The Common Earth Model: A Revolution in Mineral Exploration Data Integration

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Abstract

Success as an exploration company is the ability to explore ground and evaluate properties quickly and accurately. This depends on an accurate and timely understanding of multiple datasets from which we infer three-dimensional (3-D) geology. Whatever we are able to infer from our data, becomes our "model" of the earth, which is used to justify important economic decisions such as project prioritization, advancement, abandonment, drillhole targeting, and future exploration expenditures. Typically, earth models are mental pictures of the subsurface constrained by available data, interpretation, and informed speculation rather than quantitative, testable predictions of the project area geology. As a mental construct, an earth model is a collection of qualitative thoughts and beliefs about the subsurface that can only be approximately described, communicated, and shared either within an exploration team or to management, partners, or investors. On the other hand, a "common earth model" (a term borrowed from the oil industry) is an explicit, quantitative model of the earth consistent with all data, testable by drilling, and subject to editing and refinement as the collection of new data proceeds. As a quantitative distillation of everything our data have to tell us about the earth, a common earth model is a requirement for maximizing the value we obtain from our large investment in data collection.

Although it took many years to become standard practice, quantitative data integration at the map level brought to exploration by 2-D GIS technology is generally acknowledged to have created substantial net value through the creation of integrated, consistent maps. New software technology extends to 3-D all the benefits that GIS has brought to 2-D mapping, and data integration, by enabling the creation of common earth models. The extension from 2-D to 3-D is "revolutionary" because 2-D exploration data integration technology can account for only a limited subset of available data and cannot explicitly represent the 3-D earth. The new common earth model technology allows the explicit representation of 2-D and 3-D spatial exploration data and specific interpretations in a single model common to, or shared by, geologists, geophysicists, geochemists, and exploration managers. The result is a consistent spatial earth model; geological models, geophysical models, and geochemical models are simply subsets of the common earth model.

We have been experimenting with 3-D geological modelling as a tool for camp-scale exploration, property-scale and project-scale interpretation, and for in-mine ore delineation. We have made substantial progress in the integration of diverse datasets – for example, in forcing the consistency of sectional or drillhole interpretation, 3-D lithological models, 2-D GIS coverages, geophysical datasets, and physical property databases. The result is a consistent spatial geological model common to all disciplines. Such models can be visualized, shared, modified, and most importantly queried. They can be used in designing drillhole trajectories, and as a background geological framework for geophysical data interpretation. They also exist as an archival record of geological understanding of an area and how that understanding is constrained by data. Without such models, each earth science discipline works in isolation. Common earth models provide a sound basis for the development of new geophysical technology in which quantitative geological constraint is a key advance in interpretation. Building such models takes time, patience, and the will to apply new technology, but the resources required are small in comparison to the dollars spent in exploring such volumes of ground.

Résumé

Pour une société d'exploration, le succès réside en sa capacité d'explorer un terrain et d'y évaluer ses concessions rapidement et avec précision. Cela repose sur une compréhension juste et à jour de multiples ensembles de données permettant d'en déduire un portrait 3D de la géologie. Tout ce qui peut être déduit de l'étude de ces ensembles de données devient notre "modèle" de la Terre, et c'est à partir de celui-ci que seront prises les décisions d'importance économique comme l'établissement des priorités, la poursuite, l'abandon du projet, le ciblage des lieux de sondage, ainsi que les dépenses d'exploration à prévoir. En somme, ces modèles de Terre sont des représentations mentales du substratum qui sont définies par les données disponibles, par interprétation et une spéculation informée, plutôt que par des prédictions quantifiées et vérifiables de la géologie de la zone du projet. En tant que produit de l'imagination, un modèle de Terre est fait d'un ensemble d'idées et de croyances sur le substratum qui ne peuvent qu'être approximativement décrites, expliquées et partagées au sein d'une équipe d'exploration, de gestion, de partenaires ou d'investisseurs. Par contre, un modèle géoréférencé commun (common earth model) - terme emprunté à l'industrie pétrolière - est un modèle de Terre explicite et quantitatif compatible avec toutes les données, qui peut être vérifié par sondage, et qui peut être modifié et amélioré par l'apport de nouvelles données. En tant qu'outil d'intégration de tout ce que les données peuvent nous apprendre sur la Terre, un modèle géoréférencé commun est nécessaire pour maximiser la valeur de nos gros investissements de collecte de données.

Bien qu'il ait fallu plusieurs années avant qu'elle ne devienne une pratique normale, l'intégration de données quantitative en cartographie découlant de la technologie d'exploration 2D par SIG, on reconnaît généralement qu'il y a eu création substantielle de valeur par l'apport des cartes à données intégrées uniformes. En permettant la création de modèles géoréférencés communs, cette nouvelle technologie informatique permet l'intégration des données ainsi que d'étendre au domaine tridimensionnel (3D) tous les avantages que les SIG ont apportés à la cartographie 2D. L'extension du 2D au 3D est simplement "révolutionnaire", parce que la technologie d'intégration des données d'exploration 2D ne peut représenter qu'un sous-ensemble limité des données disponibles et qu'elle ne peut prétendre représenter une Terre tridimensionnelle. La nouvelle technologie de modélisation géoréférencée commune permet une représentation explicite en 2D et 3D des données spatiales d'exploration ainsi que des interprétations spécifiques dans un modèle commun ou partagé par les géologues, les géophysiciens, les géochimistes et les gestionnaires de l'exploration. En définitive, il n'existe plus qu'un modèle spatial géoréférencé commun; les modèles géologiques, les modèles géophysiques, et les modèles géochimiques ne sont que des sous-ensembles du modèle géoréférencé commun.

Nous avons mis à l'essai la modélisation géologique 3D à l'échelle du camp minier comme outil d'exploration, à l'échelle de la concession et du projet pour l'interprétation, ainsi que pour la délimitation du gisement en contexte d'exploitation. Nous avons accompli des progrès importants en matière d'intégration des divers sous-ensembles de données - par exemple, en forçant l'uniformisation de l'interprétation à partir des données de coupe et de sondage, des modèles lithologiques 3D, des couvertures SIG 2D, des ensembles de données géophysiques, ainsi que des bases de données de propriétés physiques. Il en est résulté un modèle géologique spatial, commun à toutes les disciplines. De tels modèles peuvent être visualisés, partagés, modifiés, et ce qui est plus important, interrogés. On peut s'en servir pour définir les trajectoires des sondages et comme contexte géologique pour interpréter les données géophysique. Ils représentent aussi des répertoires de connaissances géologiques d'une région et indiquent comment ces connaissances sont définies par les données. En l'absence de tels modèles, les efforts de chaque discipline géoscientifique demeurent isolés. Les modèles géoréférencés communs constituent une base de référence propice au développement d'une nouvelle technologie où les contraintes géologiques quantifiées représentent un avantage clé pour l'interprétation. L'élaboration de tels modèles demande temps, patience et la volonté d'utiliser des technologies nouvelles, mais les ressources requises sont limitées en comparaison des énormes sommes requises pour l'exploration de tels volumes de terrain.

INTRODUCTION

Until the last decade there was almost no explicit 3-D geological modelling done in the mining industry. "The third dimension of a geological object generally is accessed through the mental image that the geologist has of it. But this image of course is inaccurate and ephemeral (Kelk, 1992), difficult to communicate, and not necessarily the same for every geologist. Moreover, its consistency cannot be checked" (Renard and Courrioux, 1994). Interpretation of 3-D geological geometries has traditionally been done through projection onto 2-D sections, whether at the exploration scale or at the ore-reserve scale. The value of 3-D geological modelling in the process of resource estimation is now generally acknowledged – in the last decade, 3-D modelling at the ore-reserve scale has become fairly routine. It is now common for ore-boundary surfaces to be represented as 3-D meshes, and the ore reserves contained within them to be represented as block models of geostatistically calculated grades. The value of 3-D modelling in exploration, however, has not been adequately realized; 3-D models generally stop at the boundary of the ore reserve.

Although 3-D modelling beyond the ore boundary is seldom done, the importance of 2-D modelling using GIS technology has been recognized in the integration and interpretation of exploration data from the regional to the project scale. The ability of modern GIS systems to integrate many 2-D map layers of both raster and vector data, and link them to a relational database, has made possible improved mapping processes and interpretation (see Broome et al., 1993). The process benefits include more consistent mapping nomenclature, improved data sharing and archiving, and greater flexibility in the integration of maps from different sources and at different scales (see Colman-Sadd et al., 1997). The combination of relational databases and spatial analysis has brought about a new world of possibilities in map interpretation, from complex overlays to expert systems. Ultimately, however, a 2-D map shows the earth on an arbitrary erosional slice, and is not, due to the earth's complex structural history, directly indicative of the rocks below surface where new mineral deposits will be found. Just as it is important to construct an often speculative, interpreted map from outcrop data, it is important to bring that speculative interpretation into the third dimension. Ore bodies are a product of their geological environment, and traditionally we make poor use of our exploration data in constructing the interpretative geological models that will guide exploration decisions. Structural data, the geometrical relationships between map contacts and topography (which are discarded in the 2-D map-making process), and geophysical data all explicitly tell us about geological variability in the third dimension. This information is under-utilized in drilling decisions. "Extending regional mapping into the subsurface is not a new idea, as demonstrated by the early Alpine workers (Argand, 1922), who understood mapping as not just documentation, but interpretation. Providing a complementary approach whereby 3-D mapping begins to be possible even in low-relief terrain with limited outcrop is a realizable goal" (de Kemp, 2000a).

The benefits that GIS brings to 2-D mapping can be extended to 3-D modelling, although the required software is just becoming available (post-2000). Currently, surface geological mapping, drill-hole data, and geophysical data are essentially interpreted in isolation for after-the-fact comparison. This is necessarily so in the 2-D world as the connection between geology and geophysics is irreducibly 3-D: while a geological map may be an accurate representation of an arbitrarily thin slice of geology at the earth's surface, geophysical data is always a response to subsurface geological volumes. Even if cross-sections are utilized to accurately represent a 2-D geological section, geophysical data gathered on that section is always partially a response to out-of-section geology. The 3-D geological modelling provides the necessary link between the different disciplines and data streams of mineral exploration. Geological interpretation, geophysics, geochemistry, and ore-reserve models can only be quantitatively related through a common earth model containing all the spatial exploration data and its interpretation.

THE COMMON EARTH MODEL: ORIGIN OF THE CONCEPT AND ITS PRACTICAL REALIZATION

The term "common earth model" arose in the oil industry over the last decade as a new concept in the multi-disciplinary integration of data and work processes. In an introductory paper on the common earth model concept Garrett et al. (1997) claim:

> *"The advent of 3-D earth modelling computer systems suggests there is potential to transform the work processes in cross-disciplinary asset teams. By sharing common digital 3-D 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, 3-D visualization and data access. From now on, we believe that earth modelling issues will assume greater significance in the business of these teams."*

Thus, although all spatial exploration data and interpretation reside in the common earth model, the level of integration is greater than integrated database storage or integrated 3-D visualization. It is particularly important to recognize the difference between integrated 3-D modelling and combined 3-D visualization of multiple datasets, as the two notions are often confused. In the mineral exploration case, integrated 3-D modelling means primarily that geological and geophysical interpretation are consistently reflecting a single, unified earth model. Visualization of that model is essentially a separate issue. Consider the simple case of an exploration group having a geological map, a few cross-sections, and some geophysical surface coverages such as gravity and magnetics data. Is the geological map consistent with the cross-sections? Typically, the map is made in a GIS system, the cross-sections are drawn in a CAD system, and they are not explicitly tied together (see Schetselaar, 1995). If they are tied together, was the labouriously-entered map data in the GIS properly used in the cross-section drawing? For example, was structural data from outcrop mapping used explicitly for downplunge projection of contacts, folds, and faults in the cross-section generation? And even if the geology is all tied together properly, is the resulting geological model quantitatively consistent with the geophysical data? The world's established mining camps all have geological maps and cross-sections developed at the cost of many millions of dollars of field work and drilling, plus extensive geophysical data coverages gathered and processed at high cost. The level of effort that has gone into developing earth models consistent with all these data is small, primarily because the technology to effect the integration has until now not been obviously at hand.

The practical solution to the earth modelling challenge requires sophisticated new processes and the will to put them to use. Software, and methods borrowed from the oil industry, now exist to solve the common earth model data integration problem. Figure 1 shows schematically the kinds of data and interpretations of data that should reasonably be expected to be handled in a common earth model. The nature of the data integration is to be able to move data to and from any mining exploration process into a flexible data structure, and to leave highly specialized data processing tasks to specialist software (e.g., geophysical inversion). Thus, typical inputs to the common earth model are 2-D maps from GIS systems, digital elevation models, cross-sections from CAD or other software, geophysical and geochemical grids, borehole surveys with both geological and geophysical wireline logs, and ore body meshes and block models. Within the common earth model software itself, sophisticated procedures are used to build a 3-D geological model consistent with all map, cross-section, and borehole data. This model can communicate directly with advanced 2-D or 3-D geophysical modelling and inversion software to both predict geophysical responses for comparison with field data, and to use the geological model as a target reference in geophysical data inversion (McGaughey, 2003).

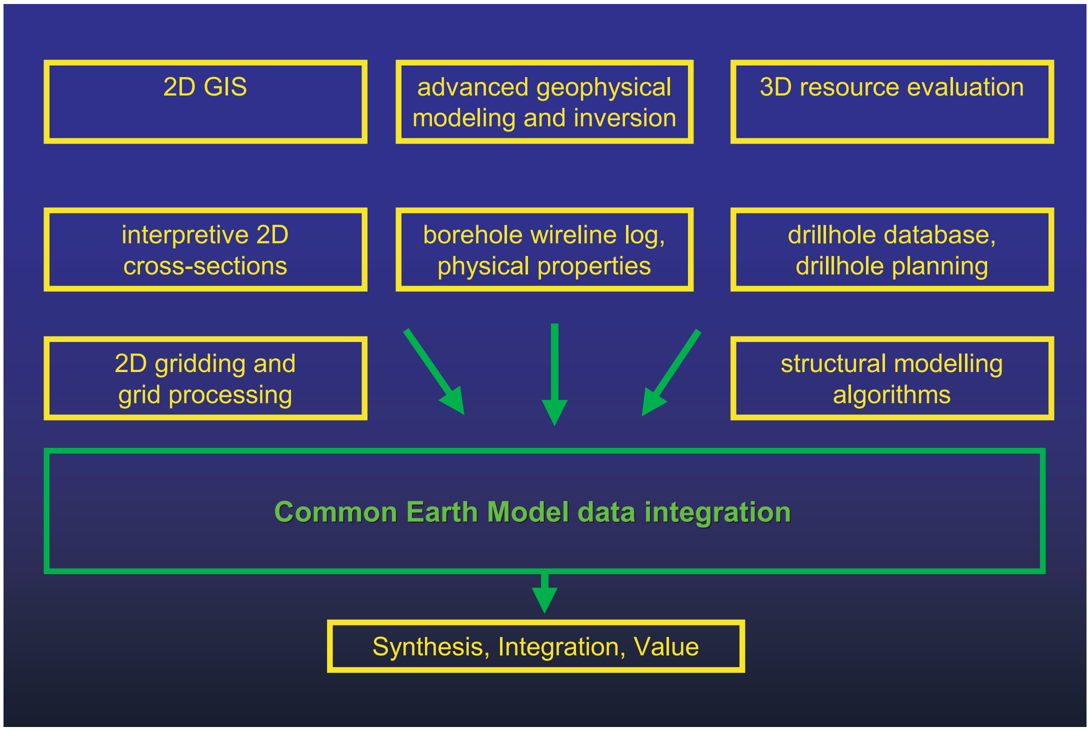

Figure 1. *The common earth model takes all conventional, spatial exploration data as input and provides explicit integration of all components into a single model of the earth consistent with all input data.*

THE COMMON EARTH MODEL: WHY NEW SOFTWARE TECHNOLOGY IS REQUIRED

The general requirements of a successful common earth technology are:

- A sophisticated geological modelling capability encompassing both geometric and topological modelling
- A comprehensive 3-D vector and raster modelling facility
- The capability of mapping an arbitrary number of both vector and scalar properties to any model element (points, lines, surfaces, or volumes)
- The capability of easily embedding customized algorithms for specific modelling tasks
- A sophisticated 3-D vector and raster model query capability
- Methods of communicating data back and forth to other applications, and
- An interpretive environment in which traceable decisions can be made concerning the model.

Topology as used here refers to, what may be thought of as, a table of relationships between geological entities, as well as the underlying data structure used to store and manipulate these relationships. These can be either stratigraphic relationships between formations (e.g., conformable, non-conformable) or structural (the fault hierarchy that cuts a 3-D space into fault blocks).

A new software technology is required because, as explained below, there is no software currently in common use in the mining industry which satisfies the above needs.

Conventional 2-D GIS and Grid-Based Systems are Inadequate

Commercially available GIS systems have had a major impact on the handling of mineral exploration data (see Bonham-Carter, 1997; Raines and Bonham-Carter, this volume). These systems combine geometric modelling, sophisticated spatial analysis, and database connectivity. The more advanced products provide explicit topological modelling in 2-D. (Topological modelling, which establishes relationships between different spatial regions of the model, is important for many aspects of model construction, updating, and query. For example, the query "Identify all geological contacts offset by a fault" is a topological query.) The sophistication of GIS in mineral exploration applications is, to a large degree, due to the size of the general, non-mining commercial market for 2-D mapping technology. The corollary to the leverage that earth scientists obtain in utilizing general-market technology is that it is useful only insofar as our information-technology needs are closely aligned with the general-market needs. Thus, commercial GIS systems have never provided the mineral explorationist with acceptable 3-D capability.

The ubiquitous mineral-industry commercial software systems for data gridding, used by both geophysicists and geochemists, are fundamentally incapable of providing a basis for a common earth model because of their inherent 2-D limitation. Such systems provide excellent functionality in grid manipulation (interpolation, smoothing, stitching, and data-specific grid processing for geophysical and geochemical data), but the grids ultimately have all the limitations associated with flat 2-D projections of 3-D property-fields sampled over the earth's surface. The final products of such software are grid or map outputs which show over the earth's surface a projection, transformation, and smoothing of input data. While such transformations and interpolations provide useful interpreted products from raw input data (e.g., a terrain- and Bouguer-corrected gravity map from raw gravity data) they cannot provide output in the form of a quantified, testable earth model.

A common earth model is an explicit 3-D model of the earth consistent with all exploration data, and testable by a drillhole. Data gridded, processed and plotted on a map is merely a 2-D image of "filtered" data (which is not to say that many of these filters are not in themselves useful). In other words conventional grid processing takes the explorationist from data to filtered data rather than from data to geological hypothesis. The analogy between a common earth model and a scientific hypothesis is strong. Like any scientific hypothesis, a common earth model is either correct or incorrect, and is experimentally testable. If proved incorrect by new data it can be either discarded or modified to be consistent with the new evidence. A grid or map (such as a processed gravity or magnetic map, or even an induced-polarization pseudo-section), while useful, does not go nearly far enough. It is merely a piece of quantitative evidence that must necessarily be viewed in qualitative terms as it carries no explicit predictive capacity about the earth: as a component of an earth model it is neither correct nor incorrect nor testable – it is just plotted data. For example, a processed gravity map shows no intrinsic physical property of the earth; it illustrates only a secondary property of the earth (its gravitational field) that one may measure at a certain location. Application of the common earth model technology, in combination with sophisticated inversion software and fast computers, should eventually render many conventional geophysical data processing methods to a secondary, qualitative aid to interpretation or perhaps obsolete entirely.

Conventional CAD Systems are Inadequate

Many geological models continue to be built with Computer-Aided Design (CAD) tools. "Mechanical CAD aims to design objects which do not yet exist, whereas geological CAD has to rebuild an existing body from partial, irregularly distributed, and more-or-less precise information. Moreover, the complexities of the objects treated are not the same for both disciplines" (Renard and Courrioux, 1994). Amongst the fundamental limitations of commercial 3-D CAD software for geological modelling are severe limitations in handling the fault topology (and it is a rare earth model that does not contain faults), and inadequacies or inflexibilities in the handling of heterogeneous property fields throughout volumes. Classical CAD modelling techniques using parametric surface representations, such as Bézier and spline interpolations, used on their own have been demonstrated to be inadequate for earth science and biological applications (Mallet, 1992). However, hybrid techniques combining speculative, design-based Bézier construction with data-fitting techniques provide a powerful combination that will balance the geologist's mental model with the constraining dataset. Optimization of such a "constrained-interpretive" 3-D environment for making common earth models is a goal of ongoing development (de Kemp 1999, 2000b, this volume).

Conventional Resource Evaluation and Mine Planning Systems are Inadequate

There are many "3-D geological modelling" software systems in use. Typically, their starting point is a set of drillholes from which one wishes to derive a mineral resource estimate. Their earth modelling capabilities are a subset of their overall functionality, which is heavily weighted to the engineering issues surrounding ore extraction. Ore boundaries are interpreted on section (in some cases they may be "snapped" directly to 3-D in the case of drillholes which are projected onto section). The practice of estimating reserves by polygonal-section methods has given way to more sophisticated block-modelling strategies in which a complete wireframe mesh corresponding to the ore boundary is developed, and grade values inside the mesh are estimated using various geostatistical schemes.

Although such systems can be used to build 3-D geological models they are inadequate to serve as the basis of a common earth model. They are "non-topological", meaning that each geological unit requires its own wireframe mesh (with neighboring units duplicating, not sharing their boundary) and that rock properties are not properly interpolated across faults. Properties are typically only modelled as scalars within a confined range of object types such as block models, drillholes, or simple 2-D grids. A suitable common earth technology must explicitly handle more complex property representations, such as magnetic vector fields or tensor stress fields on arbitrary surfaces. Although these issues become somewhat subtle and technical they have enormous eventual impact on the usability of the model. (For example, a non-topological 3-D model is difficult to edit with the addition of new data or constraints. See Euler et al., 1999, for a discussion of 3-D geological model editing in a topological software environment.)

Recent Technology Advancement in the Petroleum Industry is Filling the Gap

For reasons outlined above, no software conventionally used in the mining industry has the fundamental characteristics necessary to provide the basis for a common earth model. For this we must turn to recent experience in the oil industry where the common earth model paradigm, and the software that can serve as its basis, has been developed over the last decade. For the remainder of this paper we use "Gocad" as the most prominent example of a software technology that answers the need for a common earth modelling environment applicable across the range of geosciences (petroleum, mineral, environmental, geotechnical). The Gocad research consortium, an industry-university alliance that has brought together more than thirty resource companies and more than forty universities for this purpose, has been active since 1989 in developing the methods and software for achieving the common earth model. The resulting software has been available commercially since 1999.

The Gocad software is a very general earth-modelling application that has been used in both soft-rock and hard-rock applications at scales ranging from large regional compilations to detailed reservoir and ore body modelling. Construction of geological surfaces is largely based on a novel, patented geometric modelling algorithm

(Mallet, 1992) that successfully allows "data-fitting" rather than the CAD approach of "designing" modelled objects. In this approach, surfaces are created by an algorithm in which multiple constraints on the surface geometry are simultaneously honoured. Examples of constraints are "the surface must be smooth", "the surface must exactly honour drillhole pierce-points", "the surface is cut by a certain fault with a given throw", "the surface must minimize error, (according to a user-specified definition of error) in its fit to a secondary set of data points". This stands in stark contrast to the more common approach of creating surfaces based on connecting a set of input points or polylines, in which the vertices of the output surface mesh have a simple one-to-one correspondence with the vertices of the input point and line data. Gocad is fully 3-D, topological, and provides the most sophisticated geometry and property modelling functionality currently available. It is available as both a user application and as object libraries for building custom applications. It is fully customized at the user level, and is easy to link to third-party applications. Its uses have been reported in the literature to vary from providing the basis for advanced geophysical processing (e.g., Segonds et al., 1997; Guiziou et al., 1996; Aminzadeh et al., 1994) to structural geology (e.g., Samson et al., 1996b) to advanced geostatistical applications (Shtuka et al., 1996) to resource risk analysis (e.g., Samson et al., 1996a).

THE COMMON EARTH MODEL: A SIMPLE CASE STUDY

A simple case study is provided here to demonstrate the common earth model in action. The example shows a simple regional modelling of the Kiglapait Intrusive in Labrador (for data sources and previous interpretation see Morris, 1969; Stephenson, 1974; de Kemp and Desnoyers, 1997; de Kemp, 1999). A 3-D geological model will be built using only map and ground geophysical data, demonstrating that 3-D geological modelling does not require drillholes or other subsurface data. The large, rectangular box containing the model, shown throughout Figure 2, is 40 km on a side. In Gocad regional, camp, project, and even stope-level objects can coexist in the same model, so that project-level edits can be registered at the regional-resolution level.

Figure 2a shows two map contacts and a set of point structural data (dark blue) as vectors indicating normals to the measured orientation of primary igneous layering. The contacts and point set have been registered to the topographic surface as specified by a digital elevation model (DEM). Structural data have been interpolated to a regular set of downplunge projection vectors on the map contacts (shown as the small green arrows on the outer contact). A

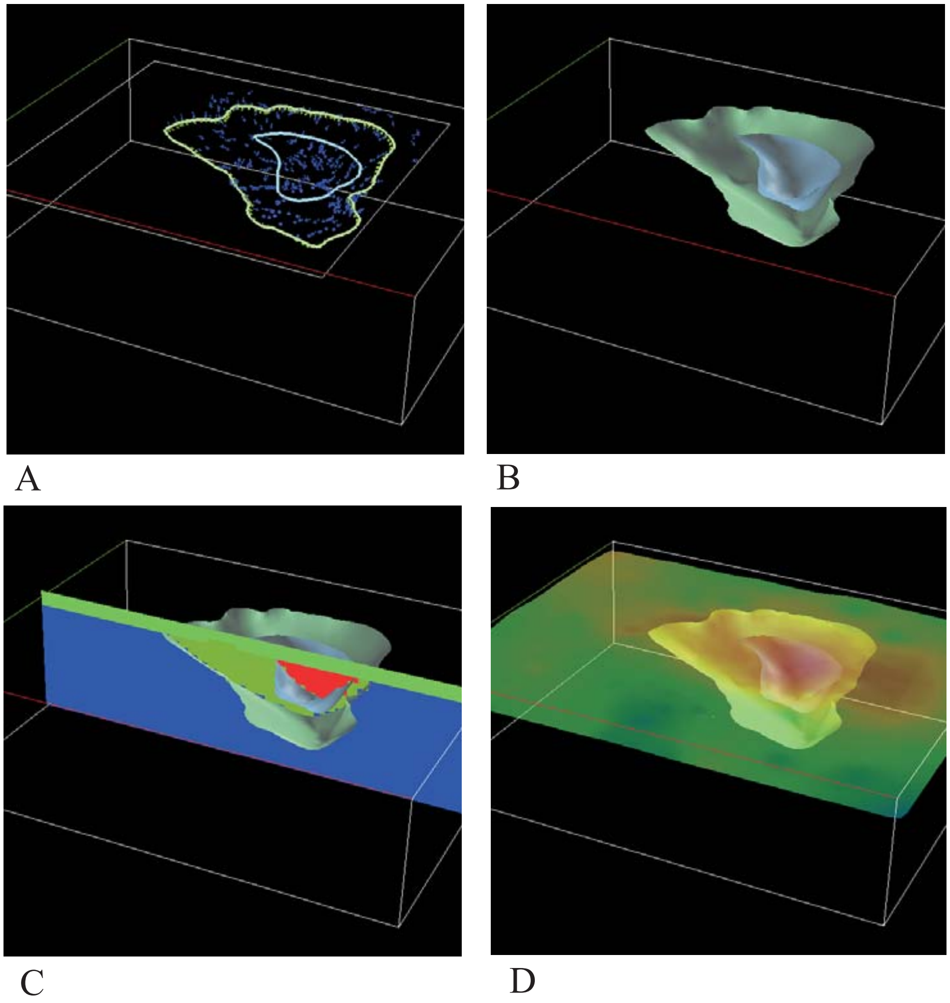

Figure 2. *(a) Map contacts and point structural data, (b) modelled formational contact surfaces, (c) section through a 3-D density grid, (d) geology seen through gravity data.*

geologist is rapidly and interactively able to construct speculative 3-D contact surfaces consistent with the mapped contact, the structural data, and the geologist's intuition about the structure (Figure 2b). This is an example of the "data fitting" process described above, in which surfaces are created based on their adherence to multiple, simultaneous constraints. Once a set of formational surfaces is constructed a 3-D property grid is established in which each grid cell is aware of to which geological formation it belongs. In this case average assumed densities for each of the units were placed into the grid, which is shown on a single cross-sectional plane in Figure 2c. Because Gocad is "topological" each cell remains aware of which solid (geological formation) it belongs to without having to ever explicitly build a wireframe mesh around the different formations. If the contact geometry is later edited to match a drillhole intersection or for any other reason, the grid cells can be automatically updated to register where they reside in the geological space. Non-topological 3-D modelling systems generally require the construction of an explicit wireframe mesh (triangulated surface or polyhedral shell) around each geological formation. In such schemes meshes are duplicated on the contact surfaces shared by adjacent geological formations. Such duplications make construction and editing of generalized, complex geological frameworks exceedingly difficult. It is rare in the mining industry that successful 3-D models have been constructed of complex geological frameworks using methods and tools developed initially for resource modelling or engineering applications.

Figure 2d shows the gravity data as a transparent property (so one can see through it to the underlying structure). The density model of Figure 2c is already consistent with the DEM, the mapped contacts, the structural data, and assumed average density values for the rocks in question. Figure 2e shows the gravity forward model, accurately modelled to the DEM, based on the density distribution of Figure 2c. In other words, if the density distribution of Figure 2c, built from geological considerations alone, is accurate, the measured gravity field should look like that shown in Figure 2e (ignoring the artifacts around the model edge). As Figure 2d (the data) and Figure 2e (the forward model) are not an accurate match, the current density model is incorrect. In a common earth model the subsurface density distribution must be consistent with the gravity data, so the next step is to perturb the density distribution to match the gravity data while attempting to maintain the consistency with other data already achieved. This is an example of the process of hypothesis-test-revise that characterizes scientific reasoning.

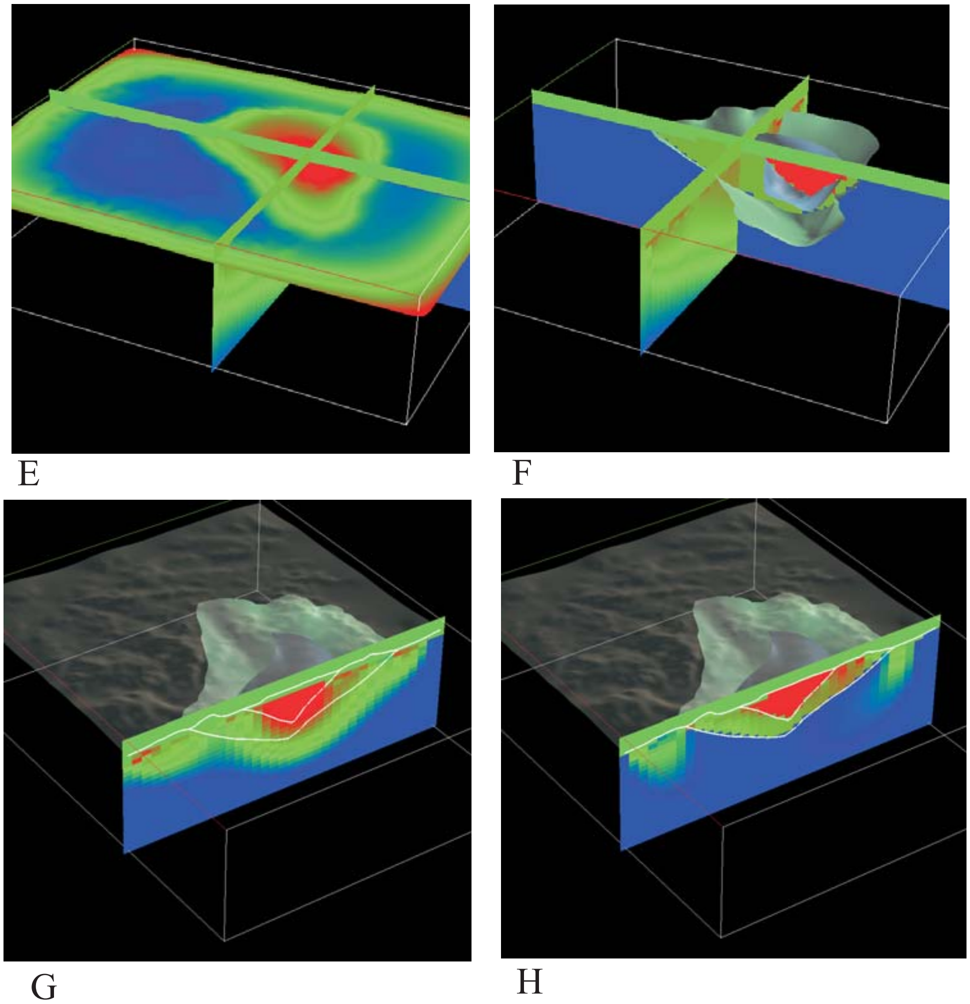

Figure 2. *(e) Gravity forward model, (f) unconstrained gravity inversion, (g) unconstrained gravity inversion, (h) geologically constrained inversion.*

All gravity inversion results pictured here were obtained using the methods and software developed by Li and Oldenburg (1998) and their colleagues at the University of British Columbia Geophysical Inversion Facility. Figure 2f shows a section through a 3-D density distribution produced from an unconstrained gravity inversion, perpendicular to the initial-model density cross-section. This is the state-of-the-art as practiced in the industry for geophysical inversion. Inversion technology provides the capability of using explicit constraints on the solutions provided but, without the tools of the common earth model, it is simply too difficult and time-consuming as a practical matter to specify them in an arbitrary geological context. The value of an unconstrained inversion, however, is debatable as it provides only one – not always interesting – solution out of an infinite number of possible density distributions that could account for the gravity data. As is typical in geophysical inversion schemes the smoothest possible solution (density distribution in this case) is provided on the justification that the minimal structure demanded by the data should result. This justification is only sound, however, if the geophysical data are looked at in isolation from supporting data. In a common earth model philosophy we do not solve for the smoothest density distribution consistent with the gravity data, but rather solve directly for the smoothest density distribution consistent with both the gravity data and the interpreted geological structure. To do otherwise propagates mapped gravity anomalies into the subsurface as density anomalies without regard to the, *a priori*, geological knowledge, giving an inversion result whose added value relative to the conventionally processed gravity map may be small. If more information were available (e.g., other types of geophysical data) then the process would in principle produce a density anomaly distribution also consistent with the other information. Our confidence that the common earth model is a valid representation of reality increases as the number of useful data constraints increases and the set of possible earth models, given all constraining data, correspondingly decreases.

Thus we get the common earth model of Figure 2h. Figures 2g-h each show (from a different visual perspective than the preceding figures) a 3-D density distribution on a single section with the two formational contact surfaces visible between the partially transparent topography, and white lines indicating the position of all surfaces on the sectional slice. The density distribution of Figure 2g is known to be consistent with the gravity data and DEM only (it is from the same model as Figure 2f) while that of Figure 2h is known to be consistent with the gravity data, the DEM, the geological map, measured structure, and the geologist's intuition about the subsurface structure. Every aspect of the common earth model of Figure 2h is explicitly testable in the field with a drillhole, and can be updated and refined rapidly with the addition of new data. The next logical step would be to refine the model to be consistent with magnetics data using 3-D, constrained magnetics inversion (Li and Oldenburg, 1996). The density distribution shown in Figure 2h indicates potential targets and gives an explicit representation of those targets. (The unrealistic appearance of the host rock density distribution in Figure 2h – the blue-to-green variation – also suggests that the host density, the blue in Figure 2c, was underestimated.) Important issues such as depth of investigation and lateral resolution can be specifically examined for the given exploration area in the real geological context. Hand-waving arguments and irresolvable disagreement about what interpretations are permitted by the data begin to give way to quantified, testable results.

THE COMMON EARTH MODEL: REALIZING THE BENEFIT

The common earth model technology when properly implemented brings to the explorationist a number of concrete products that will have a positive impact on exploration success. Most importantly, the technology will provide a much firmer basis on which to propose exploration drillholes than can be done using previous technology only, and at a fraction of the cost of the drillhole itself.

Components of the benefit, all having an impact on our ability to target drillholes, include:

- Improved analytical geological capability, including methods for downplunge projection, automatic fault detection and analysis through curvature analysis of stratigraphic contacts, drillhole formational-intersection ("pierce-point") 3-D analysis, and the algorithms of structural unfolding
- Improved analytical geochemical capability, including volumetric interpolation of whole-rock lithogeochemistry data explicitly taking into account the complex stratigraphic geometry (geostatistical interpolation conformable to stratigraphy and explicitly taking into account faults), and 3-D vector fields derived from interpolated alteration indices for drillhole targeting
- Enabling explorationists to realize the benefit promised by new geophysical inversion technology
- Incorporation of regional data at the project scale
- Improved interpretation by brigning all spatial data together into a single model
- A single query environment in which many hitherto separate datasets can be simultaneously addressed in a manner which reflects an explorationist's natural targeting criteria (e.g., "show all subvolumes of the model that are within 100 m of a major fault intersection, are above the basement and below the overburden, have a positive density anomaly from gravity inversion, and exhibit silicic alteration"), and
- Improved communication within exploration teams and to management through the capability of effective 3-D visualization and query of all spatial aspects of a model, either in one place at one time by the team, or by remote collaboration using the internet.

The impact of a systematic use of the technology will have the following important characteristics.

The Common Earth Model will Enable a New New Generation of Geophysical Technology

The impact of jointly modelling geology and geophysics will help make possible a new generation of mineral exploration geophysical technology. This is because the new interpretational sophistication is necessary to provide the exploration value required to justify the new technology investment. Examples of such new technology include extended-array, full-waveform electrical systems (see Sheard, 1998) in which the incoming volume of electrical, magnetic, and induced polarization data not only challenges basic field data reduction but also significantly challenges interpretational capability. It does not make economic sense to interpret such expensive, information-rich datasets in isolation from known constraints provided by other exploration data. Similarly, it does not make sense to enter into a 3-D seismic mineral exploration program (see Eaton et al., 1997) without attempting to model and interpret the data in the most complete geological framework available.

It should be clear that the common earth model agenda is closely aligned with the 3-D geophysical inversion agenda. 3-D geophysical data inversion provides the basic control for interpolating the earth between geological observations at surface or in drillholes. The ability of a sophisticated 3-D earth modelling system to both express earth models optimally parameterized for geophysical inversion and to communicate geological constraint to the inversion algorithm is what makes the interpretational possibilities of these new methods exciting.

The Common Earth Model will Motivate the Systematic Collection of Rock Physical Property Data

The critical link between geology and geophysics at the heart of the earth model is the rock physical properties (electrical conductivity, density, etc.). As the interpretational models will ultimately depend to a large degree on our understanding of how physical properties relate to geological description, explorationists will be driven to routinely collect more and higher quality physical property data. It is not unreasonable that the near future will see borehole wireline log data collected routinely in exploration drillholes in order to quantify the in-situ physical properties. Exploration success will depend on it.

The Common Earth Model will Exist at all Exploration Stages

The 3-D earth models can be generated from map data alone before a single drillhole exists in the model area. Figure 2b from the above case study shows such a model for a simple structure. Once a 3-D geological model has been constructed, even with very sparse data as in the example given, a container exists to hold all future data and a framework exists for interpretation of that data. The final earth model shown in Figure 2h was arrived at without any subsurface data demonstrating that a coherent, plausible model may be built with very little knowledge. Such a model, even at the primitive stage shown, provides both a useful vehicle for communication as well as basis for drill targeting. The key to the usefulness of the model is in its flexibility with regard to data type and the ease with which it can be edited. The former guarantees that the model can provide a comprehensive, visual exploration data archive in a consistent coordinate system, while the latter guarantees the ongoing usefulness of the model as an active and economically valuable exploration asset.

CONCLUSION

A new era of computational geological modelling that quantitatively integrates diverse exploration datasets is at hand through the rapidly emerging common earth model conceptual framework. The implementation of the common earth model concept is occurring through new software developments that are, in essence, providing a "3-D-GIS" that adapts the methods and tools of the most powerful 2-D-GIS systems, in which the "3-D model" is the counterpart of the "map". Vector and raster model construction and representation, topological modelling capability, powerful 3-D visualization, and a sophisticated query environment define the key technology characteristics of the 3-D-GIS being put in the service of the common earth model concept. Mineral exploration, like all other earth science domains, require these new concepts and tools because economically important decisions are being made based on the analysis of data that reflects a 3-D earth.

As noted several years ago in the petroleum industry, "3-D earth model systems will increasingly be established at the core of computer applications for cross-disciplinary asset management. Maps, cross-sections, and other 2-D representations will remain valuable tools, but will become subsets of a consistent 3-D model. The full advantages of a common earth model are attainable in the near future" (Garrett et al., 1997).

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