made within the geoscience disciplines. In fact some steps in this direction are incorporated in a new periodic table (Figure 3) for geoscientists published by Bruce Railsback (Railsback, 2003).

Within this periodic table, elements are grouped in clusters related to charge and chemistry rather than the traditional division of mass. The chart basically indicates that the chemistry and the charge are related to mineral assemblages. This basic observation is significant and helps the geophysicist relate more to other parameters that may be of significant interest to the geologist such as alteration halos and chemical gradients. It demonstrates the complicated relationship between physics and chemistry, and indicates the potential of using geophysics to map the subsurface more accurately rather than the more common attempt to use it as a utility to directly detect a geologic feature of interest.

As the explorationist is required to look deeper into the crust, there is an increasing pressure on the geophysical world to develop better targeting methods. As the methods for measuring the physical rock properties become more precise at depth it will be even more important to relate them to the geology, structure and alteration as best as possible. To start bridging the gap, the measurement of the physical properties in boreholes and rock samples should be incorporated routinely in exploration so that we can relate our collective knowledge about known orebodies , alteration and chemical composition to the tools that we will be using to identify these features at depth. To date our industry has greatly lagged the sophistication of our distant exploration cousin, the oil sector.

Relevance and Importance of Measuring Physical Properties

For years the wish has been that geophysics could directly map lithology. Expectations for geophysical data to ever match have a direct correspondence with lithological boundaries should be set aside, and more work needs to be done at the research and university level to relate the chemistry of the rocks to their physical properties, and from there use it as a guide to draw us nearer to mineral occurrences.

Perhaps, new initiatives in our educational institutions are warranted to help us close the gap between the geologic and geophysical world. One example for instance would be to broaden the scope of geological definitions so as to include true physical properties and their relationship to chemical composition, mineralogy, and rock textures. The principle point is that if we do not measure these parameters and make the effort to understand these relationships, we may not be able to utilise the advantages of the deeper-looking technologies to ultimately help us make discoveries faster. By increasing geological knowledge per drill hole and obtaining a better understanding of the physical properties in the third dimension, more informed decisions can be made with respect to exploration target models, ore bodies, better drill targeting and overall mining practices.

Physical property information retrieved from samples or from borehole measurements can assist airborne, ground and drilling exploration programs. The value of obtaining physical property measurements was realised as early as 1940 when geologists in the oil industry began years ago to measure the earth's physical properties to improve consistency between geologists. Core was found to have been logged with the bias of the day towards a particular geologic theory or model. Further scrutiny led to the conclusion that different geologists under slightly different backgrounds, theories or influences created different logs. Additionally, interpretations varied dramatically between geologists, primarily because they were unconstrained in their thinking. It became apparent that, over many holes, the error bars on interpretation became greater and greater. These same principle reasons for logging are being applied today to assist with identifying the non-visual characteristics of the rock and improving consistency between geologists.

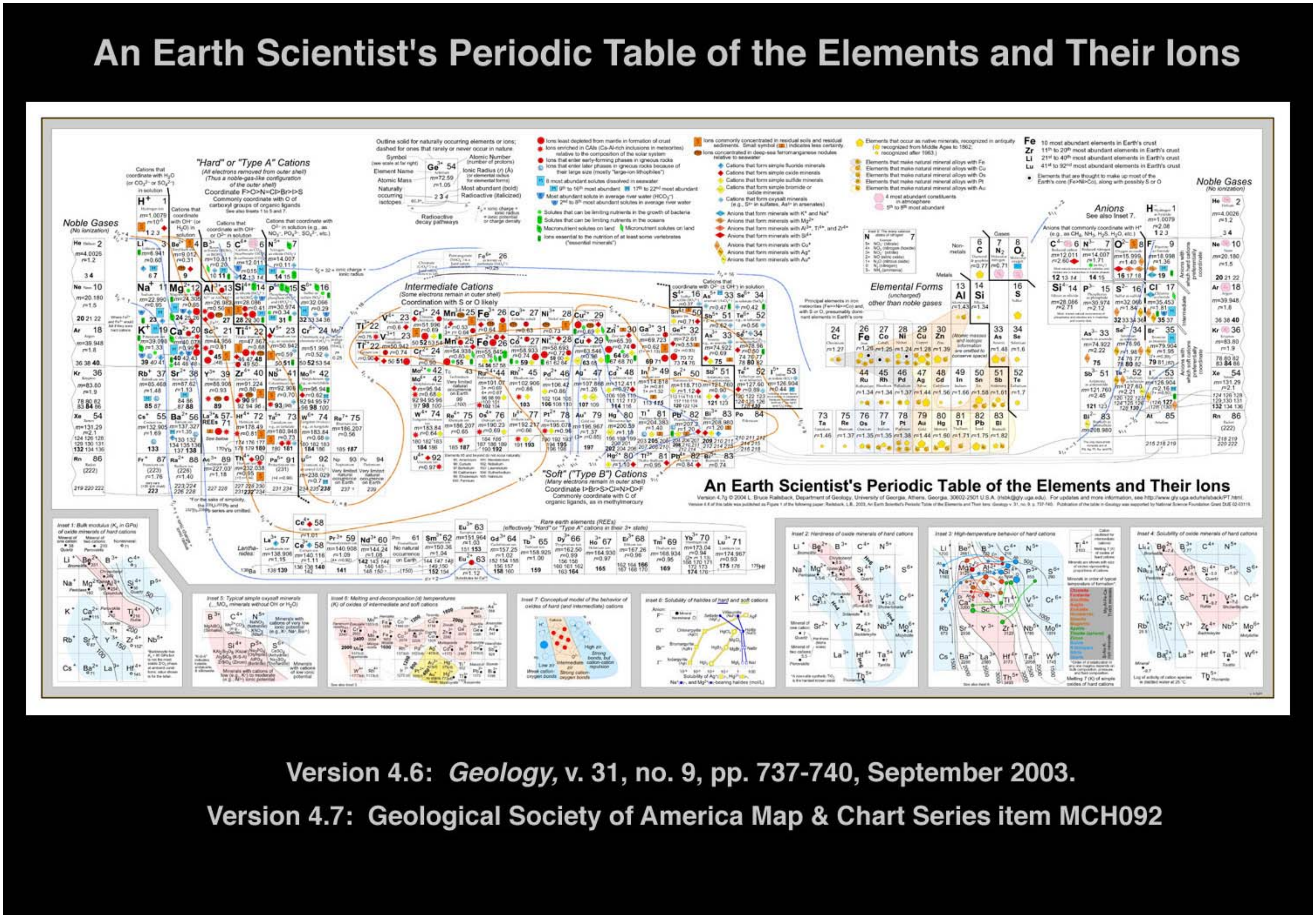

Figure 3. An Earth scientist's Periodic Table of the elements and their ions (Railsback, 2003)

Multi-parameter Deep Earth Imaging Technology

Although on its own geophysics does not produce a picture that is directly related to the geology, the images developed by these technologies provide the most advanced clues to the subsurface that we have. Generally speaking, large economic ore deposits of most types have disturbed the background geophysical signatures in such a way that characteristic signatures exist. Being able to sample key vectoring parameters such as resistivity and chargeability accurately to very great depths should provide a starting point for efficient exploration. .

An example of a system that provides deep multi-parameter geophysical data (in this case DC resistivity, chargeability and MT resistivity) is the Titan 24 distributed DCIP and MT survey system. It was introduced to the industry in 2001 following earlier developments with distributed acquisition by M.I.M. and works from a premise of collecting data through a large array. The large array style of acquisition contributes to deeper IP measurements, on the order of 700 m. Information is collected simultaneously over great distances in a 24 hour period. The high volume of data, improved signal processing, and increased array size, provides accurate deep images of the subsurface for key physical property parameters. Deep MT resistivity investigations have had increased usage within the last 20 years for a number of applications including geothermal exploration and regional transects. The new approach of measuring very closely spaced MT sites simultaneously in a constant natural field have led to very high quality data and improved lateral resolution which makes the use of this technology more robust for deep mapping on more local scales.

Recently, in a case study performed by Newmont, depth of investigation of at least 400 m was achieved easily without sacrificing the spatial resolution that was typically only achievable with small dipole spacing. The cost-benefit and speed of acquiring a higher density of data points were also noted (Goldie, M, 2007). It has also been recognised that for 3D bodies of limited extent, an optimised configuration for deeper ore bodies would be to use array style configurations with multiple electric field measurements, as most of the anomalous response would be from the electric field components. To resolve bodies at depth, station spacing must be sufficiently close. A broadband wide frequency range of AMT data is necessary to detect and to delineate the deep geometry of 3D bodies (Queralt et al., 2007).

Advanced digital signal processing of full waveform data means that these systems that have advanced digital signal processing of full waveform data have applications in brownfield (near mine) exploration, where cultural interference usually renders traditional approaches ineffective (Figure 4). The ability to filter out much of the random noise in these environments has contributed to the increased usage of MT in conjunction with IP in minesite and near-mine applications. Use in the mine environment include applications throughout the mine life cycle, for example: early stage delineation and condemnation applications for mine planning and active stage for near-mine exploration. Additional benefits are achieved by revisiting old and dormant mines where the application of thorough deep imaging in highly prospective near-mine environments have occurred.

Figure 4. Distributed acquisition survey system collecting DCIP and MT data in active open pit mine. Receiver nodes shown with 50 m spacing in this application mapping side walls in kimberlite. Photo taken in Venetia Diamond Mine, South Africa.

Project Management with CEM

The repository for all this new information exists thanks to the development and refinement of practical relational, visual databases for Common Earth Models (CEM) or full 3D-GIS such as Gocad.

A CEM is a complete representation (a snapshot) of the total information available on a project at a point in time (an information balance sheet). After a budgetary cycle a new CEM can be generated and the difference in the models calculated to demonstrate the knowledge gained from the budgetary expenditure. This level of accountability should increase the sensitivity to the total cost/value added of each aspect of the project implementation.

During the execution of the project, the CEM is a rapid way for expert teams to communicate, across the room or the world via the Internet. Virtual exploration teams of the best professions in the world can participate in your exploration without the same level of travel and time cost as was previously required to build a team (McGaughey, 2006).

BOTTOM-UP EXPLORATION

A new, bottom-up approach trusts that the geological team is correct when outlining a prolific belt or region that is prospective for ore discovery, and sets out to test the geologic models systematically throughout the area. This radically new approach is within reach due to the advancement of the above-mentioned technologies. In particular, deep electrical earth imaging with distributed geophysical systems has recently become available, which provides very deep scans, on the order of 1 km, of key physical properties such as resistivity and chargeability. Combining sophisticated project management and visualization software with deep searching technologies, physical properties (Gordon and Leriche, 2000), geology, and other geoscience data all provide a means to interrogate volumes of ground in three dimensions to depths of 750 m to 2 km (Figure 5).

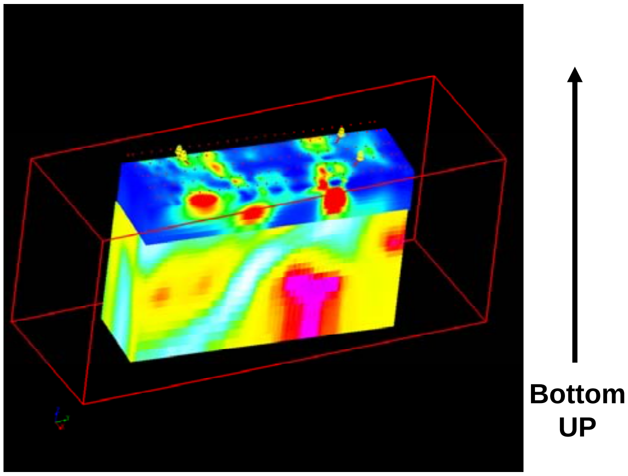

Figure 5. New bottom-up exploration approach provides opportunity to be more thorough and cost effective. 3D volume filled with both deep IP information (blue) and deep MT resistivity information.

Deep Volume Exploration Process

A sophisticated deep volume exploration process utilizing the advances we have made in the last ten years with technology has been developed around this "bottom-up" concept to optimize the return on exploration projects that are either of key strategic importance (brown field) or require the confirmation of deep targets with associated high drilling costs.(Figure 6). This process utilizes Common Earth Modeling (Gocad), calibrated borehole petrophysics and Distributed Acquisition System technology (Titan-24) along with other geophysical tools. The process provides geologists with *quantitatively integrated* data sets in 3-dimensional geological models. These models are used to communicate amongst the technical exploration team and to drive prudent project management decisions. This should help optimize total project costs and improve the companies return on investment by maximizing operating mine lives.

Figure 6 outlines the key aspects and elements of this process along with the benefits that can be had by adapting this approach to exploration. Each phase takes advantage of the most sophisticated technologies available and applies these technologies in a manner that can be put forward as a "best practices" approach to thorough exploration at either the greenfields or the brownfields exploration.

This process addresses the basic concerns regarding exploration success, which are to "overcome the errors related to highly uncertain activities surrounding the exploration process" (Mackenzie, 1987). The first error is a false negative, meaning a no-go decision when the hypothesis is true, an ore body is there. The second error is a false positive, meaning go, when the hypothesis is false, an ore body is not there. The ability to image at depth and see if the big one exists, or whether features are depth-limited prior to expensive drilling, yields improved targeting and faster decision making and addresses the problem with the first error without saturation drilling at depth.

The benefits of a deep integrated exploration process include:

- Integration of existing exploration data to re-examine its significance.
- 3D geological models are used to communicate within the technology team and more importantly to management.
- Calibrated petrophysical logs become corporate assets, as the information that they include can be used as part of project or regional statistics.
- Sensitivity studies enable survey design based on economic assumptions, define expectation and improve budgetary decisions.
- Distributed systems are capable of mapping lithology, structure, alteration and mineralization to beyond most economic limits.
- Titan-24 surveys are proven with VMS targets below 1100 m from surface and lithologic alteration targets at depths below 2500 m. Each system is capable of producing an average of 2.5 km per day (terrain and access average) of continuous AMT/MT/IP. Field interpretation products include smooth 2D and 3D inversions, generally within 48 hours of acquisition.
- High quality deep geophysical data enables the use of aggressive inversion routines to perform constrained referenced inversions of the 3D geological models.
- Drilling decisions are focused and precise in the information and value that they add to the CEM.

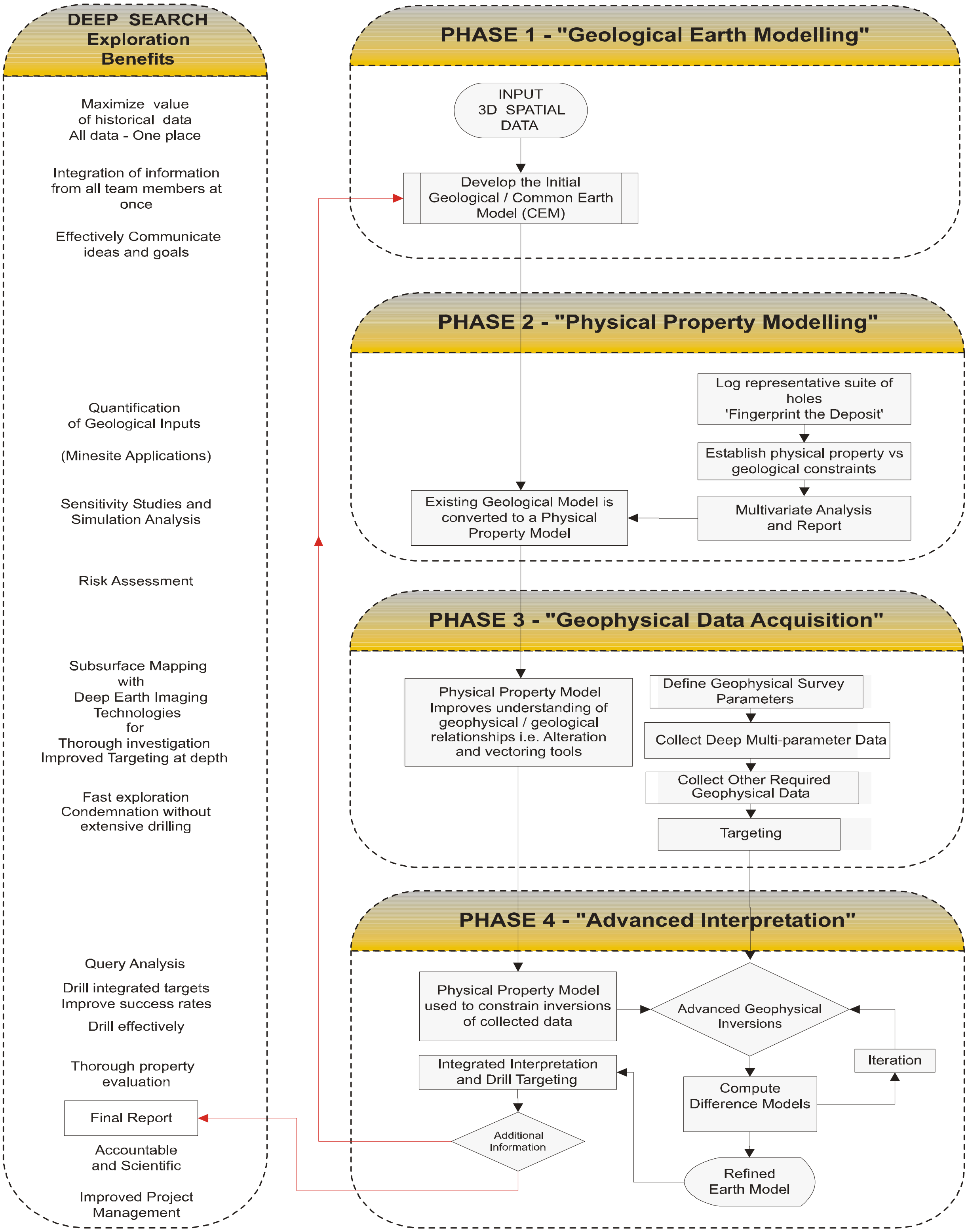

Figure 6. Deep Volume Exploration Process utilizes Physical property analysis, Common Earth Modelling and Distributed DCIP and MT Deep Earth Imaging.

Application: from grassroots to mine environment,

Maximum benefit from these new deep geophysical earth images is achieved when the data can be properly utilised and integrated with geological information. Constraining geophysical information to geology is useful when a lot of previous information within the area is available or the geological model is well understood. In grassroots cases the process begins with geophysical information and incorporates subsurface geological information following the drilling of the first hole to further enhance the subsurface image of the geophysics. As mentioned, the measurement of the physical properties of the geology is a key step in making the link between the geology and geophysics in this process.

For basic constraints, the starting model can be geological assumptions and physical property estimations. Improvements to the model leading to more accurate results are obtained with the sequential addition of geologic boundaries and measured physical property information through geologic mapping and logging of the drill holes, coupled with borehole physical properties. By comparing the results of the constrained geo-referenced survey inversions with the original geologic model, the exploration team are able to see areas where the model needs refinement through further exploration. This provides other targeting criteria to the program.

A regimented deep volume exploration process creates truly integrated geological and geophysical models. The geological reference model is perturbed by the inversion algorithms in a manner which is consistent with a constraint mesh and the known variability of the petrophysics. The original reference model can be subtracted from the integrated model to show what has been changed by the inversion (a variant analysis plot). These plots clearly demonstrate the value added of the geophysical survey. In the areas of the reference model that have not been changed, the geological model is substantiated by the geophysics (to the limit of its resolution). In the other areas of the model that have been changed, the new petrophysical attributes of the integrated model can be re-evaluated in the geological context in terms of potential economics and drill testing. Figure 7 illustrates such a process from a project near Sudbury.

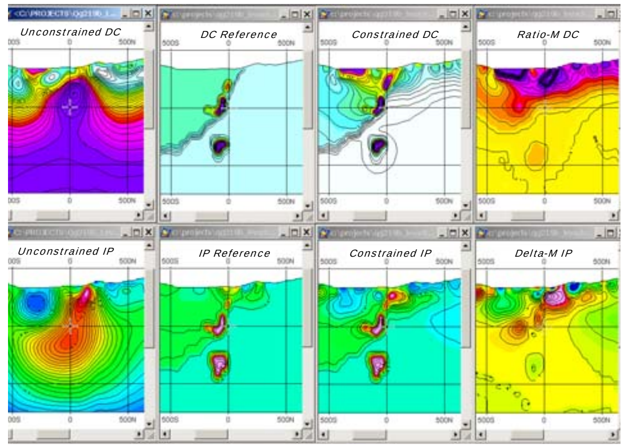

Figure 7. Example of constrained inversion results. Deep DCIP data inversions to typical depths of 750 m, DC resistivity on top, chargeability on bottom.

In Figure 7, unconstrained inversion results from a deep (750 m) DCIP survey are shown on the left. The reference model or images are what were believed to be known (second from left) of the subsurface based on geologic and geophysical knowledge have been sliced from a 3D earth model. The constrained inversions use the reference models as a starting point and are essentially constrained to the known geology. On the right we have the ratio of the constrained DC resistivity to the reference model and the difference between the constrained IP and the reference IP. These products (variant analysis) provide information highlighting areas for further investigation. For example, if the constrained inversion is the same as the reference model then further investigation utilizing these parameters is not warranted. In this example differences which may require follow-up are noted. For example the images of both the unconstrained and constrained have a near-surface feature in the upper left which does not appear in the "known" reference model. Although a potential near surface target, it turned out to be an overgrown historic tailings pond. Data in this example are used by permission of FNX mining and OMET.

In another example we highlight the whole process through a series of figures. This project occurred near the Kidd Creek Mine in Northern Ontario. Kidd Creek is a VMS style deposit. The area near the mine is considered highly prospective despite the fact that it has experienced extensive exploration over the years. A volume for exploration is chosen and an earth model is constructed. The time to construct the model was about three weeks. Physical properties are assigned to the model (Figure 8).

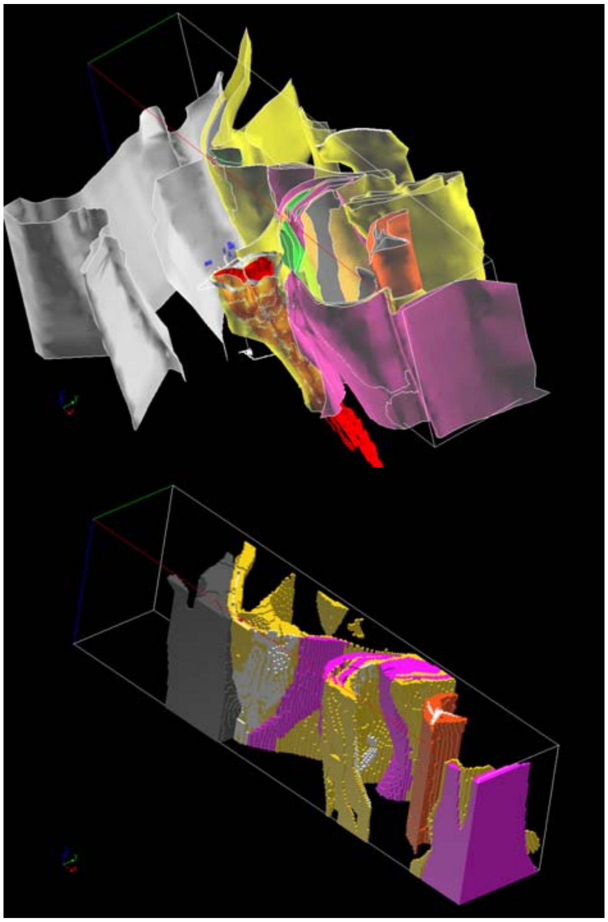

Figure 8. (a) Top shows starting geological model, (b) bottom shows Physical Property model of the resistivity as inferred at the Kidd Creek Mine and property nera Timmins, Ontario. The study area shown by the cube is 5 km x 1 km by 2 km deep. Data used by permission of Falconbridge and OMET. From Legault et al., 2002.

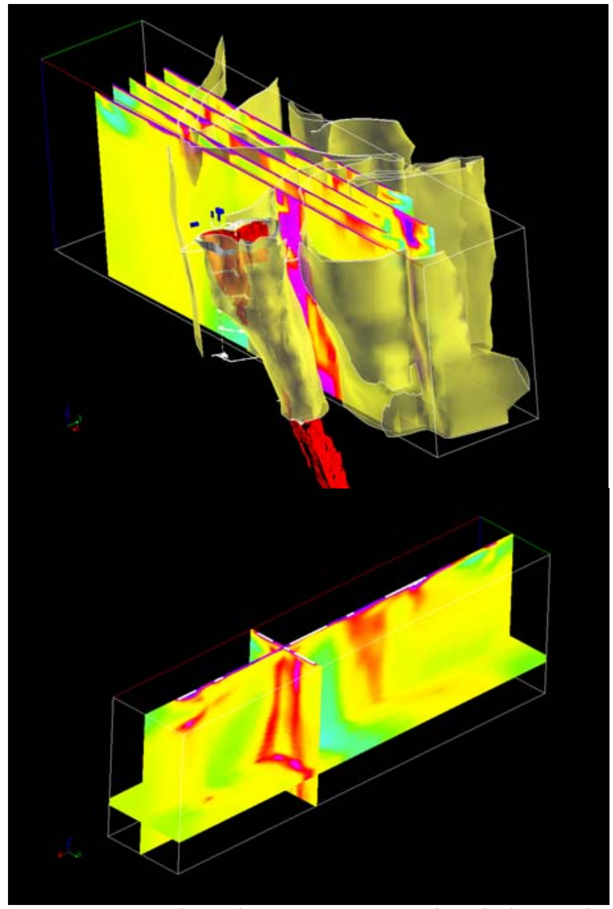

Figure 9. (a) Top shows deep MT sections to 2km, (b) bottom shows constrained MT ratioed to the starting resistivity model. Targeting at 1500 metres depth is done utilizing a horizontal slice through the model. at the Kidd Creek Mine and property, near Timmins, Ontario. The study area shown by the cube is 5 km x 1 km by 2 km deep. Data used by permission of Falconbridge and OMET. From Legault et al., 2002.

The volume was then interrogated with both a deep IP survey and a deep MT survey (Figure 9). The survey was executed in December, lines were 5 km long, spaced 200 m, with a station spacing of 100 m. The survey took roughly 14 days to complete. The results were then placed in the Gocad common earth model. Additional results from constrained inversions are placed in the model. The model was then queried for potential areas of interest. In this case conductive regions along a favourable ryholite horizon are highlighted and targeted. Although the volume had been previously explored, 45 of 45 positive drill results were identified by the deep survey. Additional deep targets were identified (Figure 10).

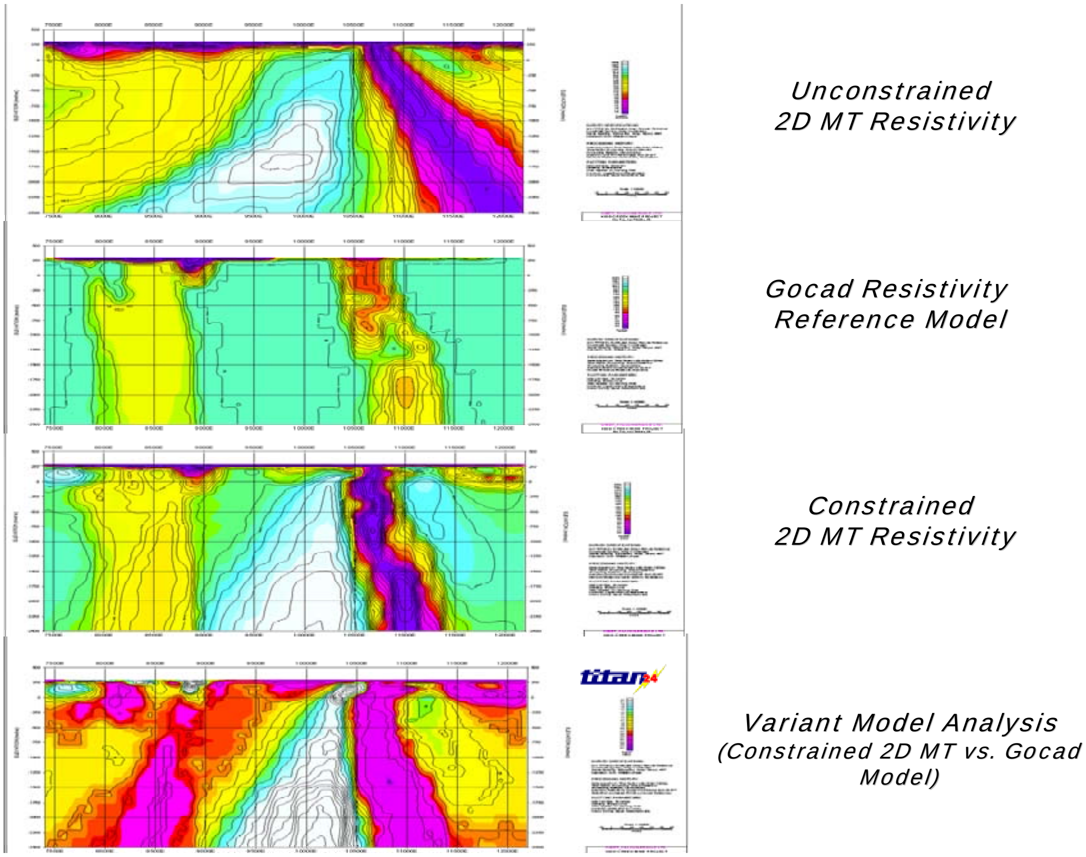

Figure 10. The top figure represents unconstrained inversion, middle figure represents slice of ground with applied physical property resistivity information (constraints for inversion), bottom figure represents constrained inversion. The constrained inversion shows us in great detail how the surface data collected can be explained by the subsurface. Where it does not agree with the starting physical property model it represents specific target areas. The resistivity information is shown to a depth of 2 km. Data used by permission of Falconbridge and OMET. From Legault et al., 2002.

In this very early stage application of the technology it was demonstrated that imaging could have saved millions of dollars in drilling expense near the Falconbridge Kidd Creek Mine if the technology had existed 15 years earlier. The region within the circle was extensively drilled at that time because it was "near" favourable and prospective ground yet no favourable results were ever returned (Figures 11 and 12).

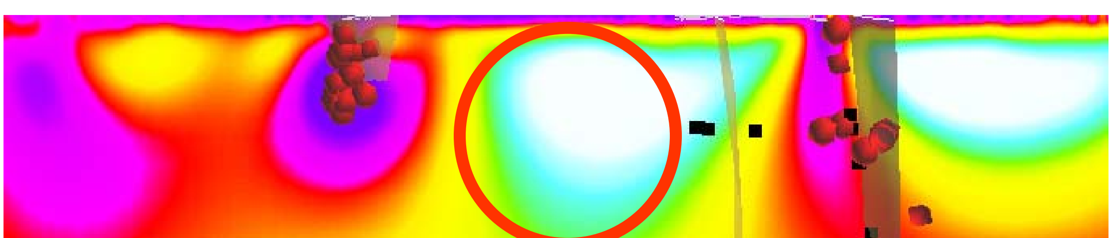

Figure 11. Distributed deep earth imaging – resistivity section. 5 km long section, 800 m deep at the Kidd Creek Mine property (a volcanogenic massive sulfide deposit). The survey was able to penetrate thick (50 m) conductive overburden. Data used by permission of Falconbridge and OMET. From Legault et al., 2002.

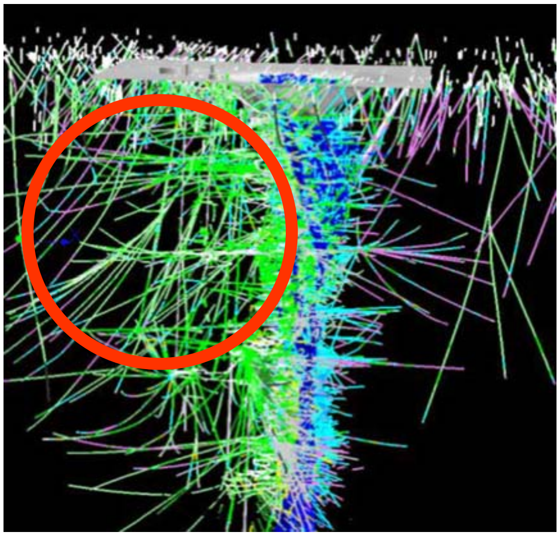

Figure 12. Previous (pre-deep survey) drilling cost near Kidd Creek Mine occurring over 20 year period has been estimated at roughly 20 million dollars.

PLANNING

This process can drive exploration very rapidly through the condemnation of non-prospective ground in early stages. Vast volumes of ground to depth can now be imaged rapidly. From a project execution perspective though, it is important to budget the time and cost required for using such advanced geophysical technology in the initial stages of fund raising and project planning. In the case where these activities are not planned, such costs and time for advanced geophysics could end up competing with drilling budgets, instead of enhancing the effectiveness of drilling activities. So awareness is critical. The technologies, while more expensive than most traditional technologies, allow the explorationist to make more informed decisions at earlier stages within a project cycle regarding whether further exploration would be warranted or more importantly when further exploration is not warranted and real dollars can be saved. In time, as more and more groups embrace this approach, more case studies will demonstrate this. Appreciation of current technology capabilities by decision makers is therefore important and could significantly improve the return on their investments in exploration activities and ultimately improve shareholder value.

CONCLUSION

To date, every major exploration technology advancement, particularly geophysical, has aided in new discoveries by better focusing drilling efforts. Our scouring of the top 200 m has been relatively efficient. The likelihood of making new mineral discoveries at depths greater than 200 m is increasing due to the ability of the latest geophysical subsurface imaging capabilities and other advances in 3D earth modeling and geophysical inversion. Some of the biggest issues within the mineral sector continue to be the economic question "What real value?", in terms of wealth, does exploration provide. This question is asked more and more as time passes without new discovery. In addition, due to financial pressures at some head offices of large mining corporations, exploration may be considered a necessary evil that simply takes money away from the annual bottom line. As long as discovery seems to appear as some form of serendipity it will be harder and harder to justify. If some positive return can be attributed to exploration annually, then we may all feel a bit safer with respect to employment even through low price cycles. Essentially, the industry must demonstrate that exploration can be efficient and thorough. Advancing these and other technologies and pushing for more information on the relationships between chemistry, physics, and geology is one avenue to help the business of exploration and demonstrate that the exploration process can reduce risk and ultimately provide greater return in a shorter time frame.

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