Assessing the workflow for regional-scale 3D geologic modeling: An example from the Sullivan time horizon, Purcell Anticlinorium East Kootenay region, southeastern British Columbia

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Abstract

We have developed a regional-scale 3D geologic model, highlighting the Mesoproterozoic Sullivan time horizon (approximately 1470 Ma) throughout the Purcell Anticlinorium in the East Kootenay region. This 3D geospatial model of the region is constrained with an extensive surface and subsurface database of stratigraphic, structural, and geophysical observations distributed throughout the study area. This modeling exercise was conducted over a four-year period from 2011 to 2015 in which several iterations of the model were produced. The final model includes what is locally referred to as the Lower-Middle Aldridge stratigraphic contact (LMC), a map unit at the very top of the lower Aldridge Formation where the Sullivan world-class Pb-Zn-Ag deposit is located. Local mineral exploration initiatives focus on this key exploration target horizon, which is now modeled in 3D. The regional LMC model provides a much needed geospatial reference used to characterize and understand sedimentary exhalative, a type of ore deposit (SEDEX) ore systems as well as a key 3D exploration target. Developing regional 3D geologic models for orogenic interiors such as the Purcell region, and older shield regions is a challenge. This is largely due to data sparsity at depth, lack of standards for 3D data collection, storage, integration, and interpretation practice. Current algorithms use only a partial set of available observational or knowledge constraints and exist in workflows that do not allow for complicated geologic event histories. We have mitigated some of these challenges with a new implicit algorithm (SURFE), applied in this Purcell case study, to estimate major regional faults and horizons through variably distributed and clustered data. These modeled geologic elements are then fed into the SKUA structural and stratigraphic workflow to produce the volumetric model. Reflection on the general 3D modeling workflow for these regional situations highlights the need for embedding more knowledge constraints into the process.

Introduction

The Mesoproterozoic Aldridge Formation within the Purcell Anticlinorium in the East Kootenay region of southeastern British Columbia, Canada, has been extensively mapped on its surface, prospected, drilled, and subjected to numerous geologic, geochemical, seismic, electromagnetic, and potential field surveys. Current regional modeling activity has been driven largely by the mineral potential of this region that is host to one of the world’s largest Pb-Zn-Ag sedimentary exhalative, a type of ore deposit (SEDEX) deposits, the Sullivan Mine in Kimberley, British Columbia. This deposit has contributed close to $50 billion in current U.S. dollars throughout its life. The abundant data collected over one century of mining and exploration activities have been compiled, analyzed, and interpreted in a 3D geospatial environment. Here, we present results of a four-year Geological Survey of Canada (GSC)-led project focused on developing a 3D regional-scale structural and stratigraphic model. Historically, the tendency to examine basin architecture for indications of SEDEX deposits (e.g., the presence of synsedimentary faults, subbasins, geophysical responses, geochemical dispersal patterns) resulted in “conceptual” models often influenced by corporate or individual bias, which were difficult to test, communicate, and reconcile among multiple disciplines. This is mitigated to a certain extent because 3D geologic modeling is increasingly being used in mineral exploration. In historical, well-explored mining regions such as the Sullivan camp, we can take advantage of 3D modeling technology and expertise that exists. It is now possible to make a constrained...
3D regional-scale model of a stratiform ore horizon because laterally persistent stratigraphic markers extracted from a digital geologic map series can be integrated with the same stratigraphic markers recognized in local clusters of drillholes. The regional-scale 3D geologic model can then be converted to a curvilinear grid, with the geometry defined by the contacts of the lithostratigraphic units. The geologic grid model can then in turn be used for future exploration targeting, taking advantage of a variety of quantitative analytical, and 3D geographic information systems (GIS) query tools (de Kemp et al., 2010). This approach to regional-scale 3D modeling is becoming important in enhancing geologic understanding of the subsurface, which can have a significant impact in reducing risk and cost in the exploration for mineral deposits at greater depths.

However, there are still fundamental challenges to the 3D modeling effort that were encountered in this exercise, which we reflect on in this paper and which are likely not all that uncharacteristic of similar efforts elsewhere. The primary modeling challenge is the radical drop off in availability of hard 3D data beyond the footprint of existing resource exploitation sites due to high costs of offsite drilling and deeper high-resolution geophysics. Second is the increased time and expertise requirements for conducting regional compilation, integration, and preparation for 3D interpretation and modeling. Currently, this consumes 75%-90% of the effort when the bulk effort should be in data analysis, interpretation, and modeling. Third, the workflow and required algorithms are not yet adequate for conducting what should be operational exercises in industry and the public sector. This workflow is still not adequate to handle and characterize the increased uncertainty resulting in modeling from poor at depth data, although this is an exciting and active area of research (Lindsay et al., 2012; Wellmann and Regenauer-Lieb, 2012). Importantly, the complex geologic histories encountered in our mineral-endowed regions in ancient orogenic interiors and shield terrains are much too difficult to handle by current software that uses codes adapted from oil and gas applications or require the gross simplification of geologic features to achieve geologically reasonable results.

These key challenges will need to be articulated to the mineral exploration and academic communities and addressed through investment in new research and development to move forward. This case study along with others in this volume will hopefully serve to highlight the opportunity that is upon us for doing what could be termed “beyond the head frame” 3D modeling or “regional hard rock” modeling. We attempt to give a realistic assessment of what is needed to make the job easier, achieving high-quality results, which positively impact stakeholders interested in 3D regional modeling in the future.

**Objective and scope**

The main objective of developing the regional-scale Purcell 3D model was to provide a wider spatial perspective of the structural and stratigraphic geology of the subsurface focusing on the SEDEX hosting horizon in the East Kootney region. Building on a major synthesis volume of the Sullivan Mine (Lydon et al., 2000a) and regional geologic compilations including a 1:250,000 scale effort (Høy et al., 1995), a 2D GIS geoscience data compilation (nine Open File 1:50,000 scale geology maps covering NTS 82F01, 02, 07, 08, 09, 10, 15, 16, 82G04, 05, 12, 13), (Brown et al., 2011; Joseph et al., 2011a, 2011b), a reprocessed seismic compilation (Cook and Van der Velden, 1995), and using British Columbia TRIM Digital Elevation Model for vertical control, an initial 3D data set was developed for the Purcell Anticlinorium. This was supplemented with inclusion of identified markers and 3D path calculation from information contained in regional legacy drillhole logs (for details, see Schetselaar et al., 2015). From the integration of this extensive data set and some follow-up field work in 2011 and 2012, a 3D structural and stratigraphic regional model of the southern Purcell Anticlinorium was developed (Figures 1 and 2).

Three-dimensional geologic modeling and integration has been successfully applied in mineral exploration primarily at, or near, mine sites worldwide over the past two decades (Pflug and Harbaugh, 1992; Dubois and Ben, 2003; Feltrin et al., 2009; Schetselaar et al., 2010). However, to go to broader scales (i.e., Regional: Brownfields and Greenfields), new 3D modeling methods are needed in which the distribution of subsurface constraints is generally sparse. Interpretive support is needed for constructing regional-scale 3D geologic models, such as interpolation and extension tools, which estimate spatial continuity or “trends” of subsurface geologic contacts beyond drillhole and outcrop constraints. In a conformable series of strata, this can be achieved by incorporating, in addition to drillhole markers, strike, and dip measurements of the strata. These bedding orientation data are either acquired at surface by geologic mapping or in the subsurface by drillhole measurements or analysis of bedding-drillcore angles. This is an underdeveloped area of research in which sample distribution and anisotropy of the structures being modeled play an important role. For this reason, we included a significant research component in the Purcell 3D activity for the development of new interpolation methods in sparse data environments. Results of this work are presented in Hillier et al. (2014, 2015). If key exploration features, such as a prospective target horizon, can be better interpreted and spatially integrated with other 3D data (electromagnetic, potential fields, seismic, drillhole data), then reproducible subsurface models of mineral systems can be generated and used in more regional mineral exploration.

The 3D regional Purcell model and supporting geoscience data presented herein are currently in GOCAD/SKUA 2014.1 software from Paradigm. The Lower-Middle Aldridge stratigraphic contact (LMC) horizon depth and structural contours are downloadable from the GSC GEOSCAN site de Kemp and Schetselaar (2015), as Open File OF7903 (includes exported DXF, GOCAD ASCII, SHAPE format files Leapfrog 3D viewer with 3D scene)
and OF7838, which describes more project details of the drill core database (Schetselaar et al., 2015) and algorithm development (Hillier et al., 2014, 2015). The stratigraphic marker points, structural observations, faults, younger Purcell Supergroup stratigraphy above the Aldridge Formation, the digital elevation model (DEM), and all geophysical data used in the interpretation are available as a GOCAD/SKUA project with exported files and a 3D geodatabase in ArcGIS also to be made available from the GEOSCAN site or by contacting the main author.

**Geologic context**

The Purcell Anticlinorium in the East Kootenay region of southern British Columbia (Figure 3) is a 100 km scale shallowly northward plunging upright fold system (Höy et al., 1995; Price and Sears, 2000; Sears, 2007) with a shallowing upward sequence from deeper water basin turbidites to basin edge facies carbonates (Höy et al., 2000; Lydon et al., 2000a). The succession of the Belt-Purcell Supergroup represents a major pericratonic rift-fill succession (Chandler, 2000a) formed at the leading western edge of North America in Mesoproterozoic times (1.47–1.40 Ga) and extends from the East Kootenays in Canada through northern Washington, Idaho, Montana to Wyoming in the United States (Lydon et al., 2000a; Price and Sears, 2000; Lydon, 2007; Sears, 2007). Commonly referred to as the Belt-Purcell, in Canada, it has more than 25 km in stratigraphic thickness (Figure 4) with the Lower Aldridge (15 km) being extensively thickened by Moyie gabbro-dioritic sills, at least one of which was most likely a significant heat engine for the evolving Sullivan SEDEX system (Lydon, 2007).

The Sullivan (Pb, Zn, and Ag) SEDEX deposit and its hosting subbasin sits within and is enveloped by the distinctive and regionally extensive uppermost unit (20 m thick in the Kimberley region) of the Lower Aldridge Formation (Ransom and Lydon, 2000). This interval, termed the Lower-Middle Contact (LMC), consists predominantly of massive carbonaceous wacke laminate (Ransom and Lydon, 2000). The Middle Aldridge Formation is approximately 2.5 km thick and is dominated by turbidites and contains numerous diagnostic laminated siltstone markers (Huebschman, 1973) recognized by Cominco geologists in the mid-1960s. The sets of unique microlaminae of these markers have been correlated over distances as great as 300 km (Figure 5). The stratigraphic position of these markers is exploited by exploration geologists to target the LMC.

Tectonic deformation has geometrically transformed the orientation and distribution of the LMC through

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**Figure 1.** Location in the southeastern British Columbia, Canada, and regional extent of the Purcell-3D model. The thickness of LMC is approximate.

**Figure 2.** Red contoured surface represents the Sullivan time horizon or “LMC” in which the Pb-Zn-Ag Sullivan deposit is located. Major elevation intervals (black contours) at 2 km and minor intervals (yellow contours) at 400 m above mean sea level.
faulting and ductile folding. There are two early pulses of deformation and metamorphism in the region. The first event referred to as the East Kootenay Orogeny (1350–1300 Ma; McMechan and Price, 1982) terminates rift-related sedimentation, involves folding, regional metamorphism, and granitic intrusion (i.e., Hellroaring Creek stock). The second event, the Goat River orogeny (900–800 Ma) is a Windermere equivalent uplift event, involving block faulting and low-grade metamorphism. These events produce at least one high-grade sillimanite-bearing metamorphic zone along the St. Mary River within the Lower Aldridge and higher grade looking rocks in the core of the anticlinorium north of the Hall Lake Fault (McFarlane and Pattison, 2000) and south of the Moyie Fault. Generally, rocks in the region are metamorphosed in the subgreenschist facies and display well-preserved primary structures common in turbiditic sediments, such as graded bedding load casts and flame structures, which constrain younging direction in modeling.

The main phase of deformation occurred in the Phanerozoic, with the western Cretaceous-Tertiary Laramide orogeny, which produces the common folding and thrusting patterns observed in rocks of the region (Price and Sears, 2000; Sears, 2007). These are characterized by upright, east-vergent, shallow, north-plunging folds separated by wider spaced more regional east-north-east-trending, northwest-dipping, generally dextral, top to the east thrust systems that affect the entire stratigraphy of the Belt-Purcell (Figures 6, 7, 8, and 9). The last significant movement occurred from extensional fault systems in the Eocene (50–33 Ma), such as the Rocky Mountain Trench (RMT) with up to 10 km of throw and which cuts the eastern portion of the Purcell Anticlinorium. It is important to appreciate that the deformation history that has affected the region has completely re-oriented and dissected the original Purcell Basin geometry, obscuring the effects of features responsible for controlling ore formation.

To better understand the SEDEX ore system at a regional scale, it was important to develop a 3D model that could give spatial context for existing and future geochemical, lithofacies, and basin analysis studies. Treating the deformation as part of the ore system (pre-syn and post ore) with 3D reconstruction, and ultimately 4D structural restoration, is the way forward toward better ore system analysis. This 3D regional geometric framework, although difficult to achieve, will hopefully contribute in developing a more precise understanding of ore-forming processes down the road. This motivated us to undertake field work in the region that was to give the modelers exposure on the ground to the style of deformation, as well as the degree and extent of folding and faulting. In the end, this project required a fair degree of interpretive work either from including legacy cross sections, developing new cross sections or insertion of interpretive points to constrain the geologic surface calculations.

Data analysis/methodology
Geospatial database management
Much effort was applied to organize all spatial data used for this project including the subsurface constraints from drillhole and seismic data used for modeling the Sullivan time horizon. All the relevant geoscience data, including those from legacy archives, were stored in a 3D GIS environment (Microsoft — Access, ArcGIS, ArcScene, GOCAD/SKUA) in which the various source data sets were inspected, standardized, and georeferenced to a common Universal Trans-Mercator projection regional projection and interpretations reconciled. Development of this 3D geospatial data store has been critical to the success of this project and represented more than 80% of the total effort. The 3D data integration activity included compilation of a drillhole database from the legacy archives of exploration programs consisting of 675 drillholes.
with more than 1000 lithostratigraphic markers (Schetselaar et al., 2015), subsurface data from the Sullivan Mine (more than 4000 drillhole logs; for details, see Montsion et al., 2015), and surface-mapped contacts as well as more than 11,000 surface structural measurements, including bedding and foliation (for details, see Joseph et al., 2011a, 2011b). In addition, all 2D seismic profiles acquired from previous projects (Cook and Van der Velden, 1995) and 2D potential field forward models (Thomas et al., 2013) were imported into the 3D GIS database.

3D modeling of lithostratigraphic surfaces and faults

A new surface calculation engine (SURFE) was developed during the course of the Purcell 3D project, as a GOCAD/SKUA plugin, based on an implicit modeling approach. This approach is widely used in 3D geologic modeling (i.e., Geomodeller, GOCAD/SKUA, Leapfrog), but has been extended and enhanced with an algorithm called SURFE, using general radial basis functions (Hillier et al., 2014, 2015; Figures 7 and 8). SURFE uses markers of lithostratigraphic contacts (from drillholes and outcrop data) and structural orientation data (bedding, fold axis) to compensate for the sparse and clustered distribution of drillholes on a regional scale. This allowed us to model faults and horizons without the use of oil and gas seismic interpretation workflows dependent on 3D seismic surveys, which do not exist for this area. The SURFE method is useful in upscaling and integrating mine and regional data by making it easier to develop consistent models that use dense and sparse data. For example, regional-distributed outcrop-scale contacts and dense drillhole contacts can be combined with strike and dip data, local tangents from fold plunges as well as off-surface observations, to collectively model individual geologic surfaces.

Structural analysis of the field data focused on organizing input data sets into structural domains (spatial regions), which essentially reflected regional-scale fault blocks (Figure 10). Three hierarchical levels of domains were classified, and one of these was used to develop the final fault network (Figure 11). Applying SURFE to define the fault network elements and then the subdomain level horizons resulted in an array of local continuous surface patches representing more reasonably the important faults and horizons of interest. These could all then be fed into the GEOGRID building workflow of SKUA, which would take care of topological management of stratigraphy and fault-horizon contacts.

The regional fault model presents one interpretation of the present-day fault topology, largely interpreted from surface geologic map patterns and historical information such as cross sections. Ideally, there needs to be a check on how mechanically realistic the fault network is and a set of alternative network proposals calculated, which also fit the input data (Cherpeau et al., 2012). This approach was not undertaken, mostly due to time, expertise constraints, and perhaps more importantly the complexity of movement history. Alternatively, geologic reasonability checks relied heavily on vetting from knowledge experts active in the area for critique. Several outreach workshops and presentations were given to solicit feedback from stakeholders, which proved useful in adjusting fault and horizon geometry through the course of the project (Schetselaar et al., 2011, 2013; de Kemp et al., 2012, 2015b; Schetselaar and de Kemp, 2013).

Discussion/models
Structural analysis and modeling

Bedding-cleavage relationships, fold vergence, and the plunge geometry of fold axis of outcrop-scale folds in Aldridge Formation and younger rocks generally fit with the regional scale picture of an east- to southeast-vergent shallowly north-plunging upright fold and thrust system produced during Laramide convergence (Figure 9a and 9b; Höy et al., 1995). To better model
the Purcell Anticlinorium, the region was divided into structural domains (Figure 10a), which are areas bounded by significant faults. The domains are also divided at a finer scale into local subdomains (Figure 10b), which display more common structural styles and are at least partially bounded by faults. Individual domains can display strong internal contrasts in structural style, which become more accentuated within subdomains. For example, the Goat subdomain where rocks of the Creston and Kitchener formations are exposed through a series of steep thrust faults bounding steeply dipping units (Figure 10b) contrasts with the apparently flatter, less-faulted St. Mary domain (Figure 10a).

Units overlying the Aldridge Formation are exposed in the Goat domain, which sits in the footwall of the St. Mary Fault. Throw on the St. Mary Fault creates this contrast in stratigraphic level. Additionally, reverse and normal throws of steep local faults in the Goat domain show a more complex earlier movement history than in the St. Mary domain. The central St. Mary domain poses a modeling challenge north of the Perry Creek Fault (Figures 10a and 11e) in which the Middle Aldridge markers are not exposed and drilling on the northern edge of the domain has not penetrated deep enough to intersect the Middle Aldridge strata. In contrast, the Moyie Lake domain (Figures 2 and 10b) south of Moyie Lake has broad open folds with relatively shallowly dipping beds that are laterally continuous for kilometers. Perhaps one explanation is the structural strengthening from the greater than 50% volume of Moyie sills within the Lower Aldridge Formation underlying much of the Moyie Lake domain. The structural characteristics of a given domain between these two end-member styles determines how these areas can be modeled in 3D, and in turn, the degree of predictability for mineral exploration strategies. Other areas in the 3D model also show local steepening of the LMC, for example, between the Carrol and Spyder normal faults in the south of the study area (Figures 2, 11c, and 11e), as well as overturned LMC in the Hughes Range east of the RMT (Figures 2 and 9). It is interesting that the model indicates some local overturned horizons only on the east footwall side of these normal structures. One possible explanation is that these steep zones may be localized by early, more regional, Laramide upright and eastward-verging fold hinges, which could provide axial zones of weakness for later extensional breaks.

The 3D modeling indicates along-strike differential displacement patterns along many of the major faults (Figure 11d). This can be observed along the Hall Lake Fault, St. Mary Fault, and RMT. There is a high degree of uncertainty in displacement estimates of these faults, which perhaps are over or underestimated in which data are most sparse. However, the partitioned patterns are worth noting because this could help either improve the model (assuming individual faults should show con-
tinuous, less partitioned displacement fields) or the patterns may indicate the complex partitioning history of movement along these networks. For the RMT, late differential normal movement may explain any lateral differential displacement along perpendicular faults truncated by the RMT such as the Moyie and St. Mary thrust faults, which also abut along the RMT. Significant internal deformation of Laramide compressional fabrics is expected in areas of extreme block faulting with rotations up to 56° indicated by reconnaissance paleomagnetic study of late Cretaceous plutons east of the RMT (Ransom et al., forthcoming). Importantly, partitioned extensional movement along the RMT could account for throw discrepancies along adjacent St. Mary and Moyie thrust-related transverse faults. Such complicated fault histories are likely to occur on several other faults as well. Previous studies have suggested several stages of movement history along the Kimberley Fault, acting on an early graben system transfer feature, overprinted by local Laramide folding and reverse dextral motion and later dominant sinistral transcurrent (Eocene) motion (Turner et al., 2000). Identification of the Sullivan Mine stratigraphy north of the Kimberley Fault makes this early graben-related link for the Kimberley Fault impossible. Eocene extension in piano key-like partitions along the RMT, superimposed on a fold and thrust system, which in turn may have earlier syndepositional history, would be difficult to restore because original throws on the earliest fault systems are not easily recovered.

**Benefits of the 3D regional model**

The mineral exploration community directly benefits from development of the Purcell 3D model by enhancing exploration for SEDEX deposits in the East Kootenay along with others, such as orogenic gold exploration companies, which can benefit from regional 3D structural analysis. There is now a 3D framework to more accurately set up specific targeting activities. All surface and subsurface data and modeled objects are 3D, and in a common UTM coordinate system. All of this infor-

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**Figure 7.** (a) Geologic measurements of S0 (bedding) and S1 (axial plane cleavage) at outcrop scale can constrain larger features, such as the LMC regional surface viewed in panel (b). (c) LMC is interpolated with a new implicit algorithm called SURFE using general radial basis functions, which enables the input of bedding orientation and contact locations as well as other structural constraints.

**Figure 8.** SURFE algorithm is able to use the more common types of geologic constraints that are not generally available for use in other implicit modeling approaches. This is especially true for inequality constraints (where the surface is above or below a given constraint) and lineations (tangents) derived from fold plunges, apparent dips, and anisotropy directions such as derived from bedding cleavage intersections (for details, see Hillier et al., 2014).
Information is stored in one repository, which saves mineral exploration companies' time and money. Practically and because of this, there is now a block-by-block mapping of depth and dip estimation for the LMC throughout the region. The model provides a depth estimate and structure (dip estimate) of the SEDEX-hosting Sullivan time horizon, as well as a reference datum for drill targeting in the region. Of interest are areas containing steeper, and occasionally, overturned LMC, such as the Hughes Range, east of the RMT, and the Spyder-Carrol fault block. There are also many areas, which have relatively shallow LMC, that are in the north–south to 160°–180° trend line with known deposits (i.e., St. Eugene and Star). It would be advantageous to develop more detailed 3D models in prospective areas, such as Findlay Creek, Vulcan, Vines, and Kootenay King (Figure 4; for detailed locations, see de Kemp and Schetselaar, 2015).

The value of new data can now be immediately enhanced by integration with the existing 3D database. Many exploration companies face the challenge to upscale information available in densely drilled mine sites to regional 3D models in sparsely drilled environments. This case study demonstrates how integration of geologic map, drillhole, and geophysical data is leveraged in a 3D environment to support interpretation of the entire ore system geologic framework, thereby increasing the potential for deep discovery.

Data management best practices supporting 3D geologic modeling that can only benefit the mineral exploration industry. The development of the Purcell Anticlinorium and Sullivan Mine models demonstrates how important it is for exploration and ore system studies to use modern data management practices. The efficiency gains when everyone is looking at the same data sets in a realistic 3D interpretive environment are multifold. Initiating this cultural shift toward rigorous spatial data management and 3D modeling allows for full use of 3D GIS as a decision support tool, quantitative targeting (Figure 12), training, and support for regional scientific analysis. Future drilling or field observations will be more accurately plotted within the 3D model, allowing updating of the model and potentially giving more meaningful representation to the data, whereas explorationists try to reconcile and interpret these in a consistent spatial framework. Significantly for the Sullivan region near the Sullivan deposit, the Mine stratigraphy and geologic information (lithofacies, structures, assays, and alteration) can be compared with information from regional exploration holes because they now have a common 3D spatial framework (Montsion, 2014). This could prove useful for the future works in delimiting the extent of the subbasin hosting the Sullivan deposit and providing leads for exploration throughout the Purcell Basin. Studies of the association between early tectonic and/or synsedimentary structures through regional intermarker thickness and lateral lithofacies variation estimates can now better be addressed. Ultimately doing a full structural kinematic

**Figure 9.** Fold geometries throughout the Purcell Anticlinorium are generally characterized by upright, shallow (5°–25°) north plunging, east verging, and occasional short eastward overturning of fold limbs. These folds patterns show up at outcrop, mine, and regional scales. (a) Measurement of bedding and cleavage orientations and intersection angles along with top indicators support development of the 3D model. (b) In the Rocky Mountain domain, outcrop-scale overturned structures are reflective of the regional steep to overturned character of the region; for example, this is well-illustrated by the LMC (red plane). The blue surfaces are regional faults, and the olive green surface is the top of the Middle Aldridge Formation. The stereonet shows poles to bedding in the Rocky Mountain domain. The blue arrows show the directions of rotation of these poles, thus indicating fold axis of rotation.
restoration, which has not yet been accomplished, would improve our understanding of the paleogeographic setting of the Aldridge Formation, increasing the discovery potential of SEDEX deposits in the region.

**Uncertainty estimation**

Uncertainty estimation and uncertainty modeling needs to be a critical part of the 3D modeling workflow for regional scale mapping. It is definitely the case that in regional settings, the 3D geologic and geophysical control set is much more limited than at the mine or camp scale (Schetselaar et al., 2013). The impact of this drastic reduction in spatial constraints will increase the uncertainty value throughout the model space especially with depth. The ability to embed and model uncertainty into sparsely constrained models is an area of active research (van der Meijde et al., 2015). The Purcell case study presented here could benefit from more rigorous uncertainty modeling, including the upfront spatial uncertainty estimation of the various observational data sets (e.g., drillcore marker locations) used before model calculation. Unfortunately, 3D uncertainty estimation techniques currently being developed (Lindsay et al., 2012, 2013), often using simulation approaches (Wellman and Regenauer-Lieb, 2012), are not yet fully operational in commercial software. In the meantime, simple measures such as proximity to data or depth from ground surface can be used as a very crude proxy for uncertainty (Figures 13 and 14).

One way to check the geologic reasonableness of the model, in addition to showing it to experts, is structural restoration. The geologic modeling package (SKUA 2014.1 software from Paradigm), used in this project to calculate the stratigraphic and structural model, tries to calculate a deformed grid with minimal internal strain and maximum preservation of stratigraphic thickness and area continuity. This comes close to what would be achieved if many 2D balanced cross sections (Dahlstrom, 1969) were used to build the volumetric model. Initial attempts to structurally restore the regional fault network using the Kine3D (a SKUA plugin developed by IFPEN (formerly IFP) which uses the open source finite element code CODE ASTER

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**Figure 10.** Reconstruction of the regional structural architecture involves characterization of structural domains, which corresponds to fault blocks. Domains are separated into (a) coarse regional domains and (b) finer structural subdomains. Significant contrasts can exist between domains at all scales. Regional domains can mask internal steep structures; for example, (a) St. Mary domain (poles to bedding shown on the stereonet) masks the predominately steep features of the Goat subdomain shown in panel (b).
as computational engine) and GEOGRID models as input were unsuccessful. It is not completely clear why this was the case; however, it was important to have another check on geologic reasonability of the model. Undeformability of a stratigraphic-structural model can be a useful indicator that a model is consistent with at least one deformation path. However, more work needs to be done to determine the importance and relative timing of the major faults used in the model if proper kinematic restoration studies are to be undertaken in the future.

More elaborate uncertainty estimation and checks for geologic reasonableness (de Kemp et al., 2015a) are hopefully on the horizon as we get better at handling more complex geologic histories in sparse data environments. This would necessarily mean that new functions for generating multiple models through automated (i.e., implicit, stochastic) model calculations will need to be available for these more complex geologic histories (i.e., polyphase deformation, intrusion, and metamorphism). Because these are not yet available, we will need to rely on making sure models that have a clear representation of what data were used to make a specific model and what underlying calculation biases were used.

3D regional-sparse data workflow

Consolidating the many steps required to achieve a robust 3D regional geologic model in sparse data settings within the context of a workflow is not easy. However, workflows are essential. Workflows are standardized processing and parameter selection steps used to focus a complex task (Sternesky, 2010). A workflow can be implemented in software or undertaken as deliberate user-driven tasks, which can be returned to iteratively without having to always start at ground zero in a long process chain. Without a workflow, we become quite unfocused and increase risk of data corruption or loss, under- or overestimation of the features being modeled, and in the worst case achieve a result that is not useful for the intended audience. Ideally, a good workflow can be used by different people to achieve the same result given the same input data and processing parameters. Workflows are a significant innovation achievement of the oil and gas sector over the past 20 years and are now becoming realized in the mining and mineral exploration communities (e.g., Mira Geosciences Targeting Workflow, Geosoft — Target For ArcGIS, Leapfrog Geo Workflow). However, it is the early days for workflow development for modeling in regional-sparse data domains, making it essential that more successful practices get shared, tested, and critiqued for a wide variety of geologic settings.

Through the course of this project, a simple workflow emerged for constructing the LMC stratigraphic and structural model (Figure 15). After reflection of the entire process, a more detailed workflow for future projects was developed (Figure 16). Essentially, the 3D modeling workflow focused on developing 3D regional faults and the folded stratigraphic sequences within and across the fault blocks. The key horizon was the LMC,

Figure 11. Data integration and 3D interpretation of the regional fault network. Major fault traces from 2D maps were corroborated with field observations of high strain zones represented by C-S fabrics, steep F2-L12 megacrenulation L12 intersection lineation (photo in panel [a]), as well as contrasting stratigraphic levels. (b) Integration of seismic data from 2D (3 s depth corrected) profiles (Cook and Van der Velden, 1995), dip estimations from cross sections, and magnetic modeling (Thomas et al., 2013) illustrated for the RMT. (c) The interpreted 3D fault traces and dip estimates are input into the SURFE calculation, which outputs a 3D fault surface. Once the stratigraphic and fault surfaces are developed, the local throw of faults can be calculated to produce on-fault displacement values for the major thrust faults (blue) and normal faults (red). This displacement field could in turn be used to constrain future fault restoration models. (d) Differential displacement on the RMT showing normal offset of 2–10 km. (e) Final fault network model.
but several of the overlying strata were also modeled. In the end, a single GEO-
GRID, which is a volumetric structural and stratigraphic model, was produced.
In this process, no intrusions were taken into account because the main goal was to estimate the key target horizon, the LMC. Thus, there was a significant volume of material such as the Moyie gabbro — dioritic dikes and sills, as well as later Cretaceous and Eocene plutonic suites (i.e., White Creek, Fry Creek Batholiths, Mount Skelly Pluton, and Read Lake Stock) that were ignored. The workflow for including these significant geologic features into the event history is currently not very clear, but certainly needs to be accommodated in future exercises. These bodies have variable thicknesses, a wide range of shapes, and complex topologies with rare at depth constraints provided by sparse drillhole intercepts. Similar to working with salt bodies, these features prove difficult to model (Collon et al., 2016). Thicker accumulations of Moyie dikes, much more prevalent in Lower Aldridge turbidites, are imaged along the 2D seismic profiles (Cook and Van der Velden, 1995; Figure 11b), which provided anisotropy information and more textural information than discrete marker data used in modeling faults and horizons. The impact of not directly including intrusive features into the model has yet to be determined, but no doubt they play an important role in increasing original stratigraphic thickness by in situ injection or reduction by assimilation, providing heat sources to drive fluid ascent, focusing mineral pathways, and likely influencing deformation patterns. In regional metamorphic settings, where there is most of the potential for mineral wealth, we will need to know how to model intrusives in a much better way.

It is useful to picture what a 3D workflow might entail for handling not just intrusions, which we were not able to do in this case study, but a range of difficult geologic features and histories. This workflow design process has already been initiated to deal with for example polydeformed terrains (Maxelon et al., 2009; Laurent et al., 2015). Other complex scenarios would need to be accommodated such as high-strain zones, their associated fabric fields, low angle-
parallel fault and horizon contacts, early regional, possibly diachronous events such as unconformities and intrusive boundaries, lithology-based modeling needed when stratigraphic-geochronologic control is absent, and early faulting or cryptic deformation events that juxtapose regions of variable complexity to name a few. Regional 3D modeling of more complex terrains means dealing with these sorts of multiple geologic events that produce complex cumulative effects through geologic time. The events need to be modeled in sequence starting with the most recent and working backward respecting binary event to event overprinting relationships and a range of geometric transformations. Not a simple task to embed in a workflow. Existing event to event transformation tools already exist for modeling simple geologic scenarios, for example, the UVT transform (Mallet, 2008; Dutranois et al., 2010) used in SKUA and used for this case study. The UVT transform effectively maps simple prefaulted depositional geometries to a horizontal Cartesian grid through stratigraphic correlations across fault blocks. A more advanced system would need a more elaborate geologic event manager (GEM) (Figure 16) using geologic event logic and event algebra similar to that already developed (Burns, 1975). It would also need to use yet to be developed physically coupled and possibly simulation-based algorithms, which are consistent with deformation pathways for given material rheologies, in deeper crustal terrains for noncoaxial heterogeneous deformation and fluid flow for volcanic and intrusive emplacement.

Workflows for 3D modeling in regional “hard rock” settings will need to consider the following issues:

Figure 15. Simple general workflow for construction of stratigraphic and structural 3D model. Steps 1–6 are common in oil and gas applications but can be applied in mineral exploration in which there is good stratigraphic knowledge and relatively simple structural history. Note in this workflow, no account is made of intrusive rocks, and all faulting is assumed to be postdepositional. Step 1: assembly of the regional fault network from sparse constraints, step 2: defining the geologic relationships (geologic topology) for the fault network, step 3: calculating a 3D volumetric partitioning into fault blocks, step 4: defining stratigraphic constraints, step 5: estimating/interpreting the horizon surfaces, and step 6: calculating the 3D stratigraphic and structural volume to produce a GEOGRID.

Figure 14. Representation of data distribution through (a) distance to drillhole intercepts (red dots) of the LMC and (b) distance to map traces (red lines) of LMC. Combining simple model uncertainty map (Figure 13) with distance maps, and normalizing, produces (c) a simple favorability map indicating areas that are not favorable (dark blue) generally deep zones away from data and are highly favorable zones (dark red) shallow zones near data, and as a rule of thumb, better areas or “favorable” for predicting LMC surface.
Figure 16. Detailed workflow showing key required elements and critical dependencies for environments with the combined challenge of more complex geologic event histories and sparse data, a characteristic of regional shield settings. Hypothetical event history shown here with more intrusive and deformation events (i.e., S1, S2, S3, F2, etc.). At the core of the workflow is the GEM, which would be critical in organizing and controlling how events (the small rounded-square boxes) combine to form geologic relationships (the bigger circle symbols with internal representation of the temporal order and type of relation). The entire set of events and relationships can be ordered in a legend graph (Harrap, 2001), which provides the geologic feature estimation algorithms (implicit, stochastic, etc.) with a framework to operate. For example, estimations of early faulting would need to respect preceding calculations of younger deformation or intrusion histories. These more challenging features may use different algorithms and parameters suited to those event types, geologic entities, and data distributions (Burns, 1975; de Kemp et al., 2015a).
1) Data management: Standardization of data management practice for structural, stratigraphic, and rock property constraints. The adoption of 3D corporate standards for geologic observation data (geologic, geophysical, and geochemical) is still in its infancy. Integrated transproject geospatial data (2D and 3D) is a long-term collective asset, which needs much more managerial support. A 3D regional modeling workflow for complex geology is directly dependent on accessing this type of constraint data store. Reducing the 75%-90% time effort currently required for 3D modeling projects will only occur if there is innovation on this front. Hand-in-hand with this will be efficient spatial and attribute search tools required for choosing the input data into the modeling process. Reclassification tools for organizing, coding, and filtering data are all essential to this process, and these need to be embedded in the modeling environment.

2) 2D and 3D GIS and drillcore data interchange: Ability to efficiently connect to and visualize key information on maps generally from GIS databases is critical when doing regional work. This is still a large bottleneck and a linear one way process. A fully integrated system is needed in which the 3D and 2D environment are fully operational either through much more streamlined interchange of data between systems or the direct embedding of functionalities to the point where there is no distinction between 2D and 3D interpretive environments. For example, cross section tools need to be able to render and project off-section structural data resulting from queries. These also need to better support the interpretive process with digitizing, balanced sections, on-the-fly polygon filling, and better labeling.

3) Advanced analytics: We need to know if our models are geologically reasonable. Embedded analytics for structural, stratigraphic, geophysical properties, and geoevent management can help in this. A range of analytics could be envisioned that are embedded in the workflow rather than as independent activities outside the modeling environment. Tools for developing an event schema within a GEM should be at the heart of the modeling system. In complex terrain, each of the geologic events (sedimentation, intrusion deformation, etc.) has an impact on what and how things can be modeled. These all need to be coordinated in an integrated fashion. There is a need to develop key indicators that test for and reflect the level of geologic knowledge of a given region and similar geologic systems elsewhere. Matching model complexity, geologic topology, and property distributions with the underlying data characteristics will be key in assessing the level of uncertainty and geologic reasonableness in the future.

4) Advanced algorithms: The workflow needs to support more automation to maximize geologic analysis and critical thinking. Calculation of model suites instead of single “tweaked” realizations is needed. A range of geologic models should be able to be produced especially in regional environments in which the geology is much more unconstrained. Exploration of the geologic model space through multimodel generation will enhance geophysical inversion and simulation processes, which currently requires only a single input geologic model (Jessell et al., 2014). Despite increased automation on the constraint management and topology calculation, there is still a lot of user intervention, insertion of “interpretive” points, to make a modeling run work. Systems are often not able to provide appropriate feedback to solve internal geometric problems, often because underlying conditions need to be satisfied for algorithm purposes. In the 3D Purcell project, these preconditions were not always clear and could conflict with the interpreter’s assumptions that the system is doing geologically reasonable things. Significant research and development needs to take place to expand the use of all the available constraints, most of which are currently left out of the process (Jessell et al., 2010), and most importantly algorithms need to be at a minimal doing geologically sensible calculations.

5) High-performance computing: More high-end computer resources will be essential as we add more constraint types to implicit codes, as well as when demand increases for regional multiparameter higher resolution models at increasing depths.

6) Collaboration: Best practice tends to emerge when there is collaboration. Workflows for regional modeling will need to be flexible, shareable, and allowed to evolve for specific terrains. For example, the workflow for working in the lower crust will necessarily be different than modeling in an active orogenic front. Distribution of these workflows to an active user base will encourage collaboration, increase innovation potential as well as enhance tool, and knowledge exchange.

Conclusions

From this study, we recognize that 3D regional geologic models are needed to enhance the wider spatial context for mineral exploration and mineral systems research. To move forward, we will need better workflows and algorithms to deal with the more complex geology encountered in these terrains (e.g., polydeformation, intrusives, and cryptic early structures). Three-dimensional regional “hard rock” workflows will need operational tools for embedding geologic knowledge to better support the interpretive process. As with all current 3D geologic modeling methods, better handling of uncertainty is needed. This is especially true in the regional context in which sparse data are the norm. We can also affirm the need for better 3D and 4D observation and model suite database systems. These systems need to be integrated directly into the constraint selection (query process) and interpretation stages of the
workflow. Geologic databases, unfortunately, rarely store geologic histories for even simple cross-cutting relationships. Any improvements in the encoding, storage, and access of primary geologic relationship observations will necessarily enhance the interpretation and modeling process toward making more realistic models. Ultimately, we will feel the impact and benefits of 3D modeling of complex geology at regional scales through investment in research from public, private, and academic stakeholders. Our intellectual resources should focus on the development of 3D regional geology workflows, algorithms, and case studies in this fertile research domain.

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References


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