Earth Model Construction in Challenging Geologic Terrain: Designing Workflows and Algorithms That Makes Sense


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ABSTRACT

Workflows are essential for establishing a successful community of practice. In the challenging domain of exploration for minerals in ancient orogenic belts there is currently a major gap in the 3D model development workflow. The essential exploration requirements for 3D modelling beyond the head frame in brownfields of mature mining camps or in greenfields of frontier regions must support rapid multi-realization calculation of geologically reasonable models. The current workflow supporting this task has been adapted from the hydrocarbon exploration industry and is not suited to handle the combined problem of data sparseness at depth and geologic complexity that is typical of the mineral exploration domain. Geological reasonableness is an essential quality of a model which resonates with the acquired knowledge of the geologist. Much of this knowledge however remains un-encoded in the constraining data such as the core geological relations, the full range of geologic observations and corresponding feature producing events as well as the character of controlling processes that sum up to produce the final configuration of a complex geologic model. The key to achieving geologically reasonable models is in designing a sensible workflow that complements what has been a more data driven approach with procedures that better capture all the knowledge we can derive from the terrain of interest. The high degree of uncertainty in these models will also require a workflow for better modelling of sparse data with a mixture of algorithms and approaches in a simulation environment that can produce a number of realizations based on natural ranges of observational data and possible geologic histories.

INTRODUCTION

“Structural analysis yields, in common with geophysical methods, a physical characterization of the rock. However, it also yields, in common with geological methods a history of the rock. It has therefore, unlike geophysics, a considerable power of prediction which extends beyond the region surveyed.”

K.L. Burns et al. 1969

Perhaps unique to the practice of earth science is the combined application of spatial and historical reasoning used to solve what are often complex geological puzzles. These puzzles come to us in the form observation sets that are both incomplete in giving us the whole geologic story, and in being spatially limited to a small subset of the volume of rock under investigation. Herein we attempt to forward the position for focusing this complex effort into what are called workflows supported by algorithms designed for 3D geological modelling.

The advancement of implicit modelling codes into the 3D geological modelling workflow has made a significant impact in reducing model construction times by replacing much of the laborious digital hand carving in CAD type explicit modelling common to early approaches of 3D modelling. Unfortunately, we still need this level of user interactivity because implicit models are not always reflecting reasonable geologic configurations. Hence the need for insertion of ever more user driven tasks that can be returned iteratively into something that makes sense geologically. The expectation by our community of practice is for meaningful geologic map interpretation, or the equivalent in 3D or 4D geospatial model development. This expectation is to solve for and extend through the map/model space our interpretation of rock unit distribution, but also for the unit or class-relations and trends of those classes to make geological sense. A geological map or a geological model is a spatial extension of these class-relationships that at a minimal respect known geologic history. Creation of these geologically reasonable models will happen only if the workflows used to create them and the algorithms that support the estimation of the model components makes sense. This summary is an attempt to set our sights on defining a workflow for modelling what can be considered complex geology (Figure 1), in sparse data terrain, and hopefully help focus the discussion on defining the core essentials of what is needed to better accomplish this challenging task.

GEOLOGICAL MODELLING WORKFLOWS

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 that can be returned 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 over estimating the features being modelled, and in the worst case achieve a

Figure 1: Examples of difficult to model geologic scenarios using current 3D modelling workflows: a) Archean metamorphic terrain, poly-deformed paragneiss with folded intrusion, Teton Range, Wyoming. Courtesy of Marli Bryant Miller, Eugene, Oregon, marlimiller@earthlink.net from http://marlimillerphoto.com/contact.html. b) Composite cross-section and deformation event sequence. Early cryptic tectonic event (S1/F1) of early recumbent folding causing stratigraphic repeats and overturning of beds, second generation tight refolding with axial plane fabric development, brittle extension and finally reverse faulting and rotation (de Kemp and Scott 2011; Scott, 2012), Northern British Columbia. c) Neo-Archean faulted dioritic intrusion network (purple) injected into felsic (yellow) to intermediate (green) volcanic sequence, Central Camp, Noranda, Québec.

Figure 2: Processing components and pathways of the current 3D modelling workflow.

Figure 3: Workflow concept for a combined data store for 1, 2, 3 and 4D objects, 2D (MapSim) and 3D GIS / GeoModelling system. (See Table 1 for component descriptions).
### Table 1: Geological Workflow Component Descriptions (presented in Figure 3) with the main concepts and linkages presented later in text

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Concepts/Linkages</th>
</tr>
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<tbody>
<tr>
<td>Earth Data Store</td>
<td>A spatial and attribute geo-object data base capable of storing geometric objects representing geological features. Controlling data objects and the resultant models derived from algorithms and/or interpretations which are accessible through spatial and attribute query mechanisms (1, 2, 3, 4D).</td>
<td>Knowledge Embedding</td>
</tr>
<tr>
<td>Geologic Event Manager</td>
<td>An organizing system which temporally orders and controls how geologic features are sequenced in the modelling process. Raw geo-objects are put in a geological context by encoding their relative binary temporal relationships. Also, geological knowledge is embedded from occurrence metrics or proxies from other similar geological scenarios.</td>
<td>Geological Reasonableness, Knowledge Embedding</td>
</tr>
<tr>
<td>Query Engine</td>
<td>A mechanism to ask spatial, attribute and geological type questions.</td>
<td>Geological Reasonableness</td>
</tr>
<tr>
<td>Event Features</td>
<td>A geo-object that has essentially a unique temporal occurrence in the geologic record for a given region. Geological processes produce these features at specific events in the geological history.</td>
<td>GEM, Implicit Modelling, Spatial Agents</td>
</tr>
<tr>
<td>Intrusive Features</td>
<td>Geo-objects that form from injection, dilation and/or assimilation of pre-existing material. Includes Sills, dykes, domes, plutons and batholiths</td>
<td>Sparse Regional Modelling, SURFE, Spatial Agents</td>
</tr>
<tr>
<td>Structural Features</td>
<td>Geo-object over printings and geometric transformations of pre-existing features. Folds, faults and associated observation or derived sites with planar and linear fabrics properties.</td>
<td>Knowledge Embedding, GEM, Spatial Agents</td>
</tr>
<tr>
<td>Depositional Features</td>
<td>Geo-object volumes formed by accumulation. Marine or Aeolian sediments, lavas and sediment gravity flows.</td>
<td>Knowledge Embedding, MapSim</td>
</tr>
<tr>
<td>Event History</td>
<td>The total sequence of temporal events that make up a rock record.</td>
<td>Knowledge Embedding, GEM</td>
</tr>
<tr>
<td>Event Processes</td>
<td>The earth processes responsible for creating event features.</td>
<td>Geological Reasonableness, Knowledge Embedding</td>
</tr>
<tr>
<td>Event Relationships</td>
<td>Binary younger over older relative age relationships as observed from cross cutting, over-printing or superposition geometries.</td>
<td>GEM, Knowledge Embedding</td>
</tr>
<tr>
<td>Simulation and</td>
<td>A stochastic and/or deterministic spatial estimation calculator that can produce one or many model(s) or specific geo-feature realizations. For example a vector field of S2 on a cross-section or a volumetric model of a batholith. Includes implicit calculators such as SURFE and/or plugins to Geomodeller, Leapfrog and SKUA.</td>
<td>MapSim, SURFE, Spatial Agents, Sparse Regional Modelling</td>
</tr>
<tr>
<td>Interpolation Engine</td>
<td>A 1,2 or 3D graphics environment which can represent various geo-feature data, with 3D glyphs as well as derived individual or geo-model suites. This includes simulated 2D maps and cross-sections (MapSim) and lithostratigraphic structural and property models. This could be accessible as an add-in tool in existing GIS.</td>
<td>Geological Reasonableness, Sparse Regional Modelling</td>
</tr>
<tr>
<td>Visualization Engine</td>
<td>An interactive environment for interpreting, editing and updating drill log classifications, map and section information as well as model components.</td>
<td>Geological Reasonableness, SPARSE, SURFE</td>
</tr>
<tr>
<td>Editor</td>
<td>Interface for bringing in source data and geological knowledge, as well as for output of models and their components in various standard forms.</td>
<td>2D GIS, Drill Database, Observation Tables</td>
</tr>
</tbody>
</table>
result which 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 last twenty years (Perrin et al. 2013) and are now becoming realized in the mining and mineral exploration communities. It is however early days for workflow development for modelling in regional sparse data domains, making it essential that more successful practices get shared, tested and critiqued for a wide variety of geological settings.

Several 3D geological modelling workflows are available from specific software applications (Geomodeller, Gocad/SKUA, Leapfrog (GEO), Move3D, etc.) or different workflow paths within these packages (i.e. Targeting, Geophysical Inversion, Structural – stratigraphic and property estimation workflows in Mira Geosciences for Mining in Gocad/SKUA). For 3D geological model construction applications generally share a similar structure and are part of a much bigger data infrastructure which may include 2D GIS and access to a 1D data storage for litho-stratigraphic borehole and/or electric logs (Figure 2). The workflow domains can be described in general as data to model transformation environments. For hydrocarbon and lithospheric environments we perform a transform of 3D (seismic) data to 3D models. A 2D (GIS) to 3D transform for greenfields and 1D (drill holes) to 3D for mining. In mineral exploration and mapping applications the raw data tends to go through a preprocessing stage in a GIS environment in which sub-set selection, interpretation, classification and elevation attribution can take place. This is not the case with hydrocarbon exploration workflows which start directly with 3D seismic and well log data. Functions for data conversion, input data selection, a mechanism for associating subsets of the data to faults, and stratigraphic horizon features are common to most workflows. Each workflow allows the user to set parameters defining the model space, the model resolution, and output data structure.

Most packages now have embedded implicit modelling surface estimation methods which greatly automate the 3D construction process. Currently, 3D modelling is for the most part, a one way and a one-off process. Data flows from 2D GIS to the 3D environment in a linear manner. Data can be interpreted in the GIS where there may be other supports from remote sensing for example, and a rich cartographic display with structural symbology. Interpreted geologic features, derived from maps and/or sections, stratigraphic and structural contacts are exported from 2D GIS and become the new constraints in 3D GIS. The supporting data is often left behind in the 2D GIS geodatabase. Once a 3D model has been created it is usually only done once, similarly with 2D geological map development, since it is such a laborious and technical process. We propose to alter this paradigm through a workflow in which there is no fundamental distinction between 2D or 3D modelling, and in which the observation and geological relationship data store is central to the workflow.

This workflow design process has already been initiated to deal with, for example, mid-crustal nappes and multi-generational folding (Maxelon et al. 2009; Laurent et al. 2015). Other complex scenarios would need to be accommodated such as early cryptic structures that juxtapose regions of variable complexity and metamorphic overprinting events. For example, regional high strain zones and their associated fabric fields, superimposed folding and complex intrusive overprinting, low angle - parallel fault and horizon contacts, early possibly diachronous events, and folded and intruded unconformities. Also, importantly, lithology based modelling is needed when stratigraphic-geochronologic control is absent.

**MODELLING REQUIREMENTS**

Moving toward the goal of increasing geological reasonableness in our models, we present a workflow concept (Figure 3) which is generally consistent with current practice but enhanced in five key areas. These are:

a) Integration of an observation and interpretation data store with 2D GIS and 3D modelling processes in a single environment. This is now, to varying degrees, part of many mine-oriented commercial packages.

b) Encoding of deeper geological history to allow input of controlling geological events and temporal relationships typical of complex geologic environments. This was pioneered in Noddy (Jessell, 1981) but aspects of this are included in implicit packages since they require fault and stratigraphic relationships to be defined. Recent work by Laurent et al. (2016) has extended this to other overprinting relationships.

c) Association of features (specific spatial geological objects i.e. fault, fabric, fold axis) and events to geologic environments and geological knowledge constraints. The use of geological plausibility as a constraint is in its infancy (Wellmann et al. 2014) and will remain a challenging area for research for some time.

d) A wider range of simulation based algorithms to handle sparse data (stochastic structural modelling, spatial agents, SVM, etc.; Cherpeau et al. 2010, 2012; Jessell et al. 2014).

e) Generation of multiple realization models in the form of 2D maps and sections (MapSim) and 3D model suites accompanied with uncertainty mappings. (Jessell et al. 2010; Wellmann et al. 2010; Lindsay et al. 2012; Caumon, 2014).

**GEOLOGICAL REASONABLENESS**

Geological reasonableness is a qualitative property of judgement indicating how geologically sensible a final model appears. All modellers have had the underwhelming experience of incredulity at seeing their initial model results, which fit all the data but make absolutely no geologic sense (Figure 4). This is understandable given the underutilization of the available geological constraints in the current workflows. The geological topology, namely the sum of all geologic relationships, and geometric forms are important components of ‘geological reasonableness’. Being able to represent, encode and manage geologic topology is critical to making reasonable geologic models.
Figure 4: Comparison of synthetic geological 3D models of refolded isoclinal horizons, all using the same data; a) Input data is uniaxial, with many adjacent opposing top directions as indicated by the equal-area Schmidt plot, b) Manually developed SPARSE explicit control model solution characterized by composite F1 – F2 plunge, c) Gocad/SKUA implicit model, d) SURFE implicit general radial basis function model.
Figure 5: Geometric and geologic topology: a) Eigenhoefer 9 geometric element adjacency rules for quantifying binary geometric relations. This scheme can be applied to $R^{E^9}$. The relation ‘inclusion’ would be indicated with an integer value of 261. D3 folding produces FP3 (fold axial plane 3rd generation) event, intrusive contact with older paragneiss (Orange-igneous protruding into blue paragneiss part of Circle), bottom circle indicates fold and fabric overprint of the igneous gneiss contact (blue line in circle). b) Geologic topology can be indicated with symbolology for single event features (rounded squares) in binary relation (Circles with 2 internal event elements) to younger event features of all types, depositional, erosional, structural and intrusive events. F3 folding and associated foliation overprinting igneous unit (orange), c) F2 folding and associated S2 foliations overprinting brittle normal fault - N.
Achieving geological reasonableness is indeed one of the most difficult aspects of 3D geological modelling, familiar to anyone who has had the task of building more complex models. This is perhaps an aspect yet un-quantified authenticity attribute embedded in our models which speaks intuitively to most geologists. This reasonableness factor is more than just assessing if the model or its components are geometrically consistent with all the various data sets. It is a component of a global conceptual uncertainty. Given our existing tools for uncertainty characterization (Wellman et al. 2010, 2011) we may still have the possibility of having a high degree of certainty in a model but things just look wrong geologically or the model infers a false process such as thrusting instead of normal faulting. How do we judge if a given model realization is geologically reasonable? To do this we need to at a minimum have a mechanism to encode geological relationships, which fortunately has had considerable conceptual groundwork and coding from Burns (1969, 1975, 1976, 1978) and an early 3D forward 3D modelling implementation from Jessell (1981) and a recent extension by Thiele et al. (2016).

Spatial adjacency relations between objects can be mathematically encoded using geometric topology methods. For example, one method used in GIS processing for binary object relationships uses Eigenhoefer rules (Figure 5a; Eigenhofer and Franzosa 1991, Eigenhofer et al. 1993, Zlatanova, 2000), which can be reduced to a core subset for geological features (GeoFeatures) in geologic domains (Schetselaar and de Kemp, 2006; Wang et al. 2016). The Eigenhoefer relations are solely geometric, however we are, in addition, concerned with the geologic content of those relations. For example there could be a stratigraphic sequence that has been injected with a set of geologic content of those relations. For example, syntax methods (Pellerin et al. 2014). For example, one method used in GIS processing for binary object relationships uses Eigenhoefer rules (Figure 5a; Eigenhofer and Franzosa 1991, Eigenhofer et al. 1993, Zlatanova, 2000), which can be reduced to a core subset for geological features (GeoFeatures) in geologic domains (Schetselaar and de Kemp, 2006; Wang et al. 2016). The Eigenhoefer relations are solely geometric, however we are, in addition, concerned with the geologic content of those relations. For example there could be a stratigraphic sequence that has been injected with a set of geologic content of those relations.

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An implementation of geologic topology assessment is presented by (Thiele et al. 2016) for comparing models and model suites with various graph representations (Figure 6), but is restricted to the simple Eigenhoefer relationship equivalent to non-overlapping adjacency. The method contributes significantly to geological reasonableness assessment as adjacency networks could be compared subjectively or quantitatively to what is accepted as a reasonable topology network of an area or alternatively new relations may be interesting for mineral exploration model analysis.

Geological complexity is another aspect of geological reasonableness indicating the number and range of types of relationships (Pellerin et al. 2014). For example, the number of fault-horizon contacts, fault-fault or intrusion-fault relations occurring in various models. In addition, there is a wide range of potential geometries for characterizing geologic features and feature relations. Thickness constraints between horizons or total sequence volumes, aspect ratios of plutons, smoothness-roughness and surface contact angles, plunge ranges of folds, continuity of horizons or fault networks, strike and dip ranges of features, fold style parameters, unit volume ratios, facing vector ranges, percentages of overturning, etc. (Ramsay 1967; Lisle and Toini 2007). We need a workflow which can encode these metrics, to both constrain and assess how different the sum of all geologic geometries and relationships is in a given model, from what is expected geologically (Wellmann et al. 2013). Finally, there are physical constraints in all natural systems which control the final geologic configuration expressed in a model. Using geophysical rock property constraints to assess geological compatibility with geophysical observations is a broad area of modelling research which is contributing to the notion of geological reasonableness. Presumably the geologic model would be more reasonable if embedded rock property distributions were at a minimal consistent with the geophysical data and the population parameters of similar geological situations (Jessell 2001; Jessell et al. 2010). On the far horizon geologically reasonable models will need to be consistent with expected thermal-mechanical processes (Hobbs et al. 2007). These physically coupled 3D and 4D models using geometrically constrained data would be able to develop reasonable geologic configurations consistent with specified ranges of heat flow, model rheologies and deformation phases throughout the geologic event history. One could envision separate workflows for lower, middle and upper crustal situations in which chevron folds do not get produced at the lower crust and recumbent shear folds tend not to occur in the front ranges of the upper crust. The challenge is to make a geological reasonableness property that is useful in describing how close a model is from what is expected from the knowledge base of the geological system that would essentially combine all of these properties. Such a schema for encoding the combined geometric and geologic topology, or geological reasonableness, would need to be encoded into the core of a 3D modelling platform and essentially be the basis of what we refer to as the Geologic Event Manager (GEM).

**KNOWLEDGE EMBEDDING - GEOLOGIC EVENT MANAGER**

Much of geology involves the integration and upscaling of local binary relationships (Figure 7) which help inform us about the geological history. We envision a workflow which would manage all constraint data and resultant geometric features in a geologically robust manner consistent with a complex and deep geological history (Jessell 1981; Jessell et al. 2010, 2014; Ailières et al. 2014). This would be synchronized with a 2D GIS and a 3D modelling platform. Ideally there would be a single 2D and 3D seamless GIS environment, in which data management, interpretation, modelling and visualization occur in an iterative fashion, not the linear one-way, one-model approach that currently exists (compare the flow paths of Figures 1 and 2). Ongoing standards research (Le et al. 2013) and development of 3D modelling for urban infrastructure such as CityGML, which seems farther ahead in terms of GIS and 3D modelling integration, can perhaps serve as a way forward for our domain. A CityGML integrated 3D geotechnical extension model (to be somewhat confusing also referred
Figure 6: Network topology graphs with possible adjacency matrix encodings of various geologic scenarios, modified from Theile (2016) and Burns (1975). Scenarios; 1) simple conformable sequence, 2) unconformity over overturned and folded sequence, 3) irregular intrusion added, 4) late extensional fault cutting intrusion, unconformity and early folds. Graph nodes represent geological unit and fault block volumes only. Volume adjacency relations are represented as lines connecting graph nodes and coloured by geological type (conformable = yellow, unconformable = yellow dashed, intrusive = red and tectonic = black). Matrix cells are assigned integer values reflecting relative age and geologic contact type. Values determined from adjacency of row unit to column unit. For example if unit A is older then B, a value of 1 is assigned. For unit B is younger to unit A, according to a depositional contact observation, the cell value would be multiplied by -1. If no contact relations are observed between units the value is 0, until a derived relation can be established (derived values not calculated here). Keeping age polarity (+/-) intact, each cell value increases for each contact type (depositional conformable = 1, unconformable = 10, intrusive = 20 and tectonic = 30).
to as 3D-GEM) already has an association to the GeoSciML class GeologicFeature and is sub-classes like GeologicUnit, GeologicStructure, and importantly GeologicEvent, and the feature type GeologicRelation which all exist in this standard (Tegtmeier et al. 2014).

The GEM would capture and encode all the possible geologic process based events, relatively instantaneous geological events that appear in the geological history, and their mutual relationships, that is the geologic topology, in a temporal data base, which acts as the rule set for subsequent modelling steps (Figure 8 and 9). In this knowledge system GeoFeatures reflect the process that created it, for example an intrusive contact is a GeoFeature which results from igneous emplacement and crystallization of magma. This intrusive GeoEvent will produce several geological relationships or GeoRelations that may or may not overprint other pre-existing GeoFeatures. For example four GeoRelations may exist from an intrusive cutting a pre-existing meta-sedimentary horizon, the two adjacent layers to the horizon, and the internal planar fracture set in the meta-sedimentary layers. Aside from the GeoFeature to GeoFeature relationships, each of these in turn may have one of eight possible temporal relation types. These provide a rich set of temporal constraints for controlling the ranges of possible GeoFeature-GeoFeature geometries that the modelling algorithms must respect in order to ensure the final model is at a minimal consistent with the GeoRelation data.

Each geological history can be encoded from the geological observation data and once computed, the map or model can be examined to determine how well the geological relations and history are respected, contributing to improving the overall geologic reasonableness of the model. A simple binary encoding of single event feature to event feature age relations and a dependency legend graph is suggested for this process with an algebra originally developed by Kerry Burns (See Burns 1975 for details) and extended by Thiele et al. (2016). A similar and somewhat simpler encoding was used for stratigraphic and structural knowledge embedding in a 3D workflow (Figure 10) for modelling hydrocarbon reservoirs (Perrin, 2005; Perrin et al. 2013). The Burns method could be implemented as an event schema table in the GEM and the used for selection of algorithms, geometry control and later cross-checking of geologically encoded maps, sections and models. This encoded geologic history can still be expressed with a classical form of legends but also in line graph form (Figure 11) which has advantages when comparing histories. Importantly, with the implementation of a deeper geologic history encoding through GEM it will become possible to better order and call as needed, specific algorithms that deal with complex geology such as fold interference patterns (Laurent et al. 2014, 2015, 2016), intrusive networks and more knowledge constrained sparse data situations (de Kemp and Jessell, 2013).

Figure 7: Example of mega-crenulation in fault zone with steep F2 fold plunge (blue crayon) rotated into the fault plane. Indicates late movement with S2 crenulation fabric overprint and crenulation folding of earlier S1/S0 foliation. A binary relation between F2 and S1/S0 GeoFeatures.

Figure 8: Extension of Burns (1975) temporal binary relations of geologic features with examples (Thiele et al. 2016).
Figure 9: Burns (1975) application of geologic event algebra on complex geology using map units: a) alphabetic encoding of map unit events, b) adjacency age relations of units, c) raw unordered event matrix (top left), ordered event matrix filled in top right triangle (top right), final stacked and ordered matrix (bottom left), final event adjacency graph from oldest (unit L) to youngest (G).
Figure 10: Example of Geological Event Schema for hydrocarbon applications. Arrow indicates the direction to younger fault feature, hence a branching geometry, which is opposite to the encoding of (Burns, 1975). Arrows in the Burns method point to the older feature. Graphs of fault to fault relations and horizon surface adjacency relationships \((\circ = \text{conformable}, \times = \text{unconformable})\) from L unconformable basal contact through to topography T (from Perrin et al. 2005 and 2013).

Figure 11: Two methods representation methods of a geologic event history: a) Classic legend representation of individual event features annotated on maps and sections, from oldest at bottom to youngest at the top. b) A dependency legend graph encoding consistent geologic history from event relationships derived from analysis of the event history matrix, adapted from Burns (1975) and Harrap (2001).
**SPARSE REGIONAL MODELLING**

Estimation of geologic trends is an essential component of bedrock mapping. In 3D geological modelling, sub-surface trend estimation can be challenging at the regional scale. Firstly this is due to sparseness of data which may not be adequate to directly support variogram analysis and modelling necessary for 3D geostatistical estimation (Deutsch and Journel, 1998; Journel and Kyriakidis, 2004). Secondly, geologic features are rarely sampled at depth or at the frequency required to adequately represent regional geofeature variations (i.e. McInerney et al. 2005; de Kemp et al. 2016). Where supporting continuous data sets exist, such as seismic, electromagnetic, potential fields and derivatives thereof, anisotropy and gradient directions can be used to support trend estimation of geologic interfaces (Guillen and Kyriakidis, 2004). Secondly, geologic features are rarely dealt with through unconstrained or constrained inversion and extraction of gradient samples from the solution distribution, but often presents an overly simplified model due to smoothing criteria of the global objective function (Linde et al. 2015). Deriving dip estimations from the geophysical data such as is done with WORMS (Austin and Blenkinsop, 2008) has been helpful for large regional scale features but needs to be interpreted carefully. Targeted forward modelling or inversion of the potential field can also be used at key boundaries where signal strength and enough property contrast exist to derive an estimation of dip (i.e. Percival and Tschirhart, 2017). By far the best, and until recently the most underused, estimation of local and regional spatial continuity are field based or high resolution DEM derived structural observations (Fernandez et al. 2009; Cracknell et al. 2013). When combined with eigen analysis these observations essentially serve as a proxy for the 3D variogram principal component directions (Woodcock, 1977; Hillier et al. 2013). The planar and linear features such as bedding, gneissosity, igneous layering, and mineral aggregate, and stretching lineations, plunge of folds and various planar fabric intersections often reflect bulk rock mineral and compositional anisotropy that can directly reflect the gross trajectory of regional scale unit boundaries (Houldsworth, 1990). This is important data when dealing with poly-deformed terrain were non-stationarity is the norm. Implicit codes can now deal directly with these gradient constraints by bringing these into the workflow to control the trajectory and topology of the scalar field, through dual point co-kriging (Lajaunie et al. 1997; Chiles et al. 2004; Calcagno et al. 2008), implicit Discrete Smooth Interpolation in Structural Lab plug-in Gocad (Caumon et al. 2007, 2009, 2013), and with Radial Basis Functions in Leapfrog (Cowan et al. 2004) and SURFE (Hillier et al. 2015). Also, other estimators such as Structural Field Interpolator (SFI) for 3D visualization of structural form lines (Hillier et al. 2013), and manual spline editing tools with 3D symbolization from SPARSE (de Kemp and Sprague 2003; Sprague and de Kemp 2005; de Kemp, Schetselaar and Sprague, 2006) can be added as intermediary inputs into the implicit code calculations.

What is hopeful is that there is a wealth of geometric field observations that have been collected by geological surveys over the last half century that can provide regional structural constraints for 3D modelling. Much of this data is off contact or in-equality constraint data which can be used directly in the implicit codes (Courrioux et al. 2006; Hillier et al. 2014), as well as increasingly more constraints from the deformation history (Laurent et al. 2014, 2015, 2016; Grose et al. 2015). However, regional data sets are spatially biased and clustered from non-uniform sampling at the surface of the earth. This sample bias, when using a purely data driven implicit approach will often produce geologically unreasonable depth solutions. In practice this is mitigated through inserting knowledge constraints in the form of interpreted points and form lines along cross-sections and/or combining results from explicit tools like SPARSE in a hybrid manner, as input into the implicit calculation (i.e. Collon et al. 2016; Montsion et al. 2017).

![Figure 12: Down dip traces (orange curves) estimated from constant depth dip observations (yellow tablets) using spatial agents. Red ball is the search agent. Small blue dots are simulated Bézier grip frames calculated with a random noise component.](image)

![Figure 13: Spatial agent demonstrating 90 degree clockwise quaternion rotation of bedding observation from point A proximal to data to point B at distal location. Rotation respects geologic topology (top direction). This function could be incorporated into a 3D form trace algorithm.](image)
Figure 14: Example of unconstrained triangulated surface construction using spatial agents. Note growth of surface occurs with simple geological rules, namely parts of surface cannot self intersect, must maintain consistent polarity, and avoid certain tear faults. These surfaces can be made to move toward data constraints exactly or with tolerance.
SPATIAL AGENTS

An area of current research for surface modelling in sparse regional domains is the use of spatial agents for enhancing knowledge embedded estimation, projections and extension functions (Torrens, 2010; de Kemp and Jessell, 2013). Applications of Spatial Agent Based Modelling (SABM) in the geosciences have been largely confined to problems which involve time series, such as land use change due to climate, urbanization and hazards (Torrens, 2010). We have developed a simple demonstration set that produces solutions for sparse data, at ground level \( Z = 0 \) to simulate ground traverse acquisition, for on-contact and structural data for fabric and form line estimation (Figure 12). Also, spatial agents can represent and handle planar and linear structure data as well as polarity control of observations and estimations (Figure 13). We have also been able to develop spatial agent triangulated meshing which can be controlled to grow from single point sources such as observation sites, respect simple local rules to maintain local and over all surface polarity as well as topologic rules to accept or reject meshing solutions (Figure 14).

Although yet to be completely demonstrated, some characteristics of the SABM approach may be provide us with another tool for complex geological modelling. For example, some interesting qualities of agents;

- Can explore all the model space and all the data regardless of how irregular the space is and how varied or complex the data is. The approach can make many or no solutions, simple or complex depending on the model design. Generally traditional methods use more regular partitioned spaces, fixed coordinate systems and one or two geologic parameters.

- More suitable to natural multi-scalar complex systems in which agents can preserve contributions from all data. This is important as classical techniques generally produce global means when data is sparse and generalize dense data clusters to a local mean which is often geologically meaningless. Important in combining geology-structure-geophysics.

- Rich variety of Rules, Missions (Beliefs) and behaviors can be applied while interacting with and interrogating data thus supporting the interpretive process for the domain expert.

- Many algorithms including classic ones can still be applied (Kriging, DSI - Discrete Smooth Interpolation, RBF - Radial Basis Functions, IDW - Inverse distance Weighted, SVM - Support Vector Machine, etc.) at local or regional scales depending on the requirements. Can build-on and compliment rather then replace existing systems.

- Produces group – swarm behavior that emerges from simple agents interaction-communication. They can estimate complex geometric features or trigger other spatial behaviors (discontinuities), topologic changes or spawn new agent driven events. Important when mapping and visualizing complex relationships within vector fields such as fabric intersections, fold trains, vergence relationships and multiply folded and faulted stratigraphic boundaries.

- Simple rules sets drive the agent interaction rather then solving for a single large global matrix. Agent approach has good optimization potential, it can benefit from faster CPUs and could potentially be easier to parallelize. Important when combining 3D vector and multi-scalar properties from structural fields (i.e. Burns, 1988; Hillier et al. 2013), geophysics and geology.

Currently these are implemented in NetLogo (see Spatial Agents links) which is a 2D and 3D agent based programming environment. We envision these could possibly be used for delineation of map units (in 2D and 3D) but also for internal property anisotropy estimation.

MAP SIMULATION - MAPSIM

3D Graphics technologies for hardware (graphics cards, gpu architectures, displays) and software (animation, rendering, scientific programing) are rapidly evolving to enhance many application domains, including 3D geological modelling. These advances, especially in implicit codes which are incrementally adding to the list of constraint types used for geological modelling, have increased automation and performance of model calculations. The one limitation however, is that standard workflows using explicit, implicit or hybrid approaches still tend to produce only one model from the data. This impacts
adversely on the ability to perform uncertainty analysis and model exploration activities that are required to interpret the more challenging terrains. To tackle this, we envision a multi-dimensional simulation environment, with the 2D component termed MapSim (see Figures 3 and 15), which supports uncertainty analysis and produces map and model suites rather than one-off products.

A significant amount of development would be required to implement a MapSim environment, however much of the essential components are in place, including; wide range of 2D spatial class separation algorithms from machine learning (Support Vector Machine, Self Organized Maps, Voroni Partitioning etc.) that can calculate primitive skeletal and/or polygonal sets, as well as a rich class of graphic transformation functions (i.e. wire frame to parametric) that can be used to embed shape parameters (i.e. from Lisle and Toimil, 2007, Hudleston and Treagus 2010) and which could support scale changes. Importantly there is now implicit code available to calculate 3D solutions from observational data, including off-surface unit occurrences from ground traverses (Courrioux et al. 2006), which could be accessed from more common 2D GIS environments such as ArcGIS. Extracting feature traces could be achieved by intersecting surface realizations calculated from implicit or other 3D estimation codes with map/section planes or a DEM. This could be done in a stochastic manner (see an example see Cherpeau et al. 2010, 2012) through Monte Carlo sampling of the various shape distributions from local or similar proxy data sets. A 2D map, in plan view or as a cross section, can be thought of as an instance of a 3D model (Figure 16). In the case of 3D modelling, a 3D map is a specific representation of the model which hopefully gives some geoscientific meaning to the user.

Since most of our applications are dealing with under constrained geological models it is clear that more than a single model, and hence more than one map representation, is needed. The 2D MapSim component needs to be directly connected to full GIS functionality, but there is no reason that all visualization components (i.e. boreholes, 2D maps and sections, 3D models and 4D geologic history models) should not be connected to a data store and associated GIS. Historically the 2D GIS and 3D geological modelling worlds have been separated by a tedious export-import process which is inefficient, and often causes data corruption through topology reduction and property content losses. Importantly, information exported from GIS and subsequently used in 3D modelling is not data, it is manually interpreted or modelled information, in effect with this process we model on top of a model. With a seamless integrated 2D and 3D visualization and modelling environment we mitigate this practice, with data remaining robust while being able to directly examine models/maps derived from interpreted or calculated realizations. All operations, projections, queries, re-classifications, ordering etc. would all be directly interacting with a data store that hosts corporate, multi-project geospatial information including 1, 2, 3 and 4D geologic observational events, the event relations and derived feature maps, property distributions, and model suites.

Figure 16: Example of targeted visualization of the Sullivan time horizon (red surface) from the regional model of the Purcell Anticlinorium, Southeastern British Columbia: a) GIS map view indicating Sullivan horizon as (red structural contours) on hill shaded DEM with interpreted bedrock geology, mineralization sites and structural observations (for details see de Kemp and Schetselaar, 2015), b) combined 2D east-west cross-section from Gocad/SKUA transecting 3D structural and stratigraphic model, c) fully rendered 3D volume.
DISCUSSION

Geological models need to represent the entire suite of geological events that have affected the model space. The observation record of these cumulative events, if properly collected and managed, will be able to support the spatial and temporal mapping of the region. Each event may have a unique and possibly significant contribution to the internal geometry of the model, so it is essential that the workflow support characterization and temporal ordering of all the geological events, not just the last few (See Table 1 & Figure 3). For example, an early deformation resulting in a regional décollement may have resulted in regional scale overturning of a stratigraphic succession. Early tectonic events such as this tend to be cryptic features due to later superimposed deformation and intrusive events. Their geometries becoming hidden in the cumulative complex patterns that are produced from protracted geologic histories.

One of the main shortcomings of current 3D geologic modelling workflows are the limited number of supported geological events and the possible features they produce. This is generally limited to modelling of late high angle brittle fault networks and a sedimentary stratigraphic pile. Geologic relations are encoded in the binary fault-fault branching network and a temporal sequence of conformable or unconformable horizons. Folding events are not specifically encoded in the workflow but will be represented provided there is adequate data sampling and/or interpretation supports such as from cross sections. Intrusive models, such as salt domes, are difficult to do and limited to more manual explicit, or hybrid implicit approaches (Collon et al. 2016). Complex geological environments, i.e. mid-crustal environments from most shield and convergent orogenic terrains, require a workflow with the ability to go deeper into the geological history and embed the full range of relative and absolute historical constraints that are available in the observation set. We will need to know how to model geology in a much better way, in these metamorphic settings, where there is most of the potential for mineral wealth. For example, algorithms that are great for modelling smoother mid-crustal features may not be appropriate to model thin skinned low grade foreland chevron folding (Hobbs et al. 2007).

Structural data is critical in separating and ordering the geological history. Most 3D workflows have no facility to have as input these fabric relations that can influence not only anisotropy estimation (i.e. Eigen analysis; Woodcock, 1977) but also relative age relations critical for controlling model topology. For example, a large iron formation boulder in a basal conglomerate may have an internal foliation distinct from the host matrix and other clasts, thus indicating pre-existing depositionsal event but also an earlier deformation not affecting the conglomerate and younger units.

Regional 3D modelling 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 modelled in sequence starting with the most recent and working backwards 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 modelling simple geologic scenarios for example the UVT transform (Mallet, 2008; Dutranois et al. 2010) used in SKUA®. The UVT transform effectively maps single pre-faulted depositional geometries to a horizontal Cartesian grid through stratigraphic correlations across fault blocks. A more advanced system would need a more elaborate GEM employing geologic event logic and event algebra similar to that already developed (i.e. Burns, 1975). It would also need to employ yet to be developed physically coupled and possibly simulation based algorithms (Cherpeau et al. 2010, 2012) which are consistent with deformation pathways for given material rheologies (Hobbs et al. 2007), in deeper crustal terrains for non-coaxial heterogeneous deformation (Passchier 1987) and fluid flow for volcanic and intrusive emplacement (Nelson et al. 2011; Putnam et al. 2015; Rivalta et al. 2015, Kruger and Kisters 2016). Many of these as yet underdeveloped estimators for more complex irregular geometries will need to be developed. Preliminary use of spatial agents with some geologic behaviour controls may prove useful as a way forward but there may be a wide range of other graphics approaches to reproduce multi-scaler patterned objects (Wang et al. 2017, Boiangiu et al. 2016) from computer graphics simulators. If these can be constrained to the observational metrics, or proxies thereof, we can expect to see more progress with the more challenging geological features such as intrusions and poly-phase deformation histories.

CONCLUSIONS

A sensible workflow designed to support the 3D modelling community working in geologically complex settings is urgently needed. This workflow needs a simulation based approach which can produce model suites, that fit all the data not just a narrow sub-set thereof. The workflow should be as seamless as possible between GIS and modelling functions for 2D and 3D integration, visualization and interpretation.

More complex geologic event histories need to be managed and encoded through some form of GEM. Encoding of these histories and the data representing them can be tackled through a geological relationship data base which uses geological algebra similar to that initiated by Burns (1975) and extended by Thiele et al. (2016). Spatial estimation algorithms (i.e. implicit codes) need to be integrated with this process so that results can be consistent with geologic event histories, and therefore more geologically reasonable.

Deeper ore bodies have greater potential to be discovered in brown and green fields regions through more consistent integration of geological and geophysical data. Rock property and historical survey information needs to be easily accessible to support integrated inversion and forward modelling codes. Public geoscience organizations can play a big role to increase efficiencies in this area.

New methods will be needed to support the combined knowledge and data driven approach for 3D interpretation in the regional complex geology domain. Spatial Agent based systems offer an example of a way forward to deal with sparse data regions. However, many new algorithms and new approaches
for extension, migration and projection will be needed in areas where we may have little hard constraints at depth, but more abundant geological experience and knowledge to work with.

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REFERENCES

Aillères, L., T. Carmichael, E.A. de Kemp L. Grose, V. Kolin, G. Lautent, M. Lindsay and C. Yu Chui, 2014, 20 Years of 3D structural modelling. Where are we at? Where next?: 3D Interest Group Meeting at the Centre for Exploration Targeting, UWA.


de Kemp, E.A. and E.M. Schetselaar, 2015, Structural and depth contours of the Lower-Middle Aldridge Contact, East Kootenay Region, Southeastern British Columbia, Geological Survey of Canada, Open File 7903, 3 -1:100,000 maps with 3D model.


Harrap, R., 2001, A legend language for geologic maps — Precambrian times: Geological Association of Canada, Precambrian Division Newsletter, 1, 3–9


Laurent G., L. Aillères, L. Grose and G. Caumon, 2014, Controlling folds with an implicit modelling approach and rigid method for geological structural modelling: 3D Interest Group Meeting at the Centre for Exploration Targeting, UWA.


Sprague, K and E.A. de Kemp, 2005, Interpretive tools for 3-D structural geological modelling part II: surface design from sparse spatial data: Geoinformatica, 9 (1), 5-32.


