

Geological Models, Rock Properties, and the 3D Inversion of Geophysical Data

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ABSTRACT

Integration of multiple exploration data sets is widely acknowledged to add value to the targeting process, yet is still seldom done rigorously. Geological and geophysical data can be quantitatively reconciled only through their common representation as physical property models. 3D geological models attributed with physical properties may be constructed from primary geological data. Geophysical data are transformed to physical property models through inversion. Inversion methods are also able to perturb prior physical property models, under a variety of constraints, such that the updated model is consistent with both the geophysical data and the given constraints. If the initial physical property model, and the inversion constraints, arise from a geological interpretation, then the geophysical inversion directly and quantitatively adds value to the geological model by forcing its consistency with the geophysical data. The result is a quantitatively integrated exploration model supported by multiple data sets, more certainty in interpretation of exploration data and, consequently, higher quality drill targets. Application of these principles has proven to add value and has been credited with ore discovery. Success in adding value to geological models using the methods of geophysical inversion relies on several technologies working together. These are the technologies of the geological modelling itself, the physical property attribution methods, and constrained inversion. Constraints passed from the geological model to the inversion may take many forms, such as drillhole marker constraints, physical property bounds or multi-variate distributions, direct lithology constraints, or topological constraints. The implementation of each of these technology components into a practical, working system is described.

INTRODUCTION

By integrating both geologic and geophysical techniques, the project or asset team can identify and rank opportunities driven by selectivity based on sound science and business criteria (Reeckmann et al., 2007).

Statements such as the one above, drawn from a recent paper on petroleum exploration, are representative of common practice in the oil industry for at least the past decade. Data integration practice in mineral exploration lags significantly, in spite of a number of attributed successes, including discovery.

Quality mineral exploration targets have become increasingly difficult and expensive to find and test. Obviously identifiable geophysical anomalies have generally been tested already in known productive mining camps. As depth of exploration or the complexity of target environments increase, explorationists must look at data for increasingly subtle indications of possible ore. Direct geophysical detection becomes less likely. Initial target identification becomes much more a challenge of recognizing the 3D context of the near-ore environment than finding the bulls-eye itself. Although the ore setting provides a larger target to search for than the economic orebody, its characterization is much more complex. Its recognition depends on our ability to model the 3D geometric

relationships amongst ore, the mineralized and altered environment around it, and the general configuration of the host lithological and structural variability at both regional and project scales.

The ability to simultaneously model and interrogate geophysical, geological, geochemical, and geotechnical data positively impacts our targeting capability and reduces geological uncertainty. The value to both mineral exploration (Martin et al., 2007) and mine planning (Pretorius et al., 2007) has been proven conclusively but is not widely applied. Successful implementation requires the capabilities, amongst others, of generating 3D models of ore environments, modelling their expected geophysical response, and updating existing models to enforce consistency with geophysical data. Such "common earth models", consistent with all lines of evidence, must also be subject to 3D query or expert-system inspection to identify, rank, and prioritize targets. This paper focuses on a key aspect of the required technology suite: the link between the geological model and the geophysical data.

A simple and general framework for integrating geological and geophysical data for exploration targeting is initially discussed. The remainder of the paper summarizes the geological and geophysical modelling technology and knowledge required to put it into practice. Understanding and

manipulating physical properties in prospective ground is the theme that unites each component of this paper.

A TARGETING FRAMEWORK

An ideal to strive for is a system that takes exploration data and a conceptual target model as input, and automatically generates quality drillhole targets as output (Figure 1). The technology is a long way off.

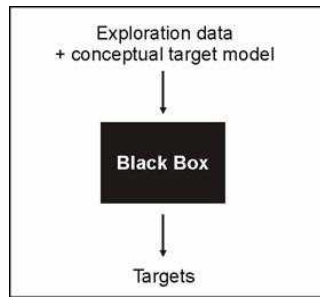


Figure 1: Ideal targeting system.

The problem of transforming data to targets could reasonably be tackled as either an automatic, data-driven, artificial intelligence approach or by the expert-driven approach of breaking the problem into components and analyzing them as geoscientists. The latter approach is taken here. Although the black box of Figure 1 is remote, it is possible to design system components that approximate it. 3D geological modelling, physical property analysis, and constrained inversion must figure prominently. The first logical step is separation of the geological interpretation from the targeting based on that interpretation. This means creating an earth model or, better yet, a range of earth models, consistent with the data and the conceptual target model. The earth models created can then be interrogated by a separate targeting system for indications of the presence of the ore system sought (Figure 2).

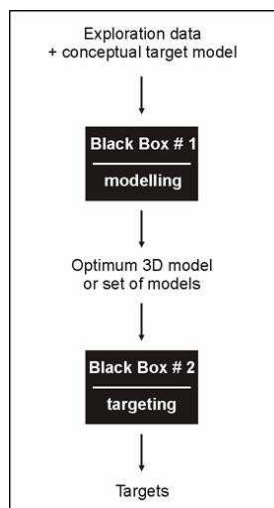


Figure 2: The exploration process as modelling followed by targeting.

Figure 3 illustrates a schematic expansion of the black boxes into one possible process: a series of steps that can be done with practical tools today, and are currently being employed by some leaders in the industry. Although the steps in Figure 3 are shown for simplicity as a linear progression, reality is more complex. The query and target generation may feed back to refining the initial conceptual model. Geophysical inversion may play a role in initial construction of the 3D structural model, with aspects of that structural model constraining a later inversion designed to map 3D physical property distributions within certain formations. (Because of the complexity of the interdependent relationships between different, quite technical, processes, new “workflow” software interfaces are being developed to facilitate the practical work by keeping the user interface close to the business problem level, as opposed to getting bogged down in numerous drop-down menus and dialogue boxes asking for detailed input, such as inversion control parameters(Perron, 2007)).

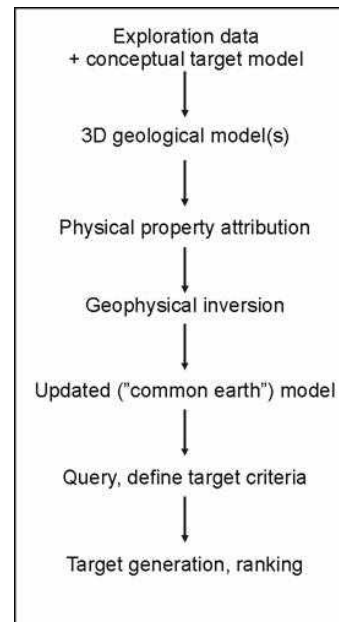


Figure 3: One practical implementation of a targeting process flow.

Each of the steps of Figure 3, and the connections between them, are conceptually simple. The technologies corresponding to both the steps and the connections between them, however, present significant obstacles to practical implementation. There are theoretical computational challenges, software development challenges, and challenges in quantitative characterization of expected ore deposit models.

The remainder of this paper reviews geological modelling, rock property modelling, and geophysical inversion technology. What is achievable today as well as present obstacles are discussed, with the scope restricted to the modelling component of the process of Figure 2. The targeting component is in a similar state of progress: descriptions and examples of data management, 3D query, and model-based targeting, not discussed further here, can be seen in Apel (2006), Sprague et al. (2006), Caumon et al. (2006), and Martin et al. (2007).

GEOLOGICAL MODELLING

Over the years there has been a steady progression in the technology available to the earth scientist to construct models based on geological concepts and field data. 2D GIS mapping systems have been commonplace in exploration offices for more than ten years. They combine modelling, spatial analysis, and query functions, although the 2D limitation makes the technology unsuitable for the purpose here. Mine planning system software, designed for resource modelling and mine engineering, has become increasingly used in 3D exploration applications despite obviously critical deficiencies such as lack of both structural modelling tools and support for geophysical data. The core limitations of conventional 2D GIS and 3D mine planning technology means we must look past them to new technology if we are to succeed in our data integration program for targeting.

Geological models take many forms, from ideas and sketches to fully 3D representations that capture many of the important characteristics of the earth. In all cases they are a partial representation of reality. Geological models can have multiple definitions, including conceptual, genetic, and spatial. For the purpose of providing a foundation for data integration and targeting, we must construct a 3D spatial geological model based on field observations. This multidisciplinary model will be based on observations that may include map and drillhole data, structural and stratigraphic histories, geophysical and geochemical data. The processes must be able to cope with the sparse data of regional, greenfields exploration as well as the rich data environments of in-mine or near-mine exploration. The last several years have seen remarkable advances in the technology and methods of 3D geological model construction. Technologies originating in the oil and gas domain have been successfully adapted and extended to mineral exploration applications at regional, camp, and deposit scales. They are now being deployed by major mining companies, junior exploration companies, and geological surveys for modelling complex, 3D geological environments for ore targeting.

In a ten-year-old oil industry paper on 3D data integration that popularized the term “common earth model”, Garrett et al. (1997) summarize the significance and benefit of multi-disciplinary modelling.

The advent of 3D earth modelling computer systems suggests there is potential to transform the work processes in cross-disciplinary asset teams. By sharing common digital 3D representations of the subsurface, the team can iterate between disciplines more easily, rapidly incorporating new information into existing models. Up to now, many cross-disciplinary teams have emphasized the importance of software communication, 3D visualization and data access. From now on, we believe that earth modelling issues will assume greater significance in the business of these teams.

The ability to iterate between disciplines and easily, rapidly incorporate new information into existing models is the core business-level requirement of the modelling technologies that are necessary to provide a foundation for the targeting process of Figure 3.

Vector and Raster Model Representation

To be useful in a general, practical sense, the geological model must have both “vector” and “raster” representations. Geological interpretation is most naturally done as a 3D vector model, while geophysical and geochemical interpretation is (usually) most naturally done through raster or gridded models. The vector model representation is the collection of 3D, triangulated surfaces that separate volumetric model regions with distinct geological identity. Faults, formational boundaries, lithological contacts, facies boundaries, ore envelopes, mineralization boundaries, and alteration zones are examples of typically modelled surfaces. Very often these surfaces represent 3D physical property discontinuities and are thus amenable to verification and modification by testing against geophysical data. (Adjusting the geometry of a physical property discontinuity to force consistency with geophysical data is a type of geophysical inversion.) Such models are often constructed from sparse observational data, and the modeller must exert interpretational control while maintaining consistency with observed data. Techniques and powerful software tools have been developed over the last ten years for rapid model building and editing with sparse data (Euler et al., 1999; de Kemp and Sprague, 2003; Sprague and de Kemp, 2005). Effective and rapid techniques of fault-block definition, formation construction, downplunge projection, and structural extension are now available. Experience has shown that it is critical for the modeller to retain direct interpretational control throughout the process, just as in the process of making 2D geological maps.

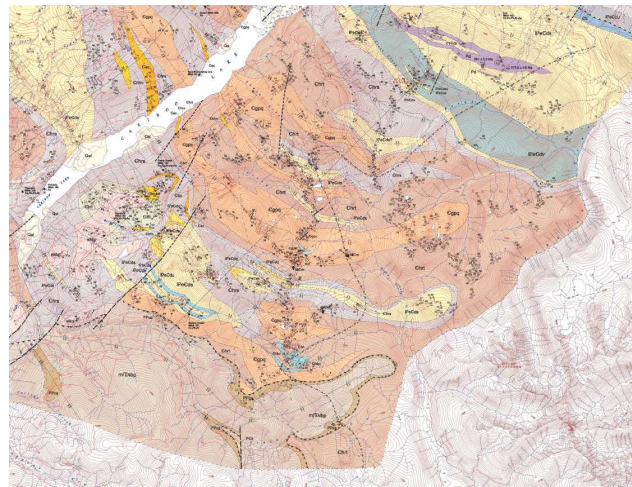


Figure 4: Camp-scale 2D geological map as basis for 3D structural model.

The following example graphically depicts a typical sequence of steps in the construction of a regional or camp-scale common earth model from a wide variety of data sources, beginning with the structural model. In practice all spatial data are incorporated, not just those shown in this example. This example is from the Frank Creek area of the Barkerville Terrane, British Columbia, completed in 2004 by Barker Minerals Ltd. The Barkerville Terrane contains occurrences of multiple ore types: porphyry Cu-Au, vein gold, placer gold, and Ni-PGE at

its margins, and massive sulphides in the central Frank Creek area. It has a mining history dating back to 1860. The primary software we use is Gocad, a flexible and powerful 3D geological modelling technology originating in the petroleum industry that has found wide use in mineral exploration over the last ten years. It is particularly suitable for creating large, 3D multidisciplinary models of very complex data.

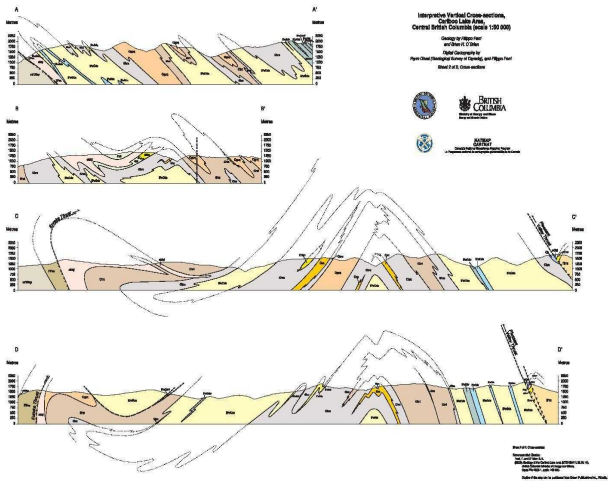


Figure 5: Structural sections used as 3D model input.

Basic starting elements in a compilation are typically a digital elevation model, a 2D geological map (Figure 4), structural measurements, and interpreted cross-sections (Figure 5). Not all these components are required, in particular 3D regional models are often made without pre-existing 2D sectional interpretation or drillhole information.

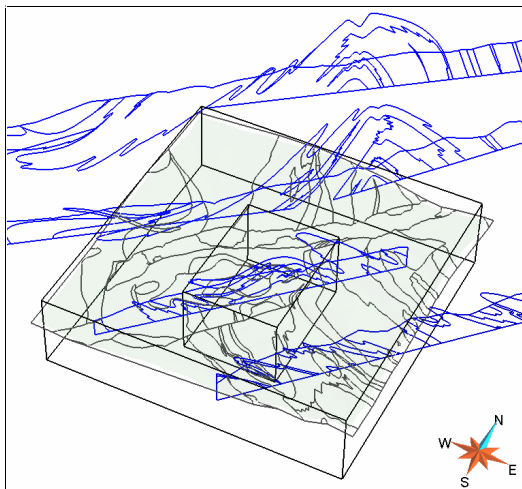


Figure 6: 2D map and section contacts digitized and rectified in 3D.

In the example shown here, maps and sections from government interpretations were digitized and rectified in 3D, as shown in Figure 6 (sections in yellow, map contacts in grey, model extents as white rectangular boxes). In this case two scales of modelling were completed simultaneously, as shown

by the larger and smaller boxes. It is a system requirement that multiple 3D model scales must be handled simultaneously, just as we demand of 2D mapping. Figure 7 shows the topographic surface coloured by elevation. Structural data are posted correctly in 3D (bedding control symbolized by rectangular plates with appropriate strike and dip; foliation control symbolized by oval plates). Visualization of structural symbols in 3D, where structural data are available, is a key interpretational step in conceptualizing the structural architecture for guiding the 3D model construction (de Kemp and Desnoyers, 1997).

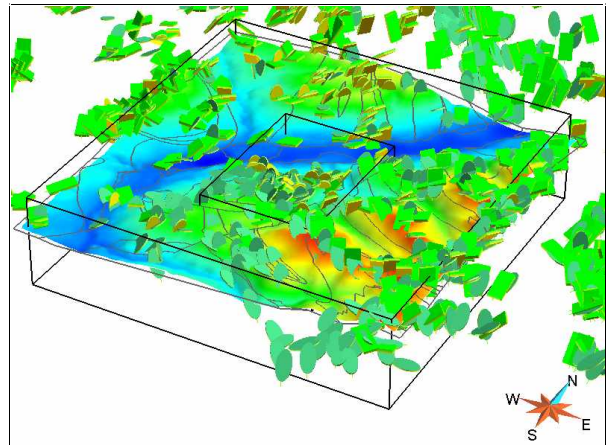


Figure 7: Modelled topography with 3D symbolization of structural data.

Structural models are typically constructed by initially building a “water-tight” network of fault blocks, working from the largest, youngest faults to the older faults. Formational contact surfaces are constructed to explicitly honour the map, section, and structural control. The “Structural Modelling Workflow” in Gocad guides the user quickly through the process, by automating repetitive tasks while enabling direct 3D editing. The vector structural model of Figure 8 (close-up in Figure 9; faults in blue, formational contacts in other colours) was quickly constructed from only the map, section, and structural data shown.

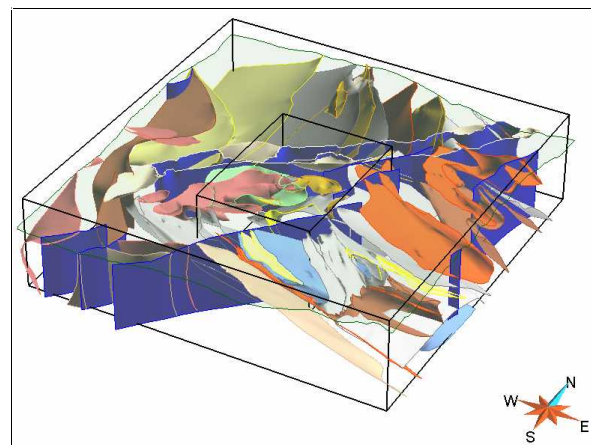


Figure 8: The 3D structural model.

A vector earth model—a collection of discontinuity surfaces enclosing volumes—is insufficiently general to capture the expected physical rock property distributions which are responsible for the geophysical data. This is true even in sophisticated models that permit rock properties to be represented by analytical functions per model volume, as is often done in petroleum applications in which velocity models are represented analytically layer by layer. We require a rasterized version of the model in which the model is fully populated by polygons that can discretize the physical property distribution. In the simplest case the polygons are rectilinear (the classic 3D grid) but the model can also be rasterized by tetrahedra or more complex polygons.

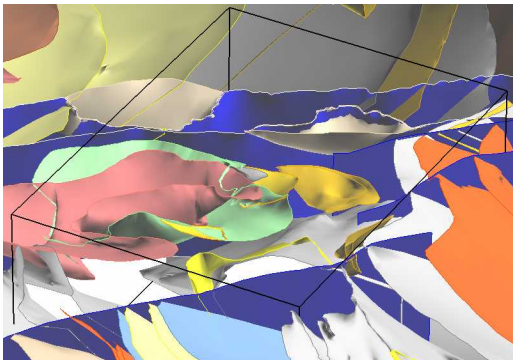


Figure 9: Detail view showing complex structural geometry.

After the 3D vector model has been divided into a series of sub-volumes (starting with fault blocks and formations), a grid or raster is superimposed on it to carry rock properties such as lithology and alteration classifications, density, electrical and magnetic physical properties, geochemical parameters, or metal content. The ability to rapidly transform the vector geometric model to a raster grid model, and then maintain multiple versions of the raster model with different properties at various resolutions, is a critical technology component. In Figure 10 the cells of the raster model are coloured by formation, some of which are cut away in Figure 11 showing a simple but highly effective visualization of the 3D solid geology, in addition to being able to carry and display an arbitrary number of scalar, vector, or tensor numerical properties per grid cell.

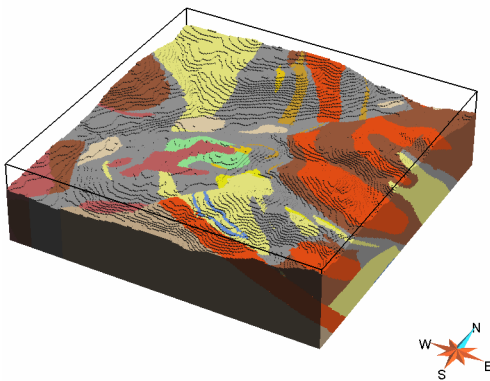


Figure 10: The raster gridded 3D structural model, simply converted from the vector model of Figure 8, with cells coloured by formation.

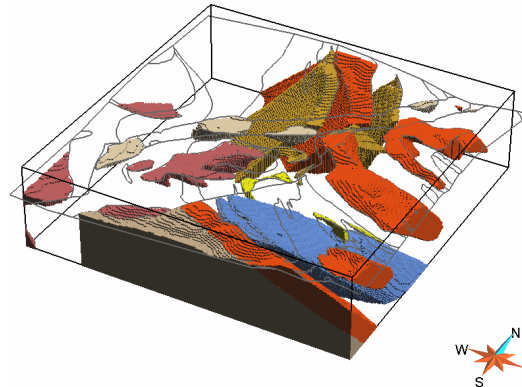


Figure 11: Raster structural model of Figure 10, with several formations cut away to expose internal grid geometry.

Once the 3D model is constructed, dynamic visualizations that make a meaningful difference to interpretation are simply made. Figures 12 illustrates formations on multiple sections that may be scrolled through rapidly and interactively. Figure 13 shows proximity to major structural breaks, another simple property of the model on the same sections.

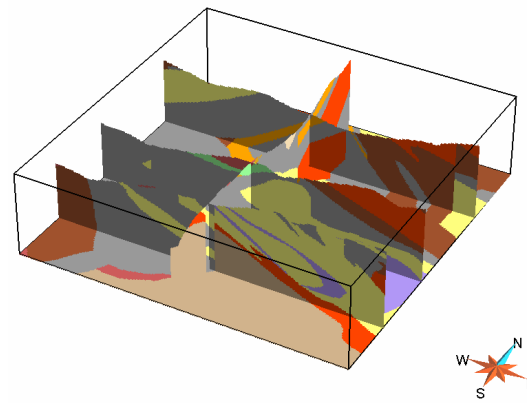


Figure 12: Sectional and level plan views of formations in the 3D structural model can be visualized rapidly and dynamically.

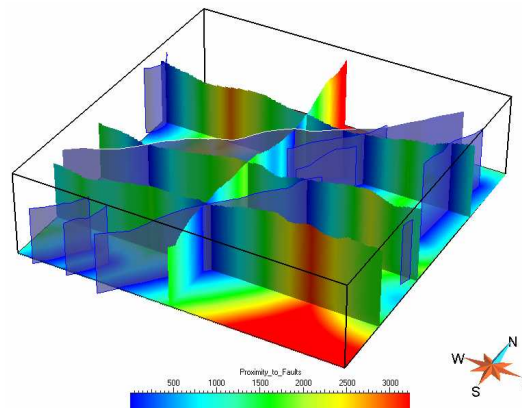


Figure 13: Sectional display of proximity to major faults. Any numerical property or classification can be interactively displayed and the model queried to identify subvolumes that match multivariate criteria.

Data Structures for Integration and Targeting

The 3D vector and raster models provide the basic data structures for reconciling geological and geophysical data. It is a simple conceptual step from a 3D structural model to a grid that can support physical properties (Figures 4–12), to forward modelling or inverting geophysical data. It is important to note that without a fluid implementation of these technologies, this simple sequence of steps is difficult and time-consuming. That is why most geophysical forward modelling for purposes of survey design or target detectability studies is still based on highly simplified earth models. Hypothetical geophysical surveys over ore targets are still primarily forward modelled by considering the host geological environment as homogeneous, which is very seldom a reasonable assumption. Even if the so-called “geological noise” is considered, it is often assumed stationary, which is not a reasonable assumption, as is obvious from inspection of any magnetic or other geophysical map.

Query of the geological model to establish quantitative target criteria (based on known ore occurrences within the model, if they exist) and to find new targets is not the focus of this paper. Nevertheless, it is worthwhile to note that at this point in the geological model construction, with the basic structural framework in place as both a vector and raster model, the foundation has been laid for supporting a quantitative query framework. The simplest targeting queries to be performed on the model are those that simply identify cells matching a set of defined criteria based on exploration reasoning. For example, it is simple to identify sub-volumes of the model that correspond to certain target depths, formations, physical and geochemical properties, and proximity to drillholes, faults, and fault intersections. Much more complex queries can be similarly performed by combining the raster and vector data structures, involving parameters of inclusion, proximity, intersection, trend, and geological feature (Sprague et al, 2006).

The Art and Science of Geological Modelling

As a final note on geological modelling technology, it is worth bearing in mind that research into the knowledge-building process of transforming data into geological models somewhat pessimistically indicates that the modelling black box of Figure 2 will not be achievable for a very long time, if ever.

Individuals interpret field evidence to constrain possible histories and explanations, and these are regularly under-determined by available theory and data, resulting in multiple valid explanatory models where selection of the optimal model is often described as being an art as well as a science... the development of geological map unit concepts is influenced by theory, data, individuality and specific situations (Brodaric et al., 2004).

Automated geological modelling approaches such as observation-based stochastic methods, or other probabilistic approaches to exploring geological model space, have profound system biases. Direct interaction of the modeller with the model will be required for the foreseeable future. More useful research will focus on simplifying the modelling steps through user-guided workflow interfaces (Perron, 2007).

GEOPHYSICAL INVERSION

Advances in geophysical inversion algorithms and computing speed over the last decade have reached the point where inversion methods can be routinely applied to many types of geophysical data. The output of inversion is a physical rock property model: quantitative estimates of physical property values at defined spatial locations in the subsurface. Through the common currency of the physical rock property distribution, inversion methods can directly add value to structural, topological, and geometric interpretations of the geological model described in the previous section. Inversion methods may directly predict the presence and location of ore, or ore environments, within the geological model.

In this section, unconstrained and constrained inversion are briefly reviewed in the context of data integration. Unconstrained inversion, as it has become commonly practiced in industry, adds generally vague value to geological models. On the other hand, constrained inversion, more rigorous and useful as the direct link connecting the geophysical data to the geological model, adds direct and measurable value. It is still seldom employed.

The Inadequacy of Conventional Processing

Although physical properties are the only link between geological models and geophysical data, conventional (non-inversion) processing methods make little or no reference to them. Most conventional geophysical data analysis tools can be seen as general filters, or “reductions”, that perform a series of manipulations of input data to produce a more sensibly interpretable output. Such well-developed and proven techniques, directly responsible for many important ore discoveries over the decades, will remain important, but have fundamental limitations.

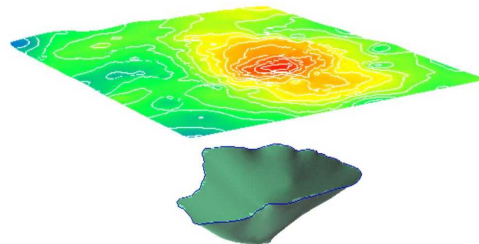


Figure 14. A map of gravity data over the anomaly-causing geological structure. The geometry of the structure is not discernable from the map.

An example is the series of corrections that are applied to gravity data. The input data is a series of measurements of the earth’s gravity field. The output is the same data series corrected for a number of factors (relative elevation, latitude, local topographic variation) that are known to influence the data but are not due to local density anomalies in the subsurface. The result is a corrected, local map of the gravity field, or a quantity easily derived from it such as a spatial derivative. The relationship between a map of the reduced gravity field and the underlying 3D density distribution is complex. The geological

model is, to say the least, difficult to discern from inspection of the gravity map (Figure 14). This is acceptable for shallow targeting, but is insufficient for interpreting complex or deep targets.

Unconstrained and Constrained Inversion

Conventional geophysical data processing has had great success in directly yielding the geophysical anomalies often associated with ore. The anomalies are identified in the data itself rather than in the model domain. The geological model, in whatever form it takes, is also conventionally not expressed in terms of expected or measured physical property distributions. Thus the connection between the geophysical data and the geological model remains conceptual, subjective, and non-quantified. Conventional data processing has severe limitations that make its use limited to heuristic geological interpretation and “picking anomalies”. Inversion, on the other hand, directly transforms geophysical data into physical property distributions that may be interpreted geologically.

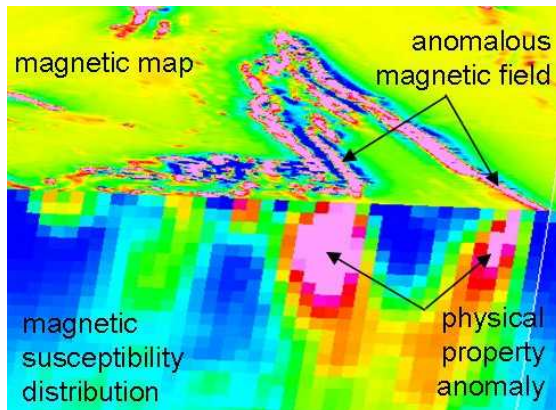


Figure 15: Unconstrained inversion of magnetic data results in a 3D susceptibility distribution, shown here on one cross-section. One of many possible physical property distributions (usually the smoothest) consistent with the magnetic data is computed.

Inversion has become fairly standard practice in mineral exploration. Most of the available inversion programs permit inclusion of prior geological knowledge, and thus offer the capability of directly adding value to the geological model. In practice though, they are seldom used in this way. Inversion is typically employed in much the same fashion as conventional geophysical data processing strategies, and is thus generally viewed as another data processing tool. In this view geophysical data is input to the inversion program and the output physical property distribution, “the inversion”, is interpreted much like other geophysical products. Because there is no direct connection to a geological model the parameterization of the earth must be highly generalized as a regular grid. It is seen as a 2D or 3D coloured map from which anomalies are identified. Figure 15 shows a typical inversion result. Physical property anomalies are generated underneath, or at least with an obvious relationship with, the mapped data anomalies. The principle advantages offered over conventional processing are that an

explicit depth scale is given and the anomaly shapes may have a direct geological interpretation. There have been many examples in which inversion practiced in this fashion has yielded tangible results with acknowledged value added, to the point of being credited with successful ore target generation at depth (Oldenburg et al., 1998).

Given less consideration is the fact that the inversion result is highly non-unique. Many other inversion results, not given, could have accounted for the data equally well. The depth scale, anomaly smoothness, and absolute physical properties are typically dependent on highly general assumptions built into the inversion algorithm—they do not derive from the specific geological context. Thus the connection to the geological model remains speculative. Such “unconstrained inversion” is attractively easy to do, requiring neither explicit geological modelling nor physical property analysis of the setting. While it is a major progression beyond conventional geophysical processing, it has severe limitations because the geophysical inversion and the geological modelling are still done in isolation, for comparison of results after the fact. Although the geophysical and geological results are at least now in the same model space for direct comparison (and often 3D visualization), the meaning of the inevitable discrepancies between them must be judged on an ad hoc basis. These discrepancies may be the subtle indications of anomalous mineralization. The value added remains vague, or at least inconsistently realized in a meaningful way.

Viewing inversion as a process of adding value to existing geological models requires moving beyond unconstrained inversion. What is needed are inversion processes that take as input both geological and geophysical data and create as output one or more geological models that are consistent with both types of data. For example, inversion that acts directly on the geometry of formational interfaces, while enforcing consistency with the drillhole piercepoint constraints, is required in addition to algorithms that act generally to establish physical property heterogeneity on large 3D grids. Mechanisms and examples of such “constrained inversion”, acting directly upon the geological model, always through a physical property parameterization, have emerged as practical tools over the last few years (for example, Fullagar and Pears, 2007).

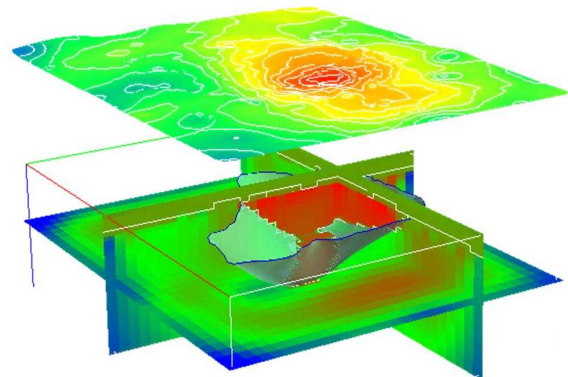


Figure 16: Gravity inversion constrained by a “reference model”, quantitatively linking the geophysical data and geological model of Figure 14 through a 3D density model, constrained to deviate minimally from a prior geological and physical property model.

Once we have a geological model that can support multiple parameterization styles, attributed with physical properties, and a range of geophysical inversion algorithms that can act on the model to bring consistency with both geophysical and geological data, we have a mechanism for using inversion to add value to the geological model by quantitatively testing its compliance with geophysical data and modifying it accordingly. A simple example is shown in Figure 16, which shows a constrained gravity inversion result as a 3D density grid. The density model is consistent with both the gravity data and the 3D structural geology model. The 3D structural model is expressed to the inversion algorithm as a 3D volumetric density “reference model” (Li and Oldenburg, 1998), on which the inversion acts to perturb minimally while enforcing consistency with the gravity data. This is a highly interpretable result, in which the structural interpretation can be verified, and residual density anomalies can be targeted for follow-up. The value added by the inversion, in comparison to either the historical standard of map interpretation (Figure 14) or of unconstrained inversion (Figure 15, showing a different model), is obvious and direct.

Constrained inversion modifies a given physical property distribution such that it will be consistent with a geophysical data set. It does so under a variety of constraints supplied by the geological model. The constraints can come in many forms, requiring a very general 3D earth modelling system and access to a number of inversion codes for various types of data and model parameterization styles. General types of constraints include physical property conditions, drillhole and other geological data “ground truth”, as well as topological and structural rules. The process of constraining an inversion minimizes, to a great extent, the problem of non-uniqueness by enforcing solutions that are explicitly in agreement with both hard geological data and interpretation.

An example (Bosch and McLaughy, 2001) with multiple data sets and constraints is illustrated in Figures 17 and 18, using the regional data and structural interpretation shown in Figure 16. In this case the inversion simultaneously solves for both a magnetic susceptibility and density model using magnetic and gravity data. A lithological model, a direct geological output, is also generated. Constraints included honouring joint physical property distributions (Figure 19), topological adjacency rules (anorthosite cannot be in contact with gabbro), and surface map constraints. This inversion used a Monte Carlo process, generating many equi-probable models (realistic for potential field methods, in which data residuals have a linear dependence on model perturbations), allowing calculation of spatial probabilities such as the occurrence of various lithologies within the model (Figure 18). Probabilities of other geological events can be ascertained, such as the chance of occurrence of a formation within a certain depth from a point on the surface.

Successful implementation of constrained inversion requires a number of technologies working together. 3D geological modelling is the foundation. It must have both vector and raster topological modelling capability, as well as an extensive capability to work with physical properties. It also must be an open system that can connect to a wide variety of external geophysical inversion algorithms. Breakthroughs in inversion research may come from many sources, so systems must be open to new inversion technology as it arises. Finally, a knowledge of

rock property distributions in the relevant geological setting is prerequisite to maximizing the value added through inversion.

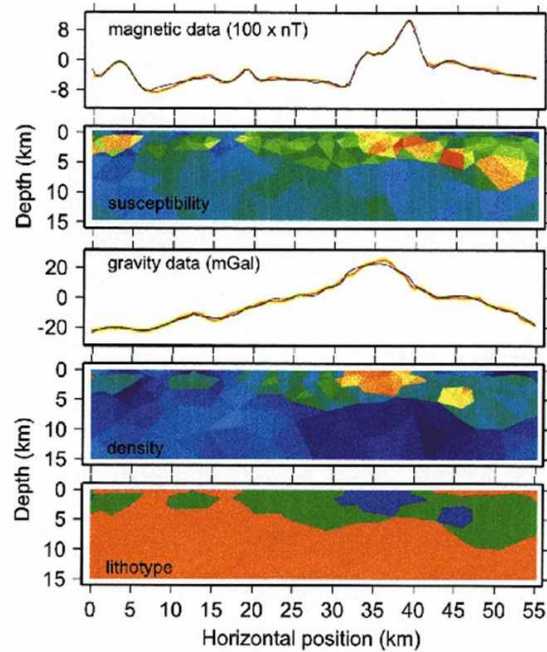


Figure 17: A constrained joint-inversion result of magnetic and gravity data. The data are shown as profiles in black line. The matching forward-modelled responses from the inversion results are shown as yellow lines on the data profiles. The inverted susceptibility and density models are consistent with all input data and constraints. The lithotype cross-section at the bottom is a geological result consistent with all prior geological data, geophysical data, and physical property data. The given joint density and susceptibility distributions per lithology are adhered to everywhere.

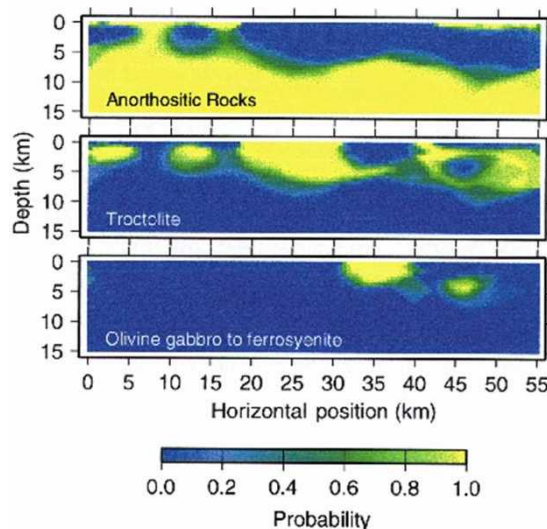


Figure 18: The lithotype section at the bottom of Figure 17 is one of a large suite of equiprobable geological sections, based on all input data and constraints. Shown here is the probability of encountering each of three lithologies everywhere throughout the section, based on the inversion set.

ROCK PROPERTIES

The inversion results of Figures 16–18 demonstrate by example real added value at marginal cost, based on new geological modelling and geophysical inversion technology that has come available in the last decade or so. The results in that example depend on the validity of the assumptions about rock property relationships shown in Figure 19. The output structural geometry, the physical property heterogeneity within units, and ultimately the value of the result for making business decisions rest on the credibility of the input physical property model.

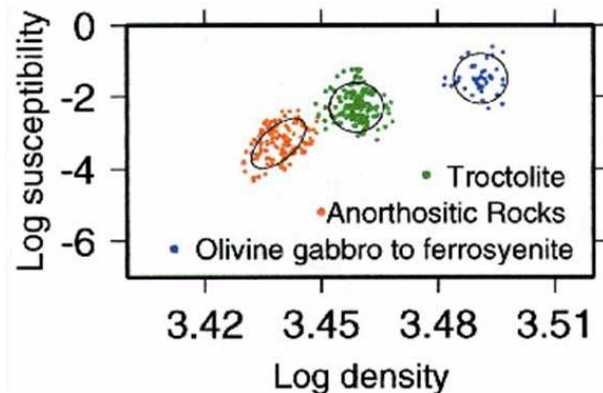


Figure 19: Crossplots of density and magnetic susceptibility according to rock type. The black lines show two standard deviation ellipses of the log-normal distributions used as prior information to simulate the properties for each type of lithology. The colour points represent the values of the properties for individual model elements. The scales are the base 10 logarithm of the density (in kg/m³) and the base 10 logarithm of the magnetic susceptibility (in SI units).

All interpretation of inversion outcomes is an interpretation of a physical property model. The value added is only as good as our understanding and expectation of physical property relationships in the relevant geological setting. It is not a reasonable expectation to confidently interpret inversion results without appropriate confidence in how geological description relates to physical properties. Correlation amongst individual physical property distributions, and their correlation with lithology, formation, alteration, and other variables all play a role. In fact, the entire question of relating geological models to geophysical data, for mineral exploration, is a question of understanding and manipulating models of physical property distributions in ore settings. We require both field-based petrophysical knowledge and the tools to work with physical property models.

Recognition of the importance of rock property knowledge is still lacking in the mineral industry. By contrast, in petroleum exploration, the importance of petrophysical data has been widely acknowledged as the foundation for geophysical survey design, processing, and interpretation (in addition to its origin in reservoir interpretation). The idea that an explorationist could maximize interpretational value of expensively acquired geophysical data without a reasonably good understanding of the physical property environment of the economic target would seem odd indeed, but that remains generally the case in mineral exploration.

Getting the most out of integrated interpretation means that reasonable physical property distributions must be attributed to geological models, either from measurement at the site or from knowledge of physical property distributions in similar settings. Experience working over a broad range of deposit types has demonstrated that physical property knowledge is generally poor. There are often magnetic susceptibility measurements available, that have been made with handheld instruments on core. Less common but still widely seen are density measurements, often made in conjunction with assays on mineralized core for eventual tonnage calculations. Electrical property measurements are rare. Calibrated wireline logging, having the twin benefits of making measurements in-situ and making many measurements over an entire package of rock types defining the ore environment, is also rare. In usual practice, when constrained inversions are carried out, physical properties are deduced from the geophysical data itself or looking up values in textbooks that one hopes may be representative (likely in vain). The former approach suffers from having to have a good prior knowledge of the 3D structural geometry, and the latter from lack of specific relevance to the area. When good, calibrated data are available it is typical to find alteration (which may be at regional scales) and ore environment mineralization to exert complex control on the physical properties. It is unreliable to make physical property assumptions based on the named rock type.

Rock Property Database System

Over the past eight years, an ongoing Canadian industry-government collaboration has resulted in the design and implementation of a reasonably comprehensive rock property database. It is called the Rock Property Database System (RPDS). RPDS brings together geological and geophysical information and facilitates interpretation of rock properties and corresponding geological description across geographic areas. This permits statistical and spatial characterization of the rock property environment for various ore deposit types in different geological settings. The significance of RPDS is that it provides a single repository for rock property data, as opposed to many disparate sources, thus allowing large-scale aggregation of data and in-depth analysis of rock property relationships (Parsons and McGaughey, 2007). This is a long-term project that should provide a valuable knowledge base for quantitative exploration analysis relying on a background rock property knowledge. Site-specific measurement must still be carried out.

Rock Property Representation and Modelling

The representation and manipulation of rock properties within the geological model is a vital technology component. In addition to 3D grids, rock properties must also be represented, and tools provided for geostatistical interpolation, on surfaces (Mallet, 1997) and other object types within the model. Recent research has shown great promise in separating the geological model parameterization from the physical property support (Frank, 2006) which will have profound consequences for

simplifying model construction and physical property interpolation by geostatistical tools. (For example, the “sub-blocking” done in resource block modelling, or other complex gridding for rock property modelling, may no longer be necessary.) Tools for mathematical manipulation of rock properties must be available, including both arithmetic and Boolean operations.

TECHNOLOGY SUMMARY

In general terms, constrained inversion provides a framework for adding real value to geological models. The process of integrating geological and geophysical data into a coherent model that can be effectively used to target drillholes is a conceptually simple three-step recipe:

1. construct a 3D geological model
2. attribute with physical properties
3. perturb the model to match the geophysical data while honouring numerous constraints.

While these three steps do not provide a comprehensive solution to the modelling need as set out in Figure 2, they can be followed now with commercial technology and have proven successful in both exploration and mine development. In practice each of these three steps requires a significant level of technology and knowledge for successful implementation, as outlined previously, which is part of the reason why the process is seldom followed. The other part of the reason is not technological, but rather the implementation of the technology.

PRACTICAL IMPLEMENTATION

The experience of playing a role in many practical 3D geological models constructed over the last ten years, over a wide range of specific objectives, commodities, geological settings around the world, scales, data types, and data densities, leads to a number of practical observations. The principle observation is this: the technologies described here make it possible to generate significantly better exploration targets—in fact it is not possible to follow this process without technologies such as those described here—but the business practices around the technology are more important for delivering ultimate value. Some general observations regarding the process:

- The model construction mechanics are always a minor part of a well organized project. Both the software and labour required for modelling have low cost in relation to the input data cost and output business value, if the business problem is well posed. Deployment of the modelling technologies described here should be seen as a necessary, relatively low-cost, service to the overall targeting project. Companies (or researchers) should not undertake “modelling” projects because models, in and of themselves, do not deliver value. They should undertake “target generation”, or other business-level projects, in which advanced, integrated 3D modelling is a well-defined step serving the business objective.

- Never start model building without a well-developed picture in mind of the final query and targeting process.
- Conceptual target models have a major, early impact on model construction decisions.
- Data compilation is the most significant challenge, particularly in brownfield environments with rich data archives. The data compilation and preparation in almost all cases takes an order of magnitude more time and effort than the modelling itself.
- Determination of model extents, resolution, choice and standardization of coordinate system, normalization of lithological and formational nomenclature, and legend standardization are important decisions made prior to any modelling. They can be difficult decisions because they demand perceptive anticipation of final targeting criteria and data elements. For example, assumptions regarding the gravity processing prior to inversion (Free air only? Bouguer-corrected? Terrain corrected?) may impact vertical model grid-resolution or decisions at a similar level of detail.

It is important to appreciate that, although the visualization power of the 3D compilations is great, the critical value added by this process is the 3D geological modelling itself, and its integration with the multitude of cross-disciplinary datasets. It is our experience that the process of creating such 3D models invariably results in re-interpretation of some aspects that were thought adequately understood in 2D. So the method or process is illuminating in itself; it is not simply a process of importing, rectifying, and visualizing various data sets.

CONCLUSION

In summary, a geological model to which one can, in a general fashion, usefully add value using geophysical inversion requires both a vector and raster representation, and powerful tools for rapidly creating, editing, and mapping between these representations. Structural modelling tools, geometrical interpolation, topological relationship management, tools for detailed model editing or updating, and the ability to manipulate physical property distributions are all essential. The ability to work successfully with physical property distributions also require the tools of geostatistics, including conditional simulation if uncertainty is to be managed. An open system that can connect with reasonable ease to new advances in geophysical software as they become available, from whatever R&D source, is important.

We are fortunate in being able to utilize the product of major research and development efforts in 3D geological modelling successfully carried out, and paid for, by the oil industry over the past twenty years. The application of this work to mining is fairly straightforward, but the mathematical and computational technology foundations are challenging. These include data-constrained geometric interpolation (Mallet, 1992), 3D topology management (for example, Caumon et al., 2004), automated structural modelling, uncertainty management (Thore et al., 2002), and advanced visualization (for example, Caumon et al., 2005; Castanié et al., 2005).

The major benefit in deploying these technologies is in reducing the risk of investment by providing a rigorously testable targeting environment. Exploration investment in an area becomes a strategically driven, traceable set of geospatial decisions, based on constrained model interpretations that offer targets based on specific query criteria. Targets might still be high risk, but would be characterized as such because of a quantifiable confidence level. The black box of Figure 1 may not ever be realized, but a set of proven technologies is available now to approximate them as sound exploration business practice.

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