Paper 39

Using 3D Methods in the Management of Risk in Exploration Targeting

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ABSTRACT

The surface geochemistry techniques widely employed during the 1960's to 1980's are effective at discovering near-surface deposits, but are largely ineffective for exploring under deep cover or for deep extensions of known mineralisation in a near-mine environment. Instead, mineral explorers must focus their attention on rapidly aggregating and synthesising disparate data to build into holistic mineralisation models that can be interrogated within the framework of 3D models. For example, the Far East Zone at Red Lake in Ontario was targeted through 3D geological modelling, which identified a previously unrecognised fault that off-set mineralisation by approximately 500m in a right-lateral sense. In addition to the traditional empirical approach to targeting, automated methods such as weights of evidence, neural networks and probabilistic techniques are also being used. However, the extensive use of Bayesian statistics (eg weights of evidence) places reliance on a technique that can introduce false positives and false negatives that reduce the chances of success. In an attempt to improve targeting success, the minerals industry is increasingly looking to other industries that have tackled this problem, in particular, the oil industry which is dealing with similar parameter space. The oil industry has seen a marked increase in exploration success by assigning risk to the variables required for an oil or gas resource to be present; e.g. probabilities of the presence of source, maturation, pathway, reservoir and trap. Crude oil exploration is however dealing with a single type of deposit represented by a simple system with relatively few variables, laminar fluid flow, and relatively simple basin architecture and structure in the shallow crust. In addition, the location and form of oil deposits is controlled by the current structural geometry in the crust making it much easier to determine if a trap is present. In minerals exploration, different models are necessary to understand each type of ore deposit, and many of these models (e.g. for IOCG deposits) are not well understood. Ore deposits commonly form in complex structural environments, from highly pressurized fluids sourced from the deep crust. Many ore deposits are also long lived and have experienced significant post-deposition deformation and overprinting obscuring an understanding of the original factors that led to ore deposit formation. The coincident set of events and variables required to form a mineral deposit are considerably more complex and challenging than those involved in oil accumulation. Geoinformatics Exploration is applying a probabilistic approach in the search for ore deposits such as porphyry copper-gold systems. In porphyry copper-gold environments the variables required to form an ore deposit are a fertile source region, melting of the source region to generate hydrous and metalliferous magmas, migration pathways for the magma, and a trap to stop the magma's ascent at an appropriate depth to allow metal precipitation. Geology and lithochemistry of volcanic and intrusive rocks in a region can be used to determine whether prospective hydrous magmas were generated. Migration pathways are likely to be major structures that could be located using upward continued geophysical methods that can be used to "see" deep into the crust. The best evidence for a trap is often the presence of a porphyritic intrusion of appropriate age, which can commonly be located under cover using magnetic or gravity data. Knowledge of the regional geology and the palaeosurface can be used to estimate if the depth of emplacement is in the pressure range for porphyry copper formation. These data sets can be used to estimate the probability of all the necessary factors coinciding at any point in a project area. This provides an estimate for the probability of finding an ore deposit assuming the model being tested is correct. For prediction to have a spatial component that can be used in looking for buried targets, one of the main inputs will be the 3D model and the accuracy and validity of all data used as inputs must be known and recorded.

INTRODUCTION

This paper is a review of the evolution of exploration targeting, spanning the lives of two companies that the authors have been involved with, namely Fractal Graphics (1991-2002) and Geoinformatics Exploration Inc (2002-present). Throughout this period the underlying aim has been to get a better 3-dimensional ("3D") understanding of the earth's crust from the mine scale to the terrane scale, and to get a spatially accurate 3D representation of geology utilising 3D Geographical Information Systems (GIS) and geological modelling software tools. The fact that we can now use sophisticated targeting techniques and risk

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management strategies in mineral exploration has largely been possible by the rapid advances in computer hardware/power and development of the GIS and modelling software.

In the early 1990s, the only computers with graphics engines, memory and storage capabilities capable of building and visualizing 3D geological models were Unix-based systems. These systems were mini supercomputers, commonly multi-processor, and costing hundreds of thousands of dollars. Because of the cost, the minerals industry was very reluctant to utilize such systems, and they were mostly used by the oil and gas industry. However, mainly thanks to the computer games and film animation industries, in the late 1990s desktop and laptop computers started to have the visualization, memory and data storage capacities capable of building and storing complex 3D geological models. Software was consequently transferred from the Unix-based systems to Windows and Linux operating systems.

Paralleling the computer hardware revolution has been the software evolution. Because of the relatively niche market, software development specifically designed for the minerals industry has struggled to keep up with the rapid changes in computer hardware technology. The first geological models in the early 1990s were built by 3D Computer Aided Drafting (CAD) software and mine planning packages that had proprietary databases, such as Vulcan, Surpac and Datamine. These systems were designed specifically for the mining and exploration industries and allowed for standard inputs such as drill hole information. At that time GIS systems based on relational databases were in their infancy and limited to 2D. There were no geological data models, and there was very limited interaction ("Interoperability") between the GIS and CAD packages. Building 3D geological models using CAD systems was a very time-consuming and often due to the complexity, took many days or weeks to update.

Presently, the next generation of software has been developed, such as: GoCad (www.mirageoscience.com), initially developed for the oil industry and now adapted for the minerals industry; Geomodeller (www.geomodeller.com) and Leapfrog (www.leapfrog3d.com) with smart algorithms developed specifically for rapidly building and modifying 3D geological models. Additional software such as FracSIS, for 3D data integration and visualization and SDS (Spatial Data Server) (www.fractaltechnologies.com) which is an object-oriented database system that allows for the sharing of both spatial and non-spatial data have been developed. Furthermore, specialist geophysical inversion and interpretation tools such as Mag3D and FracWormer have enabled more 3D information to be sourced from geophysical datasets. As a result of the increased speed of the modelling tools multiple iterations of geological models can be built that incorporate the vast and variable geological and geophysical information and these models can be stored in a single database and integrated with multiple source datasets.

The reasons for taking a risk-managed approach to exploration targeting are based on the tenets that:

- Exploration is more costly, has to go deeper or under cover, and exploration success rates are declining.
- If you use all the data within a framework of 3D geological and geophysical models, you must reduce the odds of exploration failure.

The resultant is that we looked at other industries, such as the oil and pharmaceutical industries, which had also previously been faced with higher costs, diminishing success, and increasing time-frames to discovery. We also used the results of studies from Macquarie University (Etheridge et al., 2006) to provide a statistical framework, based on historical data on mineral discovery, as to what we would have to do to change the odds of discovery and make exploration a net producer of shareholder wealth; not a destroyer as it is at present.

QUANTIFYING EXPLORATION RISK

Hronsky (2004) and Schodde (2004) conclude that throughout exploration history the greatest success rates occurred during the 1970s to mid 1980s. This coincided with favourable economic conditions and the successful application of low-level detection surface geochemistry techniques that enabled explorers to target near-surface mineralization. For example, the discovery rate in the Western Australian gold exploration industry peaked in the 1980s (Archibald et al, 2006). This discovery pattern was not universal and was highly dependent on the nature of the surficial terrain. In Western Australia the oxidation profile in the near surface enabled good surface geochemistry signatures. However, in other major and significant mineral provinces such as the Mid-Continent Rift in Ontario, Canada where there is considerably more transported cover and heavily forested terrain, the success rates were correspondingly low.

Exploration success over the past two decades has declined (Schodde, 2004). The indicators for this are:

- Exploration becoming more costly and less efficient at finding deposits,
- Exploration has almost run out of outcropping deposits in the well explored mineral provinces and consequently will have to search deeper or under cover.

The results of studies from Macquarie University (Etheridge et al., 2006) provide a statistical framework, based on historical data regarding mineral discovery. The work demonstrates the statistical changes required to make exploration a net producer of shareholder wealth; and not a destroyer, as it is at present.

Using North American copper exploration as a proxy for the industry in general, Table 1 and Figure 1 illustrate the relative probability of success in minerals exploration in general. The five stages of exploration prior to construction of a mine are after Lord et al (2001):

1. Grass Roots Exploration – where regional exploration tenure has been staked on conceptual basis and early stage techniques such as reconnaissance geochemistry and geophysics are underway.
2. Exploration – where on-ground exploration has commenced and anomalies are being tested with drilling.
3. Advanced exploration – where a mineralized system has been identified but a resource is yet to be delineated.
4. Pre-feasibility – where a resource has been identified and preliminary economic analysis is underway or is complete.

5. Feasibility – where a full economic and engineering analysis is underway or is complete.

Table 1: A snapshot of the total number of copper projects in North America (source www.intierra.com as of May, 2007) where the empirical probability is based of the relative number of projects in each category.

Type	No of Projects	Empirical Probability
Grass Roots	2223	49.6%
Exploration	1722	43.7%
Advanced Exploration	185	4.5%
Pre Feasibility	50	1.2%
Feasibility	41	1.0%
Construction	4	0.1%
	4225	100.0%

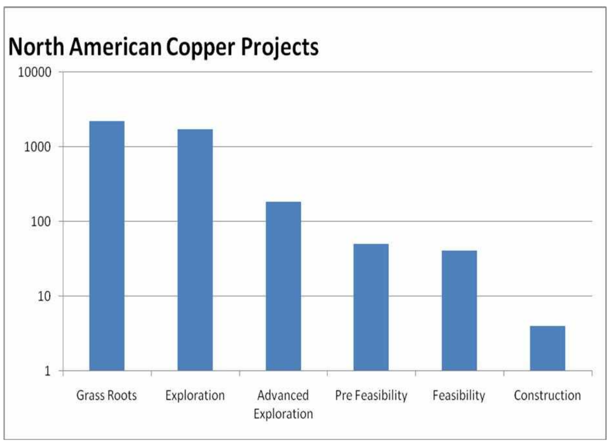

Figure 1: Graphical Representation of Table 1. The Y-Axis is a logarithmic scale representing the number of projects listed from www.intierra.com in the specific categories for North American copper exploration projects.

Whilst the statistics presented in Figure 1 and Table 1 cannot strictly be used to calculate the probability of success, they provide a proxy as to the total number of present projects versus the ones that have achieved a positive economic study. This proxy indicates that if a copper project in North America was selected randomly there is around a 1 in 1000 chance that a project will advance from the Grass Roots exploration phase to the Construction of a mine. These "chances" or "probabilities" have a direct reflection on value of a system and the risks involved in bringing it to production. The global equities markets value companies higher if they have a project that is in the feasibility to construction phase; whereas the junior companies focused mainly on grass roots exploration are generally valued lower. As a project or a company steps between the various phases from grass roots through to construction their market value increases. The step-wise increase in value is, however, greater if the transition between the first two phases, i.e. from grass-roots to exploration – "drilling the discovery hole" than it is between feasibility and construction (O. Kreuzer, personal communication, 2006). The reason for this being the largest value step is that most of the inherent risk lies in the grass roots phase. Therefore if the odds of success can be increased earlier in the exploration cycle there is the potential for a vast increase in value. The link between probability and value is a product of the "Expected Value" equation where:

$$EV = P * V - C \quad (1)$$

Where EV = Expected Value; P = Probability; V = Value and C = Costs. This provides a direct link between the economic value and technical probability and risk.

The realisation of poor and consistently declining exploration success rates has focused the minerals industry to the need to detect mineralisation deeper below the surface and to better manage the parameter space for exploration (Hronsky, 2004). This means developing ways to utilize the 3D technologies to increase exploration success rates for buried or "blind" deposits. Therefore many of the recent advances in the technology are focused on visualizing and mapping the 3D geological system which should in turn, be reflected with increasing exploration success rates. It also has forced us to look at other industries, such as the oil exploration and pharmaceutical industries, which had been faced with higher costs, diminishing success, and increasing time-frames to discovery, and who turned to a risk-managed approach to solve these problems.

THE EVOLUTION OF 3D GEOLOGICAL MODELS

The first 3D geological models that the company Fractal Graphics built were of the gold deposits of Kanowna Belle in Western Australia and Macraes in New Zealand. They were constructed using the Vulcan software package and were used to constrain ore resource estimates (Figure 2). These models were essentially a manual 3D interpolation of drill hole logging and factual geological mapping. During the next ten years numerous models of open pit and underground mines were constructed. It was only in the late 1990s that the first terrane scale models were constructed (e.g. Archibald et al., 1998). These terrane scale models used and incorporated multiple geophysical datasets (magnetics, gravity and seismic) in 3D (Figure 3). The terrane scale model relied heavily on geological and geophysical interpretation, and contrasted with models of mine environments where the geological entities where constrained by relatively dense data sets. It also used for the first time "worms", a multi-scale edge detection technique for potential field data was used (Archibald et al., 1999; Boschetti et al., 2000; Holden et al., 2000; Horowitz et al., 2000).

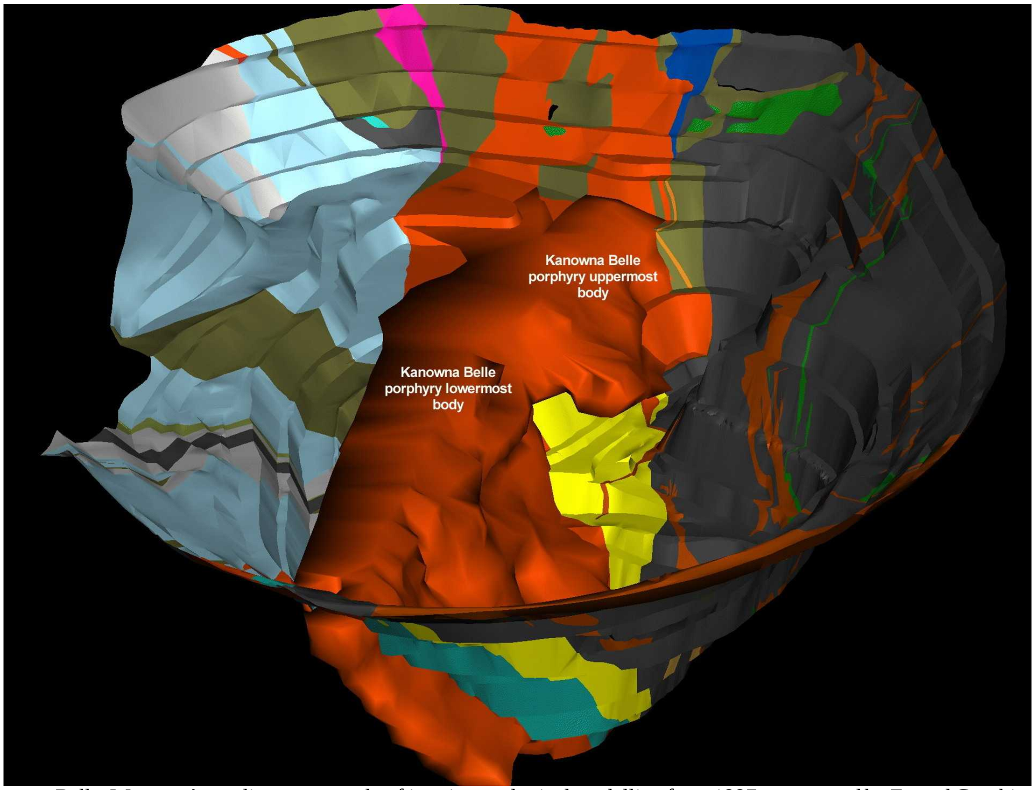

Figure 2: Kanowna-Belle, Western Australia - an example of in-mine geological modelling from 1997 constructed by Fractal Graphics for Delta Gold NL. The figure shows an oblique view of geological mapping draped on an open-pit shell, with a 3D model of a porphyry body within the pit. The model is based on geological mapping and drill-hole logging. The pit is approximately 800m by 600m.

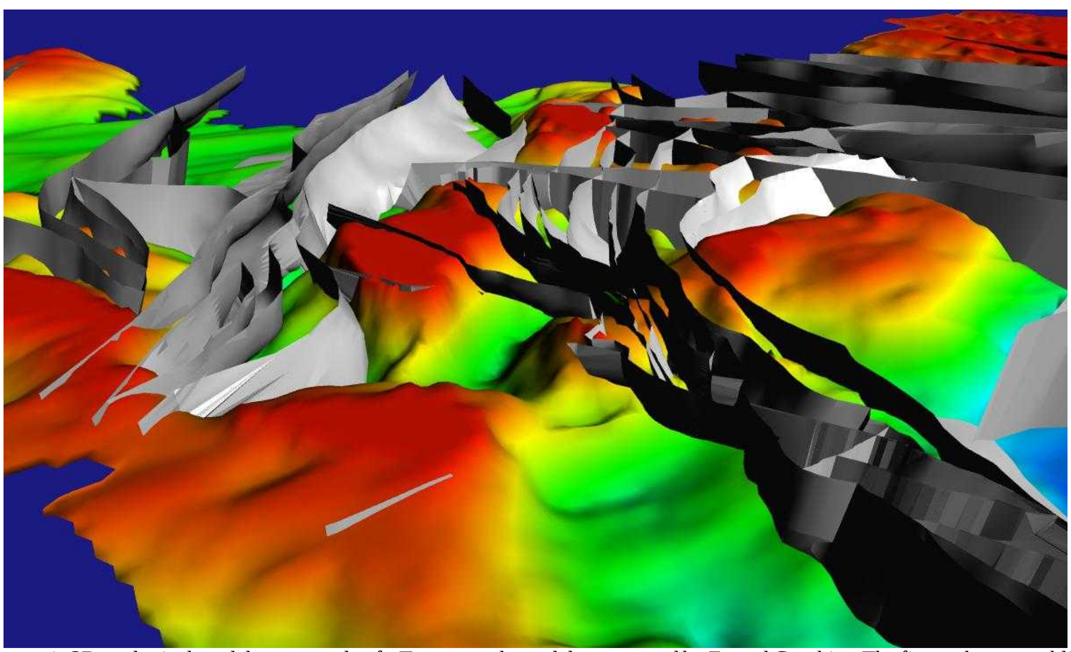

Figure 3: Tasmania 3D geological model, an example of a Terrane scale model constructed by Fractal Graphics. The figure shows an oblique view of the Devonian granitoids of NW Tasmania (coloured surface, intersected by major faults (grey surfaces). The model is based on interpretations of magnetics, gravity and seismic data as well as surface interpretive geological maps. The view is approximately 300km by 200km and to a depth of 15km.

In the early 2000's, GoCad, a software modelling package largely developed for the petroleum industry, was adapted for the minerals industry. In Geoinformatics Exploration, GoCad superseded Vulcan as the preferred modelling software package. However, model building was still slow because GoCad is a CAD-based program. It has only been recently with the development of software based on mathematical interpolation (eg Leapfrog) and geological rule-based interpolation (eg Geomodeller) that the building of multiple iterations of complex geological models has become a reality (Figure 4). Due to the increased speed, the modeller is able to understand the influence on the model of individual input datasets and can add or remove the inputs depending on the level of extrapolation required. As a result the effect of interpreter bias can be reduced and the main variations in product are a direct result of scientific uncertainty.

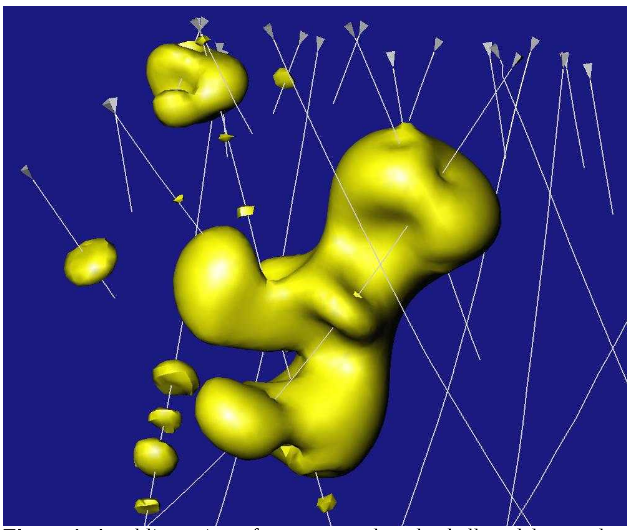

Figure 4: An oblique view of an automated grade-shell model created by Leapfrog software. The yellow surface represents ore at a specific cut-off grade. The white lines are drill-holes. The model is approximately 600m by 300m and modelled to a depth of 500m.

It is of utmost importance that all information required for interpretation is properly tagged to ensure that the information's origin and level of interpretation is fully separated. We refer to this as the separation of "Fact, Fiction and Mythology" where:

1. "FACT" – refers to measured and directly observed information such as geophysics, chemistry and factual geological data which accurate to within the bounds of scientific error.
2. "FICTION" – refers to interpretive geology maps and manually interpreted geological models that have considerable extrapolation of geophysical and geological data.
3. "MYTHOLOGY" – refers to the dogmas and biases of regional interpretation, metallogenic models and mineral exploration targeting.

Commonly a regional geological or targeting model may have between 30 and 50 input datasets. Each dataset has limitations in its coverage and accuracy. Managing these input datasets and their resulting product requires advanced spatial and non-spatial information systems. In the 1990s, Fractal Graphics embarked on a project in conjunction with CSIRO Divisions on Geomechanics and Information Technology to see if a 3D modelling package could be developed that could store and query complex geological data sets and models. One of the core results to come out of this project was a data model that was predicated on utilizing an object-oriented database. After continued frustration of trying to get the GIS and CAD worlds to interact with one another, Fractal Graphics embarked on a software development program in 1996 to develop a truly 3D GIS. This project has been continued by Fractal Technologies with the development of FracSIS and SDS. Figure 5 represents a graphical representation for a data model and allows for the user to track inherent uncertainty to the final models on the data source and data type.

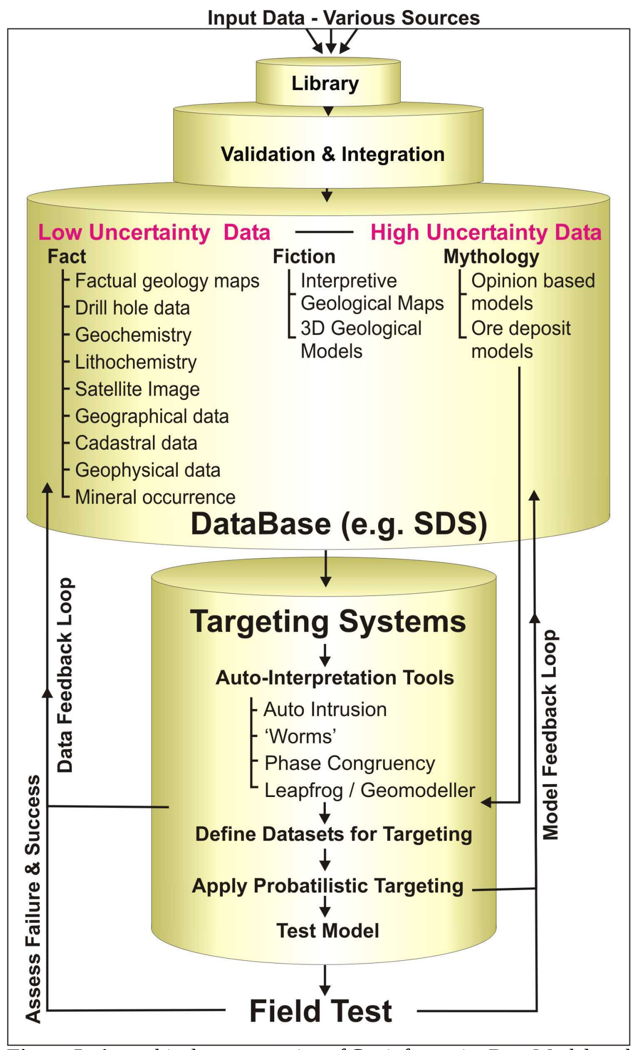

Figure 5: A graphical representation of Geoinformatics Data Model, and data flow; showing the separation of "Fact, Fiction & Mythology". The feedback loops allow targeting models to be better defined based on the results of the targeting process and field checking.

THE INTERROGATION OF 3D MODELS AND DATABASES FOR TARGETING

When the building of 3D digital models became a reality, there were major efforts made to understand how to utilize these models in exploration targeting. The petroleum industry in the early 1990s used large immersive 3D visualization environments, such as Caves, where large collaborative teams worked on 3D models and the solutions were in part, visually obvious. This approach would work in the minerals industry where there was uniform density of data, such as a mine site, but it would not be generally applicable to many of the terrane scale data sets. However a more practical reason as to why the large-scale visualisation approach has not been extensively applied to the minerals exploration industry is cost; these systems are very expensive.

The minerals industry started to look at other ways to interrogate large regional terrane scale data sets. Whilst the integration of vast amounts of spatial data enables an exploration team to better understand the distribution of the geology, it does not by itself get them closer to a mineral exploration discovery. With the advances in the control of data and its 3D representation, many explorers began to suffer from information over-load and ended up returning to one or two datasets that they believed were the key to discovery.

Whilst manual interpretation still plays a huge and key role in our industry, as exploration goes deeper and undercover the interpretation become far more subjective. In part, the key to improving this is to provide interpreters with better 3D environments and tools. The technology to synthesize the information into automated targeting are only now being developed. Most of these techniques are based on an empirical approach, whether manual (the expert interpreter) or automated (weights of evidence, fuzzy logic, neural networks)

The automated empirical approaches have been largely driven by looking at techniques employed in other industries. A "Weights of Evidence" approach (Agterberg, 1993; Gardoll et al., 2000) was based on utilizing Bayesian based query functionality available in GIS software that was being adapted for the Minerals industry. Other techniques that have been employed include fuzzy logic and neural networks. The main issues that rest with these techniques is that they are strongly biased by correlations with known mineralization. Nevertheless, these techniques have an important place in exploration targeting specifically if they are based on good data and are used in conjunction to other techniques.

A PROBABILISTIC APPROACH TO EXPLORATION TARGETING

One way to increase targeting success is to source techniques from other industries that have tackled similar problems. The oil industry has seen a marked increase in exploration success by assigning risk to the variables required for an oil or gas resource to be present (Rose, 2001). For example, if the probabilities of the presence of source, maturation, pathway, reservoir and trap can be established then a relatively accurate probability of discovery can be established. Some major petroleum companies, for example, will not drill a well unless there is a >50 to 60% probability of success is calculated (C. Bramley, personal communication, 2006). The probability of an oil deposit forming is based primarily on the simple and well understood tenets of:

1. Source – was/is there favourable hydrocarbon source region?
2. Maturation – was/is there a favourable thermodynamic regime to produce liquid or gas hydrocarbons?
3. Pathway - was/is there the conduit to allow the hydrocarbons to migrate?
4. Reservoir – is there a focusing porous body that can hold a large quantity of hyrdrocarbons?
5. Trap - is there a suitable structure with low permeability to allow the hydrocarbons to pool?

It is necessary that all of the above items in points 1 to 5 above exist(ed) both temporally and spatially. If anyone of them did not exist then there is a zero probability of discovery. Therefore the probability of discovery is a multiplication of the individual probabilities of each of the above items existing. This approach differs from other methods such as Weights of Evidence which is more focused on scoring areas using an additive approach. As a result the probabilistic approach generally reduces the number of targets in an area (Figure 6)

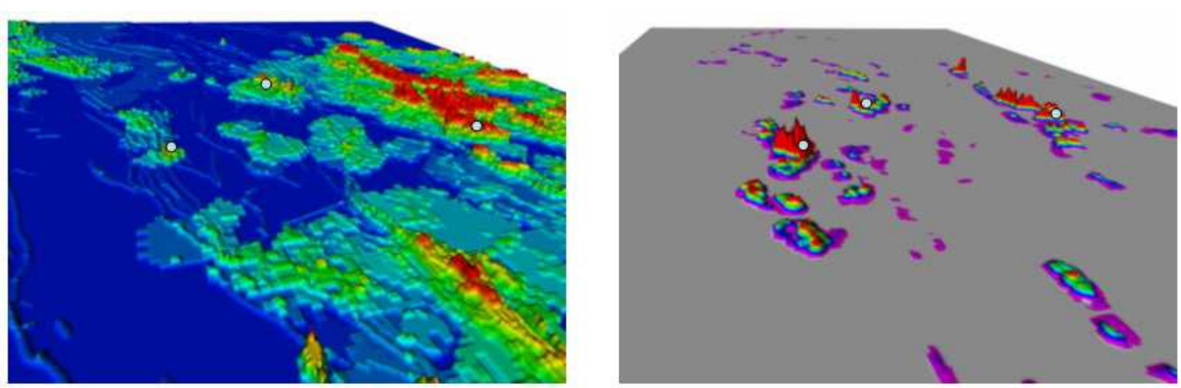

Figure 6: Automated Empirical Targeting verus Probabilistic Targeting. The figure shows two 3D representations of a targeting grid. On the left is an additive targeting grid using a Weights of Evidence approach; and on the right is a multiplicative targeting grid using probabilistic methods. Red areas are areas of increased potential and the small blue dots are known deposits. The figure illustrates that a probabilistic approach uses is more selective and allows for a prioritization of targets.

Hydrocarbon exploration is dealing with a single type of deposit represented by a simple system with relatively few variables, laminar fluid flow, and relatively simple basin architecture and structure in the shallow crust. In addition, the location and form of oil deposits is controlled by the current structural geometry in the crust making it much easier to determine if a trap is present.

In contrast within minerals exploration, different metallogenic models are necessary to understand each type of ore deposit and many of these models are the subject of considerable debate. Ore deposits commonly form in ancient complex structural environments, from highly pressurized fluids sourced from the deep crust. Many ore deposits have experienced significant post-deposition deformation and overprinting which obscure the understanding of the original factors that led to ore deposit formation. Thus in minerals, as contrast to oil, the coincident set of events and variables required to form a mineral deposit are considerably more complex and challenging.

Geoinformatics has adapted this probabilistic approach pioneered by the oil industry in its search for mineral deposits, such as porphyry copper-gold systems. In porphyry copper-gold environments, the variables required to form an ore deposit utilizing the similar descriptors that oil explorationists use are:

- Source: Geology and lithochemistry of volcanic and intrusive rocks in a region can be used to determine whether prospective hydrous magmas were generated. For example, the petrology and hydrosity of known porphyritic rocks) and the use of Sr/Y ratios (Garwin, 2000).
- Pathways: Migration pathways are likely to be major structures that could be located using geophysical worms or other methods that can be used to separate major discontinuities from minor near-surface structure.
- Focus: Hydrous fluids are usually focussed around the margins of intrusions or smaller cupolas with can be detected using automated techniques for analyzing magnetic and gravity data.
- Trap: The best evidence for a trap is often the presence of a high-level (porphyrytic) intrusion, which can commonly be located under cover using magnetic or gravity data. Knowledge of the regional geology and the palaeosurface can be used to estimate if the depth of emplacement is in the pressure range for porphyry copper formation.

The algorithims developed by Geoinformatics for mapping the features noted above allow for both the probability of their existence in space, and the uncertainty of the data. Hence in order to reduce the levels of uncertainty, where possible, factual datasets are used that largely ignore the interpreter bias.

These datasets are used to estimate the probabilities of all the necessary features coinciding at any point in a project area.

Final outcomes are targets which are ranked according to probability. While the distribution of known mineralization was not used as an input into the model, it can be used to validate the results, as an independent assessment of the success of the model, and as an aid to providing a ranking cut-off for anomalies away from known ore systems. Geoinformatics has calculated in most cases that a 'good-target' has a probability of around 1 to 3% chance of a mineral deposit being present (and conversely a 97 to 99% chance that it is not). Whilst these probabilities seem low when compared to the oil industry (which is estimating up to 60% chance using their models), these probabilities are an order of magnitude better than the current industry average of 0.1% as noted above.

CONCLUSIONS

The lack of success of targeting world class and giant ore systems over the last decade has led to multiple approaches by different geoscience disciplines. The approach taken by Geoinformatics and its predecessor company (Fractal Graphics), with whom the authors have variously worked over the last 17 years, has been predicated on utilizing 3D data to exploration targeting.

In the early years when much of the work was around mine sites, 3D modelling played a significant role in targeting for extensional mineralization. However as the company evolved and became increasingly involved at the regional and terrane scale, it became apparent that visualization of 3D models alone was insufficient to produce effective grassroots targeting. This evolved the next generation of software and techniques for storing, integrating, and interrogating very large databases that commonly ranged from 10 to 100 gigabytes in size.

Geoinformatics is far from alone in the minerals industry at trying to find solutions to targeting using very large databases of disparate geoscience data. Over the past decade many targeting techniques have evolved. Most involve an empirical approach, whether that is manual or automated, such as weights of evidence, neural networks or fuzzy logic. Intrinsically these approaches throw up too many false positives and negatives and hence have a lower probability of exploration success.

Geoinformatics is currently using a probabilistic approach to targeting that originated in the oil industry as it tried to incorporate risk management into exploration targeting. This approach appears very suited to large hydrothermal and magmatic mineral systems where the processes that control mineralization are relatively well understood. Because such systems commonly involve mantle and crustal components, the input parameters into any technique that utilizes any probabilistic simulation have to be inherently 3D. Therefore, storage, integration and visualization of 3D data and 3D geological models, and the processing of geophysical data in 3D are vitally important.

Management of risk in exploration targeting is all about achieving better discovery success rates. Recent targeting by Geoinformatics for porphyry copper systems using the probabilistic approach has increased a technical success rate that is well above the industry average.

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