3-D Integrated Geological Modeling in the Abitibi Subprovince (Québec, Canada): Techniques and Applications

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Abstract — The development of robust 3-D geological models involves the integration of large amounts of public geological data, as well as additional accessible proprietary lithological, structural, geochemical, geophysical, and diamond drill hole data. 3-D models and maps have been available, particularly in the petroleum industry, for more than 10 years. Here, we demonstrate how robust 3-D maps can be used as interactive tools for mineral deposits exploration. In particular, we show how the interrogation of 3-D data sets can constrain exploration targets at depth.

The main advantages of this technique for the mining industry are the homogeneity of data treatment and the validation of geological interpretations, taking into account geophysical and geochemical data. Data integration and cross-correlation of geology and geophysics can be achieved in two dimensions in any good GIS package. However, the added strength of 3-D analysis is the integration of separate data sets in three dimensions to build more complete, more realistic models, and in delineating areas of high economic potential at depth. Furthermore, these models can be modified and improved at any time by adding new data from ongoing drilling and geoscientific surveys.

This paper presents two examples of 3-D models used for mineral exploration: the Joutel VMS mining camp and the Duparquet gold camp, Quebec. In both examples, the creation of the model is discussed and queries specific to the relevant exploration model are introduced. Eight potential exploration targets are generated at Joutel and seven at Duparquet. Although the targets defined are dependent on the details of the chosen queries, it is apparent that this technique has the potential to generate promising exploration activity that can engender new targets.

Key Words: Three-dimensional geological model, Abitibi, Volcanogenic massive sulfide deposit, gold, gOcad®, 3-D querying, Exploration targets.

Sommaire — Le développement de modèles 3-D géo-intégrés fiables implique l’intégration de grandes quantités de données géologiques publiques ainsi que des données lithologiques, structurales, géochimiques, géophysiques et de forages en provenance du secteur privé. L’industrie pétrolière dispose de modèles et de cartes 3-D depuis plus de 10 ans. Ce manuscrit présente un exemple d’utilisation de modèles et de cartes tridimensionnels détaillés comme outils interactifs dans l’exploration de dépôts métallifères. L’emphasis est mise sur le processus d’interrogation des données en 3-D pour la définition de cibles d’exploration en profondeur.

Les avantages principaux de cette technique sont l’uniformité du traitement des données et de la validation des interprétations géologiques, tout en tenant compte des données géophysiques et géochimiques. L’intégration de données et la corrélation de la géologie et de la géophysique peuvent être accomplies en deux dimensions dans n’importe quel logiciel SIG. La plus grande force de l’analyse 3-D demeure cependant la possibilité de construire des modèles complets et réalistes permettant de cibler des secteurs à haut potentiel économique en profondeur. De plus, ces modèles peuvent être modifiés et améliorés de manière interactive en ajoutant de nouvelles données provenant de forages et de levés géoscientifiques en cours.

Ce manuscrit présente deux exemples de modèle 3-D géo-intégrés développés pour l’exploration minérale : le camp de SMV de Joutel et le camp aurifère de Duparquet, Québec. Dans les deux cas, la construction du modèle est décrite et les requêtes spécifiques à chaque type de gisement sont présentées. L’exercice a permis de définir huit cibles d’exploration potentielles à Joutel et sept à Duparquet. Bien que les cibles identifiées dépendent des contraintes utilisées pour les requêtes choisies, cette technique permet de générer de nouvelles cibles qui pourraient relancer l’activité d’exploration dans les camps miniers “matures” ou dans des secteurs moins explorés.

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Key Words: Three-dimensional geological model, Abitibi, Volcanogenic massive sulfide deposit, gold, gOcad®, 3-D querying, Exploration targets.

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Introduction

Recent discoveries and ongoing exploration for mineral deposits in mature mining camps within the Abitibi subprovince (e.g., Perseverance in the Matagami camp, and La Ronde 3 in the Doyon-Bouquet-La Ronde camp, Quebec; Fig. 1) have emphasized the need for integrated three-dimensional (3-D) modeling at a mining camp scale. Like many major and mid-tier mining companies (e.g., Noranda, Barrick Gold, Placer Dome, Falconbridge, Inco, Aur Resources, Cambior), the Quebec Geological Survey (MRNF) has favoured the gOcad® software as being best adapted for this type of project. In mature mining camps, the integration and the optimization of geoscientific data within a single 3-D map is likely to generate new mineral exploration targets. The development of these models involves compiling large amounts of public geoscientific data, available in Quebec through the MRNF’s database (SIGEOM), as well as additional lithological, structural, geochemical, geophysical, and drill hole data made available through private companies that are involved as project partners (Fallara et al., 2001, 2002a; Marquis et al., 2003).

Since 2000, the Unité de recherche et de service en technologie minérale, Université du Québec en Abitibi-Témiscamingue (URSTM-UQAT), in close collaboration with the MRNF, has used 3-D integrated geological models of two mining camps to define base metal (Joutel) and gold (Duparquet) exploration targets. This was accomplished through the identification of extensions of alteration zones, structures, and the interpretation of subsurface geology. These projects follow the current trend in mineral exploration, which focuses on finding increasingly deep deposits within mature mining camps.

Three-dimensional modeling requires a structured quantitative approach, and it is therefore necessary to have adequate, high-quality, multidisciplinary data with a relatively uniform distribution over the entire study area. Unfortunately, this kind of detail is rare in the majority of regions. In order to demonstrate the method, we have selected two areas within the Joutel volcanogenic massive sulfide (VMS) and the Duparquet gold camps where sufficient data exist to build detailed models within a regional 3-D model.

3-D Integrated Geological Models

A 3-D geological modeling environment provides a single platform that uses a common 3-D coordinate system for the integration of geoscientific data. Three-dimensional modeling involves the addition of data sets to enable querying and visualization of various types of spatial data. Therefore, 3-D geological models contain quantitative geological, geophysical, and geochemical data and interpretations. Consequently, the resulting model allows the examination and querying of all the data using a single tool kit.

The borders of a 3-D integrated geological model are bound by a “voxet”, which is a volume divided by a group of three-dimensional cells containing various numerical data, including: lithologies, alteration indices, diamond drill hole densities, geochemical and geophysical surveys, and certain point-source petrophysical data (rock density, magnetic susceptibility, etc.). Figure 2 shows sections through a voxet exposing different types of numerical data.

Hence, 3-D integrated geological models represent a dynamic data integration method of great utility as an exploration targeting tool that can be questioned according to criteria reflecting the geological properties associated with various mineral deposits. The main advantages of such a technique for the mining industry is the homogeneity of data treatment and the ability to refine and validate geological interpretations taking into account geophysical and geochemical data. Data integration and cross-correlation of geology, geophysics, and geochemistry can be achieved in two dimensions in any good GIS package. However, the added strength of 3-D analysis is the integration of data sets in three dimensions to build more complete, realistic models that can be used to delineate areas of high economic potential at depth. Furthermore, these models can be modified and improved at any time by adding new data from ongoing drilling and mapping surveys.

Methodology for 3-D Integrated Geological Model Construction

The type of data integrated within a 3-D model depends on data availability, density, and distribution, as well as project objectives and working scale. The methodology presented here is well suited for various working scales (from ore-body scale through camp scale, and even up to regional scale). It is particularly suited and most useful for camp-scale or regional synthesis to constrain structural and stratigraphic relationships of a studied area.

For exploration targeting, the following data are useful:

1. Surface data (2-D):
   i. Topographic elements (digital elevation models, hydrography);
   ii. Mining and road infrastructure;
   iii. Main lithological and stratigraphical contacts (key horizons marker);
   iv. Fault and fold surfaces, planar and linear structural measurements;
   v. Lithogeochemical analyses, alteration indices, and economic assays.

2. Diamond drill hole (DDH) information available in 3-D:
   i. Drilling data (collar, deviation, geology, mineralized intersections, alteration indexes, magnetic susceptibility, density, etc.).

3. Ground-based, downhole, and airborne geophysical surveys:
   i. Magnetic data;
   ii. Gravitometric data;
   iii. Electric methods (DC, IP);
   iv. Borehole EM;
Fig. 1. Simplified geology of the Abitibi subprovince, showing the locations of the Joutel and Duparquet study areas. Modified from Doucet et al. (2000).
Fig. 2. (a) General steps involved in constructing 3-D integrated geological models (after Fallara et al., 2002b). (b) Generalized model: a unified platform that contains quantitative geological, geophysical, and geochemical data.
v. Seismic data.

The UML (Unified Modeling Language) flowchart illustrates the steps to accomplish a task; the Fowler (2000) flowchart highlights stages requiring a decision, as opposed to those needing parallel treatments in substages. Figure 2a outlines the construction steps of 3-D integrated geological models as defined by Fallara et al. (2002b):

1. Data handling steps:
   a. Acquisition and compilation of the data (allowing for rigorous quality control):
      i. Compilation of geological information, such as outcrop, contacts, structures, mine plans, DDH;
      ii. Compilation of geophysical information, such as airborne and ground magnetic, and gravimetric surveys;
      iii. Digitization of paper documents (i.e., sections) and their integration and validation with numerical data;
   b. Importation and integration steps:
      i. Importation of digital elevation points to create the topographic surface;
      ii. Integration of regional infrastructure and hydrographical network: the numerical data are imported into gOcad® and are then draped on the topographic surface;
      iii. Integration of the 2-D geological data: importation into gOcad® of outcrop, mineralized zones (data points), and geological contacts in AutoCAD® (.dxf) format;
      iv. Diamond drill hole (DDH) importation.

2. Construction steps:
   a. Interpretation, construction, and integration of regional sections used for the homogenization and the simplification of the regional geological contacts. The number of necessary sections depends on the complexity of the units to be constructed.
   b. Geological surfaces are built from both the contact curves and dip vectors extracted from the surface geological map and sections.

3. Interpretation and validation steps:
   a. Validation of the 3-D geological surfaces: major DDH markers are used as additional control elements between the regional interpreted sections. Surfaces are modified in order to account for these additional constraints.
   b. Creation of 3-D geological regions: these are geological volumes bounded by the 3-D geological surfaces.
   c. Validation of the 3-D geological model using unconstrained and constrained 3-D geophysical inversions according to quantitative relationships between geological data and geophysical data: the differences between the two models are adjusted in iterative and interactive processes.

4. Querying steps:
   a. Selection of 3-D properties: lithology, alteration indexes, assays, etc., are then allotted to each cell of the voxel according to the region to which they belong.
   b. Elaboration of 3-D properties according to the selected metalogic environment (VMS, gold, etc.) in order to define queries that may lead to new exploration targets.

Three-dimensional integrated geological modeling cannot be defined and followed like a cookbook recipe: each project or study area requires a different approach based on the objectives and the available databases. Therefore, while these steps ensured the success of the 3-D integrated geological models at our specific study sites, they should not be thought of as a standard, but rather as guides that other users can follow or modify.

**Joutel Study Area**

**Geological Setting**

The Joutel volcanic complex (JVC) contains VMS deposits that produced Zn, Cu, Ag, and Au from massive sulfide deposits from 1966 to 1975, and semi-massive sulfide deposits from 1974 to 1993. The JVC (2728–2721 Ma; Mortensen, 1993; Legault et al., 2002) is an integral part of the first volcanic cycle (2730–2720 Ma) of the Northern Volcanic Zone (NVZ) of the Abitibi subprovince (Fig. 1), which represents an extensive, subaqueous, primitive basalt plain with dispersed mafic/felsic and felsic complexes collectively defining a diffuse and incipient arc (Chown et al., 1992).

The 5- to 7-km-thick JVC, traceable for 25 km along strike (Legault et al., 2002), comprises the Joutel-Raymond and Harricana groups (Legault et al., 2000; Fig. 3). The Joutel-Raymond Group consists of a basal mafic volcanic sequence (Valrennes Formation) overlain by mafic to felsic volcanic and volcaniclastic rocks (Joutel Formation), whereas the Harricana Group is a minor but significant volcaniclastic sedimentary unit (Legault et al., 2002). The Joutel Formation is further subdivided into the Poirier (primarily lobe-hyaloclastite felsic flows), Kistabiche, and Eagle (predominantly mafic to felsic tuffs) members. VMS deposits are only found within the Poirier member, whereas gold deposits are located within the Harricana Group.

Three major intrusions are present in the JVC area (Legault et al., 2002): the Valrennes intrusion, Mistouac pluton, and Joutel tonalite. The Valrennes intrusion is a syn-volcanic (2728 Ma; Legault et al., 2002), 4-km-thick, shallow-level, mafic-ultramafic sill that has been mapped over a 20-km strike length (Dubé, 1993; Legault et al., 2000). It is mostly composed of diorite, quartz diorite, gabbro, quartz gabbro, and hornblende-gabbro, with local magmatic layering at its base. It is interpreted to have been the heat
source for hydrothermal convection cells responsible for the VMS deposits (Legault et al., 2002). The roughly circular Mistaouac pluton (2726 ± 2 Ma; Davis et al., 1993) covers about 2,500 km², is mostly of tonalitic composition, and is interpreted as a deep-level intrusion (~10 km depth; Chown et al., 2002). The Joutel tonalite represents a younger assemblage of dikes and sills (2721 Ma; Legault et al., 2002) that crosscut the Valrennes intrusion and the Poirier member (Legault et al., 2002).

Joutel Mining Camp

The Joutel mining camp (Fig. 3) contains Zn-Cu-Ag deposits (Poirier, Joutel copper, and Explo-Zinc) and Au-Ag deposits (Eagle and Telbel). Three-dimensional geological modeling was focused on the VMS deposits. Lacroix (1998) estimated combined production and reserve inventories of more than 215,000 tonnes of Zn and 148,000 tonnes of Cu within the camp.

The Joutel copper deposit lies in the lower portion of the Poirier member in the hinge area of the McClure-Plamondon anticline (Fig. 3; Dubé, 1993). Chloritic stringer zones underlie massive sulfide beds on both fold limbs (Legault et al., 2002). The orebody is composed of several folded and moderately dipping sulfide lenses, hosted by intensely chloritized and locally talcose rhyolite breccias with spherulitic and cherty rhyolite (Legault et al., 2002). The Joutel tonalite crosscuts the Joutel copper deposit at depth at a 30° to 40° angle (Jébrak, 2000).

The sulfide lenses at the Poirier deposit are also found in the lower portion of the Poirier member (Legault et al., 2002) and are hosted by strongly chloritized volcaniclastic rocks with a sericitic halo (Piché, 2000). The orebody has been interpreted as a V-shaped fold with distinct copper-rich zones along the northern limb near the contact with the Joutel tonalite, and zinc-rich zones to the south (Boniwell and Dujardin, 1964). This metal zonation substantiates geological observations that suggest stratigraphy tops to the south (Legault et al., 2002).

Detailed mineralogical studies indicate that the Te-Co-Ag-Pb-rich composition and chlorite alteration (pipe zonation and coexistence of Mg-rich and Fe-rich chlorites; Legault et al., 2002) of the Zn-Cu-Ag VMS deposits of the JVC are similar to those of the Matagami mining camp (Noranda-type), which is believed to have formed in a deep-water environment (Franklin, 1996). However, Legault et al. (2002) observed that characteristics such as the presence of intense iron carbonate alteration and stromatolite fragments suggest...
similarities with shallow-water Mattabi-type deposits (Morton and Franklin, 1987). The carbonate alteration is restricted to upper portions of the Poirier member, as well as Kistabiche and Eagle members, and the stromatolite fragments are found within Kistabiche tuffs only (Legault et al., 2002).

The studies of Legault et al. (2002) can be consulted for complete information regarding the deformation and metamorphic history of the region or the camp, and how this may have modified the position and signature of the syn-volcanic VMS mineralization.

Duparquet Study Area

Geological Setting

The Duparquet area, situated along the Destor-Porcupine fault (DPF), was a gold producer from 1933 to 1956 (Beattie, Donchester, Central Duparquet, and Duquesne mines) and from 1983 to 1990 (Duquesne and Yvan Vezina-Davangus mines). The geology of the DPF area consists of an Archean volcano-sedimentary assemblage divided into three volcanic and two sedimentary groups (Fig. 4; Goutier and Lacroix, 1992). The base of the sequence consists of felsic to ultramafic volcanic rocks of the Kinojévis group (2722–2718 Ma; Barrie, 1999; Zhang et al., 1993), Hébécourt Formation (2706–2701 Ma; Corfu and Noble, 1992), and Blake River group (2698 Ma; Mortensen, 1993). Rocks of the Kewagama group (2686–2684 Ma; Davis, 2002) are younger than the volcanic rocks, and are interpreted as turbiditic sediments deposited in deep basins. The Timiskaming group (<2682 Ma; Mueller et al., 1996) is the youngest stratigraphic unit in the area, and consists of coarse, polygenic, unsorted sedimentary rocks deposited in an alluvial-fluvial environment. At several locations, the Timiskaming is in angular unconformity with deformed volcanic rocks. Numerous felsic to ultramafic intrusions crosscut the region.

The eastern part of the study area distinguishes itself from the western sector by an increase in geological complexity and a shallower structural level of exposure (Fig. 4b; Goutier and Lacroix, 1992). This factor has favoured the preservation of felsic porphyritic intrusions of calc-alkaline (2689 ± 3 Ma; Mueller et al., 1996) to alkaline affinities (2682 ± 1 Ma; Mueller et al., 1996), as well as an important accumulation of Timiskaming sedimentary rocks (Duparquet Formation; Rocheleau, 1980; Mueller et al., 1991). Many E–W faults are present in the eastern sector where they crosscut most of the lithologies. These faults are not necessarily subsidiaries to the DPF, because it can be demonstrated that certain faults are clearly prior to or contemporaneous with the formation of the Duparquet basin (Goutier and Lacroix, 1992). An intense ENE–WSW to E–W schistosity is associated with the DPF and the E–W faults, but is only locally developed elsewhere in the area.

Duparquet Mining Camp

Several gold showings and deposits straddle the DPF (Fig. 4c), although little gold has been extracted from the Quebec portion of the DPF (~78 t Au production and resources) compared to the Ontario side (>2,400 t Au production and resources: Legault et al., 2004). An ongoing regional metallogenic study by the Quebec Geological Survey (MRNF) has identified seven main types of gold mineralization along the DPF, each showing a distinct style, alteration, control, metal content, and timing (Legault et al., 2003, 2004). They are: sulfides associated with VMS, epithermal veins, quartz-carbonate veins, silver-rich quartz veins, disseminated sulfides associated with leaching, and disseminated sulfides associated with intrusions. The latter type has been subdivided into two subtypes based on the composition of the intrusions: alkalic and calc-alkaline. Most of the gold-bearing mineralization shows a close genetic relationship with pyrite and sericite alteration, whereas the correlation between gold and carbonates is not as straightforward (Legault et al., 2003).

Compilation of the gold deposits and showings has shown that gold was deposited at different depths and also at different stages in the geological evolution of the area. Of the seven types of gold mineralization identified to date, only quartz-carbonate veins and disseminated sulfides associated with alkaline intrusions appear to have the potential to host economic deposits. The other mineralization types are either too small, or the gold concentrations are too low or erratic.

The studies of Legault et al. (2003, 2004) can be consulted for complete information regarding mineralization history of the region.

3-D Geological Modeling Applied to Exploration Targeting

General Issues

When 3-D integrated geological models are completed, the chosen properties are interpolated (i.e., interpolation is an estimation of a value within two known values in a sequence of values) for every cell of the voxel. These cells can contain information concerning the various lithologies, the alteration indices, drill hole density and spatial distribution, and geochemical and geophysical properties.

The completed 3-D integrated geological model is a dynamic exploration tool that can be questioned according to criteria reflecting the geological properties associated with various mineral deposits. These interrogations or “queries” allow the user to define the relationship between chosen properties within a specific model, and to define 3-D zones of high economic potential. These queries can include different criteria depending on the metallogenic environment (i.e., distance to key marker horizons or faults, geochemical and geophysical thresholds, rheological constraints, etc.).

Results from both the Joutel and Duparquet 3-D models are presented below. They illustrate the importance of carefully defining the parameters used in order to maximize
Fig. 4. (a) Simplified geological map along the Destor-Porcupine fault from Legault et al. (2003). (b) Simplified geological map of the Duparquet mining camp. Modified from Legault et al. (2003). (c) Gold showings and deposits distribution along the Quebec-Ontario DPF (for symbol legend see figure 1).
the chances of defining targets corresponding to new mineralized zones. Each parameter definition, within a query, is the result of iterative and interactive (i.e., trial and error) processes.

Joutel VMS Mining Camp Example

Construction Steps

The 3-D integrated geological model was built first at a 1:20,000 regional scale (18 × 13.5 km, and 2 km vertical depth). The regional-scale 3-D model of Joutel contains a total of 27 lithological surfaces and two faulted surfaces for a total of 34 closed geological bodies (regions) formed by 50 × 50 × 25-m cells, creating a voxel with a total of 7.8 million cells.

For the Joutel VMS camp-scale 3-D model, a smaller voxel was built to focus on an area with a higher abundance of data, and also to characterize in detail the VMS deposits that were defined regionally to have typical alteration patterns associated with Noranda-type deposits (i.e., chlorite alteration centered on the deposit with a halo of sericite alteration; Piché, 2000). The smaller and more detailed VMS model (Fig. 3; 9 × 4 km, 1 km vertical depth, 25 × 15 × 15 m cells) included: (a) data from 1,500 diamond drill holes; (b) 12,697 metallic assays; (c) 1,691 lithogeochemical analysis; and (d) calculated Normat® alteration indexes (Piché, 1999; Piché and Jébrak, 2004).

Exploration Criteria (JVC)

When the Joutel VMS model was completed, interpolations and queries were done using the geochemical data, based on metallogenic criteria proposed by Piché (2000) to define VMS targets. The choices of constraints used within our VMS queries computed in gOcad® are presented on a UML flowchart (Fig. 5):

a. Initially, areas of high heat flow had to be identified because they are responsible for the hydrothermal activity that produces VMS deposits. In fact, statistical studies within the Abitibi subprovince have shown that VMS deposits tend to be located at certain distances from synvolcanic plutons: <1.5 km, or 4 to 5 km (S. Faure, pers. commun., 2001). Thus, regions within the VMS voxel with these specific distances to the Valrennes intrusion were extracted.

b. Typical VMS deposits are underwater layers within volcanic centers produced by hydrothermal activity during long periods of volcanic hiatus. Therefore, the identification of zones with economic potential necessitated the extraction of particular volcanic geological contacts (e.g., basalt–rhyolite). Hence, regions within the VMS voxel that contained both the felsic Poirier and the intermediate Kistabiche members were selected from the model.

c. A distance of between 250 and 750 m to existing diamond drill holes was used as an additional constraint to avoid creating mathematical artefacts such as border effects along the edges of the voxel, and finding known economic zones.

d. A distance of up to 1,500 m to identified synvolcanic faults was the next constraint to refine new economic zones.

e. Altered zones were then identified and subdivided into: (a) zones of hydrothermal fluid recharge; that is, where fluids that circulated in the identified regions leached out metallic elements (Cu, Zn, Pb, Ag, Au), sulfur, Fe, and Mg, leaving a rock rich in Si-Al (i.e., quartz-epidote); and (b) discharge zones for hydrothermal fluids where VMS deposits usually form. These latter zones are discordant, leached of alkalis, and enriched in chlorite-sericite, Fe, Mg, and K, as well as metallic elements. These constraints allowed identification of the hydrothermal fluid activity signatures potentially responsible for the formation of VMS type deposits. Normative alteration indices (Piché, 2000; Piché and Jébrak, 2004), presented in Table 1, were used to infer the location of these
discharge zones. Table 2 illustrates the minimum and maximum values within the Joutel VMS mining camp, as well as the thresholds (defined by the 75th percentile) used within the VMS 3-D queries. These values are compared to percentile values for the Abitibi, compiled by Descarreaux (2000) from ~55,000 greenstone belt samples (Table 2).

In summary, a combination of high heat flow, hydrothermal plumbing and conduits, stratigraphic controls, and direct evidence of hydrothermal activity was used to obtain typical VMS constraints used in for 3-D VMS targeting (Fig. 6).

**Duparquet Gold Mining Camp Example**

**Construction Steps**

A 3-D model for the Duparquet camp was built at a regional scale ($11.4 \times 4.0 \times 1.0$ km) integrating all of the geoscientific data. It contains 74 lithological surfaces and 77 faulted surfaces for a total of 126 closed geological bodies (regions) formed by 20 m$^3$ cells, creating a voxel with a total of 5.7 million cells. The data set imported into the 3-D model included 1,746 diamond drill holes, which contained 50,348 Au assays and 3,638 lithogeochemical analyses. The model was used to define 3-D gold distribution from available diamond drill hole data and to establish queries in order to propose new exploration targets. A smaller voxel named Shaft (4.32 × 1.57 km; Fig. 4), with 10 m$^3$ cells, was built to focus on an area with a higher concentration of data and to characterize in detail the gold isosurfaces that were defined regionally.

**Exploration Criteria (DP)**

For gold exploration, the integration methodology of the data remains the same as the VMS model, except that the constraints used for queries (deformation zones, ankerite alteration, lithological contacts, etc.) differ from 3-D VMS targeting. Because gold targets are usually much smaller than VMS targets, a higher density of data is needed in order to explore efficiently at the same scale.

When the DP model was completed, interpolations and queries were done using the style of mineralization at the Holloway and Holt-McDermott deposits (approximately 17 km west of the Ontario-Quebec border along the DPF; Fig. 1). These mines strongly influenced the exploration approach of Legault et al. (2004) within the DP model area, because it is likely to have similar characteristics to these two producers. The choices of constraints used within our gold-bearing queries computed in gOcad$^\circledR$ are presented on a UML flowchart (Fig. 7):

a. Proximal to the DPF, most of producing Au deposits are within 200 m of E–W faults. Thus, our first query extracts the regions close to E–W faults. The F39 fault (Fig. 4B) is a reference surface that establishes a link between the regional- and camp-scale models.

b. Most Au deposits along the DPF are hosted within units with a FeO to MgO ratio greater than 3 (i.e., units with high Fe concentration are usually favourable for gold precipitation). Thus, our second query extracts those specific host rocks having a high Fe/Mg ratio.

c. The Holloway and Holt-McDermott deposits show intense albitization spatially associated with significant gold concentrations and located in the center of wall-rock alteration halos of sercite and carbonate. Such alteration, however, is rarely observed in the DP model region (Legault et al., 2004). At the Holloway deposit, albitization and economic gold values begin at a depth of approximately 300 m (Ropchan et al., 2002). At shallower depths, only sericitization and carbonatization are present, suggesting that the highly sericitized structures should be explored at greater depths. This third query keeps regions with high levels of sercite-paragonite (>40 vol.% alteration or normative carbonate (>10 vol.%; Fig. 8; calculated using the procedure of Piché, 1999, and Piché and Jébrak 2004).

d. The exploration targets are defined in areas located at more than 250 meters from a diamond drill hole (to avoid finding known deposits).

e. Remaining regions with extrapolated gold values higher than 50 ppb.

Borders of the Duparquet basin are the locus of known gold deposits along the DPF, containing about 87% of identified gold. Within the DP model area, exploration was focused on the DPF (Fig. 4) and some of the subsidiary structures (e.g., the Duquesne fault; Fig. 4). Little exploration has been done on subsidiary faults bordering the basin, such as the Ottman and Lepine faults (Fig. 4), despite the presence of significant alteration zones of carbonate and sericite.

With the exception of a few sectors (Beattie, Shaft, Duquesne; Legault et al., 2004), little exploration has been undertaken at depths greater than 500 m. The environment of the eastern part of the DPF differs from that of the western part (Timmins sector, Ontario) by exhibiting a shallower structural level. Legault et al. (2004) suggested that the lack of gold on the Quebec side is possibly associated with its epizonal position as illustrated by the presence of epithermal mineralization. Economic mineralization may occur at greater depth in the DPF, a possibility that has been little tested to date.

**Limitations of 3-D Integrated Geological Models**

Even though 3-D models are robust and can be used as interactive exploration tools for mineral exploration, it is important to be aware of their limitations. Primary limitations are caused by uncertainties that are propagated throughout the model. The main sources of uncertainties that influence 3-D models are:

a. Data distribution:

Irregular or sparse data distribution can result in less meaningful regional interpolated values. In fact, the
wider apart the known values are, the more difficult and less precise it becomes to estimate what lies between them.

b. Interpolation method:

The resulting value varies, depending on the chosen interpolation method (e.g., less subjective for alteration zonation and trend definition).

c. Geophysical inversion methods (unconstrained and constrained):

Geophysical data sets can be used to construct 3-D models and these can help a great deal in validating the geological model; that is, applied geophysical inversions can help constrain the depth extent and dip of specific structures and lithologies. 3-D constrained data inversion can be used as a tool to complement the 3-D initial construction steps. Inversion methods provide a more robust and quantitative solution (Perron et al., 2005).

d. Chosen criteria or constraints:

A wide variance of results can be obtained by choosing different queries because the user’s subjectivity is involved. For example, if there were twice as many syn-volcanic faults interpreted there would be twice as many 3-D VMS targets. If a user chooses a different distance to syn-volcanic plutons in the JVC, or introduces a query related to proximity to Timiskaming sediments in the DP model, then the targets would be quite different. This illustrates the point that the user’s interests and perception of the metallogenic model greatly influence the results obtained.

It is important to note that data density is one of the most crucial factors in generating targets. Bringing these limitations into the discussion does not detract from the effectiveness of the tool, but actually creates more opportunities to try different geological parameters.

**Conclusions**

The goal of this paper is to promote the use of 3-D modeling in search of various types of ore deposits: this approach could be applied anywhere in the world.

The integration of geoscientific data within a single 3-D model, and the ability to display and query these data, are significant advances for mineral exploration. The multidisciplinary approach used in 3-D integrated geological

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**Table 1. Normative Alteration Indices Defined Specifically for VMS Deposits**

<table>
<thead>
<tr>
<th>Alteration Index</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIN.FRAIS</td>
<td>Albite + Actinolite + Epidote + Orthoclase + Tremolite + Titanite</td>
</tr>
<tr>
<td>MIN.ALT</td>
<td>Hydrothermal (Paragonite + Pyrophyllite + Sericite+ Chlorite + Diaspore)</td>
</tr>
<tr>
<td>IFRAIS</td>
<td>MIN. FRAIS * 100 / (MIN.FRAIS + MIN.ALT)</td>
</tr>
<tr>
<td>IPARA</td>
<td>Hydrothermal Paragonite * 100/ (MIN. FRAIS + MIN. ALT)</td>
</tr>
<tr>
<td>ISER</td>
<td>Hydrothermal Sericite * 100 / (MIN. FRAIS + MIN. ALT)</td>
</tr>
<tr>
<td>ICHLO</td>
<td>Hydrothermal Chlorite * 100 / (MIN. FRAIS + MIN. ALT)</td>
</tr>
<tr>
<td>IPYRO</td>
<td>Hydrothermal Pyrophyllite * 100 / (MIN. FRAIS + MIN. ALT)</td>
</tr>
<tr>
<td>ISERPAR</td>
<td>Hydrothermal Paragonite + Sericite * 100 / (MIN. FRAIS + MIN. ALT)</td>
</tr>
<tr>
<td>ICHLOPYR</td>
<td>Hydrothermal Chlorite + Pyrophyllite * 100 / (MIN. FRAIS + MIN. ALT)</td>
</tr>
</tbody>
</table>

Notes:
- Proposed by Piché (2000).

**Table 2. Minimum and Maximum Values Within the Jotel VMS Mining Camp and Their Thresholds* Used Within the VMS 3-D Queries**

<table>
<thead>
<tr>
<th>Alteration Index</th>
<th>Jotel VMS Mining Camp Min. Values</th>
<th>Jotel VMS Mining Camp Max. Values</th>
<th>Jotel VMS Mining Camp 75th Percentile</th>
<th>Abitibi** 75th Percentile</th>
<th>Abitibi** 90th Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>IFRAIS</td>
<td>0</td>
<td>100.00</td>
<td>75.74</td>
<td>73.66</td>
<td>35.58</td>
</tr>
<tr>
<td>IPARA</td>
<td>0</td>
<td>76.19</td>
<td>18.50</td>
<td>14.96</td>
<td>25.49</td>
</tr>
<tr>
<td>ISER</td>
<td>0</td>
<td>82.19</td>
<td>25.27</td>
<td>5.39</td>
<td>22.96</td>
</tr>
<tr>
<td>ICHLO</td>
<td>0</td>
<td>93.87</td>
<td>32.00</td>
<td>0.0003</td>
<td>0.0004</td>
</tr>
<tr>
<td>IPYRO</td>
<td>0</td>
<td>28.63</td>
<td>0.75</td>
<td>0.0003</td>
<td>0.0004</td>
</tr>
<tr>
<td>ISERPAR</td>
<td>0</td>
<td>94.11</td>
<td>41.61</td>
<td>24.29</td>
<td>48.6</td>
</tr>
<tr>
<td>ICHLOPYR</td>
<td>0</td>
<td>97.46</td>
<td>33.13</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>ISHIKAWA</td>
<td>9.39</td>
<td>99.86</td>
<td>61.87</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Cu (%)</td>
<td>0</td>
<td>29.40</td>
<td>0.68</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Pb (%)</td>
<td>0</td>
<td>12.75</td>
<td>1.44</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Zn (%)</td>
<td>0</td>
<td>44.30</td>
<td>0.28</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>magsus hs_15</td>
<td>1.635 × 10-5</td>
<td>0.06</td>
<td>0.005</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Notes:
- *Defined with the 75th percentile.

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Notes:
- Proposed by Piché (2000).
Fig. 6 (previous page). 3-D integrated geological model of the Joutel VMS mining camp applied to exploration targeting: (a) The final 3-D model of Joutel contains a total of 27 lithological surfaces and two faulted surfaces (F1 and F2) for a total of 34 closed geological bodies (regions) formed by $50 \times 50 \times 25$ m cells, creating a voxel with a total of 7.8 million cells. (b) Extraction of regions within a defined distance to synvolcanic plutons. (c) Extraction of regions within the Poirier and the Kistabiche members. (d) Extraction of regions within a defined distance to diamond drill holes. (e) Extraction of regions within a defined distance to synvolcanic fractures or faults. (f) Identification of altered zones within the above extracted regions. (g) Identification of zones favorable for metal precipitation within the above extracted regions. Final targets resulting from the intersection of the altered zones and the zones rich in metals ($\overline{B \cap A}$; Figure 5).

Fig. 7. Queries computed in gOcad® represented on UML flowchart for the Duparquet gold mining camp (orthose = orthoclase).
Fig. 8. 3-D integrated geological model of the Duparquet gold mining camp applied to exploration targeting: (a) The final 3-D model of Duparquet contains a total of 74 lithological surfaces and 77 faulted surfaces for a total of 126 closed geological bodies (regions) formed by 20 m³ cells, creating a voxel with a total of 5.7 million cells. (b) The query is refined by choosing areas near first- and second-order E–W faults. (c) Extraction of regions with high Fe/Mg ratio. (d) Extraction of regions having either high levels of sericite-paragonite or normative carbonate alteration. (e) Regions are then extracted within areas located

modeling demonstrates that this method can be used as a regional interactive exploration tool, allowing the use of various criteria to constrain and refine queries, and lead to the definition of exploration targets.

The generation of 3-D integrated geological models of mature mining camps in the Abitibi subprovince produces refined geological syntheses and new exploration targets for deep exploration programs. Many exploration projects with a solid basis in quantitative geology are being elaborated in Quebec’s principal mining region (Abitibi), and strong partnerships between the URSTM-UQAT, the MRNF, and major exploration companies are also being developed. The models benefit from continuous validation and upgrading of the underlying database, as well as the production of regional syntheses, integrating geological, geophysical, and geochemical models in a single platform.

For geological working teams, the main advantages of using 3-D integrated geological models are to:

1. Share the information:
   a. Conveys the data and their interpretation in a format that is accessible to all.
   b. Avoids loss of knowledge and interpretations that may be:
      • Distributed across various places within the company;
      • Filed in disorganized ways;
      • Never filed and existing only in employee’s memory.

2. Catalyze the development of knowledge:
   a. Easily integrates data under a common format;
   b. Preserves data in a unique archiving platform where it can easily be shared, seen, and analyzed.

3. Resolve problems with the entire team:
a. Adaptable to team-driven problem resolution;
b. Easy access to information for all team members, collaborators, and stakeholders; allows a shared comprehension of the data.

3. Accelerate the process of data integration and interpretation:
a. Defines new targets with reduced uncertainty;
b. Focusses the work on data interpretation: optimizes data subsets with the help of an integrating tool.

3. Direct access to data and data manipulation within the gOcad® software:
a. Queries the 3-D integrated geological model.
b. Saves time: rapidly validates the data and resolves uncertainties.

The natural outgrowth of these 3-D geological models would be their extrapolation away from mining camps with large amounts of data to more remote areas with less data. The development of a more rigorous geostatistical approach for data interpolation throughout the model and its application to the query definition would better identify possible 3-D targets.

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