A Perspective on a Three Dimensional Framework for Canadian Geology

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Introduction

The intensification of economic development over the past 200 years and the increasing impact and conflict in land use requires an adaptation in how we investigate, analyze, report, store, and disseminate geological knowledge. In the 19th century William Smith mapped much of Great Britain in two dimensions. Smith’s mapping was spurred on by the emergence of the industrial revolution and enormous changes required to support mineral exploration, and transportation of raw and manufactured goods. In developed countries, particularly in Europe, there is an increasing realization and acknowledgement of the need for three-dimensional (3D) geological mapping programs to address the complexity of conflicting land use practices in the 21st century. Two hundred years after Smith’s seminal map, the 21st century requires a move from 2D to 3D geological mapping, particularly at the national scale (e.g., Thorleifson et al., 2010). This transition is less dramatic than it might seem. Even in the early maps of Smith, geology was presented with an appreciation for the third dimension, through the use of cross-sections and subsequently structural symbols. A wealth of subsurface information has been accumulated from drilling and geophysical studies supporting surface mapping. With access to surface and subsurface data, Geological Survey Organizations (GSOs) in a number of jurisdictions have made significant progress in the development and implementation of 3D mapping programs (e.g., Howard et al., 2009; Berg et al., 2011; Meulen et al., 2013; Mather et al., 2014). Such programs commonly have much broader objectives than just 3D visualization of a jurisdiction’s geology. These programs are focused on a full continuum of data management, storage, analysis and classification for 3D realization (e.g., Howard et al., 2009). The recent proliferation in jurisdictional wide 3D mapping is the outcome of the maturity of a digital transformation in geological data collection and management that started over 25 years ago and includes computer hardware and software developments of the past half century.

Canada is a large country at 9 million km², and dwarfs most countries with developing 3D mapping programs by up to several orders of magnitude (Table 1). Furthermore, whereas some of these countries have relatively simple geological successions of undeformed sedimentary strata (e.g., Netherlands, Denmark), the geology of Canada is diverse, locally complex (e.g., orogenic belts) and with extensive submarine extensions of its terrestrial geology into the marine environment of archipelagos and continental shelves. An exception to this statement is Australia, which is only 20 % smaller than Canada, has diverse, complex geology, yet has made progress modelling nearly one-third of the country. A parallel initiative called DigitalCrust (Fan et al., 2014) has an objective of developing a 4D geological framework of the upper crust of the continental USA. In a number of countries physical based modelling appears to precede national geological modelling by a considerable period. Denmark had a national hydrological model over ten years before consideration of a national geological model (Henriksen et al., 2003). Similarly in North America significant progress has been made in modelling the groundwater regime of both the USA and Canada with simplified geology (Maxwell et al., 2015; Chen, 2015).

The objective of this paper is to review the extent of current 3-D mapping, address the question of data support for 3D geological mapping, consider how the geological landscape may be parsed into distinct
entities to facilitate 3D geological mapping, and illustrate a progressive approach to advance discussion on to how to achieve the ambitious goal of a 3D framework for the geology of Canada.

**Status of regional 3D mapping in Canada**

The term 3D geological mapping evolved in the 1990’s as digital geological mapping techniques started to emerge as a complementary term to differentiate the digital mapping - modelling approach from traditional subsurface studies. For decades subsurface studies had been completed, and subsurface data (borehole data, geophysics) have been analyzed and archived through the construction of cross-sections, and development of structural and isopach surfaces of geological formations. Progress has systematically advanced from more conceptual models to progressively more data driven realizations. This is true across the Canadian landscape from definition of the lower crust (e.g., Perry et al., 2002), complex bedrock structure (e.g., de Kemp et al., 2015) to sedimentary basins (e.g., McCrossan and Glaister, 1964) and the Quaternary succession (e.g., Matile et al., 2011). In the Phanerozoic bedrock basins of Canada the crowning achievement in this regard is the latest version of the Western Canadian Sedimentary Basin Atlas by Mossop and Shetsen (1994). This landmark publication heralds the transition from conventional compilation and publications as it managed and produced the 2-D structural maps using computer technology. More modest were the many maps of larger scale produced by geological surveys across Canada of bedrock surfaces, commonly at 1:50,000 scale to support a range of activities, but particularly groundwater studies. In the marine environment the wealth of data being collected by seismic surveys has also been interpreted and archived in 2D format (e.g., Syvitski and Praeg, 1990; Campbell et al., 2015). In the 1990’s as GSOs transitioned from traditional cartography to digital map production there was an increase in the use of GIS systems to manage and visualize subsurface geology. Much of this 2.5D model construction forms the basis for existing regional 3D mapping coverage developed to support environmental applications (e.g., Russell et al., 2010). At the Canadian provincial scale the three Prairie Provinces have the most advanced 3D mapping programs (e.g., McCormick and Banks, 2013; Card et al., 2010; Matile et al., 2011), with Ontario advancing both bedrock and surficial modelling initiatives. The Alberta framework model covers an area of 661,848 km using primary borehole stratigraphic logs (McCormick and Banks, 2013). Conversely, working with legacy structural interpretations from the Western Canada Sedimentary Basin Atlas Matile et al. (2011) generated a 1,425,000 km² model (Fig. 1). Using primary stratigraphic well picks from > 9000 borehole logs they also constructed a 494,000 km² model of the Williston Basin (Table 2). In Quebec groundwater funding has supported regional scale 3D mapping of the surficial geology (e.g., Cloutier et al., 2014) and to a lesser extent bedrock stratigraphy in the St Lawrence Lowlands. Saskatchewan has been particularly active in 3D modelling of uranium rich Athabasca Basin (Card et al., 2010) and the GSC has completed 3D modelling of mineral deposit camps (e.g., de Kemp et al., 2015). Less visible are the variety of 3D geological models being developed by industry for resource extraction, environmental monitoring and project planning and development. One example in Southern Ontario is the 35,000 km², 37 layer model of the Phanerozoic by the Nuclear Waste Management Organization (Itasca and AECOM, 2011).

<table>
<thead>
<tr>
<th>Jurisdiction</th>
<th>Model type</th>
<th>Size km²</th>
<th>Characteristic</th>
<th>Model extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Holland</td>
<td>Geological</td>
<td>5000</td>
<td>sedimentary</td>
<td>complete</td>
</tr>
<tr>
<td>2 Denmark</td>
<td>Geological</td>
<td>42,000</td>
<td>sedimentary</td>
<td>partial</td>
</tr>
<tr>
<td>3 Denmark</td>
<td>Hydrogeological</td>
<td>42,000</td>
<td>sedimentary</td>
<td>complete</td>
</tr>
<tr>
<td>4 Bavaria</td>
<td>Geological</td>
<td>55,000</td>
<td>Orogenic, foreland</td>
<td>partial</td>
</tr>
<tr>
<td>5 Great Britain</td>
<td>Geological</td>
<td>229,848</td>
<td>Sedimentary, crystalline, orogenic</td>
<td>partial</td>
</tr>
<tr>
<td>6 Manitoba</td>
<td>Geological</td>
<td>647,797</td>
<td>Sedimentary, crystalline</td>
<td>partial, sedimentary region</td>
</tr>
<tr>
<td>7 Alberta</td>
<td>Geological</td>
<td>661,848</td>
<td>Sedimentary, crystalline, orogenic</td>
<td>partial, sedimentary, undeformed region</td>
</tr>
<tr>
<td>8 Australia</td>
<td>Geological</td>
<td>7,692,024</td>
<td>Sedimentary, crystalline, orogenic</td>
<td>partial, 1/3 country</td>
</tr>
<tr>
<td>9 USA</td>
<td>Hydrogeological</td>
<td>~8,000,000</td>
<td>Numeric flow model, continental US</td>
<td>complete, continental</td>
</tr>
<tr>
<td>10 Canada</td>
<td>Hydrogeological</td>
<td>9,984,670</td>
<td>Numeric flow model, continental Canada</td>
<td>complete, continental</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Jurisdiction – region</th>
<th>Size km²</th>
<th>Geology</th>
<th>layers</th>
<th>Data support</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Purcell Basin</td>
<td>7,000</td>
<td>volcanic</td>
<td>15 km</td>
<td>Boreholes, outcrop, geophysics</td>
</tr>
<tr>
<td>2 OPG Repository, ON.</td>
<td>35,000</td>
<td>sedimentary</td>
<td>37</td>
<td>borehole stratigraphy</td>
</tr>
<tr>
<td>3 Athabasca basin</td>
<td>35,000</td>
<td>sedimentary</td>
<td>6?</td>
<td>borehole stratigraphy</td>
</tr>
<tr>
<td>4 Williston Basin</td>
<td>494,000</td>
<td>sedimentary</td>
<td>42</td>
<td>borehole stratigraphy</td>
</tr>
<tr>
<td>5 Alberta</td>
<td>661,848</td>
<td>sedimentary</td>
<td>23 – 52</td>
<td>borehole stratigraphy</td>
</tr>
<tr>
<td>6 WCSB</td>
<td>1,425,000</td>
<td>sedimentary</td>
<td>11</td>
<td>legacy</td>
</tr>
</tbody>
</table>
Collaboration and Data support

Data support for a national 3D initiative is diverse and reliant not only on public domain data but also accessibility to additional data that may be held by public agencies under a user-pay-system or proprietary private sector data. Data support is also dependent upon collaboration between provincial geological surveys and the federal GSC. Much of the geological data and the expertise necessary for respective regions of the country are divided between provincial and federal agencies. Given diminishing human and financial resources along with jurisdictional responsibilities collaboration is essential and has implications for the nature of the data management framework (see section 4). Unlike some other national geoscience organizations (e.g., Australia, Riganti et al., 2015), the GSC lacks a coherent data management system that could provide a turn-key operation to support 3D mapping. Rather much of the legacy data available to support 3D mapping is in paper or analogue format and is thus costly and time consuming to access and re-interpret. Where formally published this material is being systematically digitized and made available online, unfortunately as individual PDF or raster format digital files of respective publications (e.g., Geoscan). Fortunately, for the petroleum provinces of Canada, legislated data reporting has resulted in extensive and well managed stratigraphic databases (e.g., Carter and Castillo, 2006). This accounts, however, for less than one-fifth of the Canadian landmass. Private sector datasets, particularly geophysical data are extensive but difficult to access, assess, and integrate into public initiatives. On a positive note the progressive move by governments to Open Data initiatives (e.g., http://open.canada.ca/en) backed in some cases by well-organized digital databases greatly facilitates the ability to synthesize and deliver data for a Canada 3D initiative. For example a number of provinces maintain databases of water well records and for 8 of 10 provinces this data is available via the Groundwater Information Network (GIN; Brodaric et al., 2014). Similarly for petroleum provinces respective provincial jurisdictions maintain pay-for-access data repositories (e.g., Carter and Castillo, 2006). Such regional to national coverage are also available for deeper depths, for example geophysical datasets exist for the crust and Moho (e.g., Perry et al., 2002).
Advancement of the geological knowledge component of the 3D mapping is only possible with a solid data management framework. Given the diversity of data and end objective of a national 3D model the optimal option is a hierarchical system of distributed databases with a central database that manages model inputs and outputs, and metadata links to its source databases. The central database enables an evergreen approach, by which the model can be updated upon new model inputs, and it also enables thematic search and visualization of outputs and inputs. As much of the mapping data is currently in legacy holdings of geological agencies as either unpublished material, knowledge publications, published data releases, and databases means of maintaining access to the data being interpreted and coded is necessary. Many datasets have been scanned and are only available as raster or PDF publication products. There is a need for the conversion and often reattribution of this data for integration into a control dataset. The challenge of capture, storage organization, and maintenance of data during this intermediary step is likely subject or discipline specific. For example the capture, interpretation and extraction of geological interpretations of geophysical data (e.g., de Kemp., 2015). Fortunately a number of initiatives have established working components for this process. A geological database of geological unit descriptions, i.e. a lexicon of geological units, has been established and implemented through the Geological mapping for Energy and Minerals (GEM) initiative and the Tri-Territorial Bedrock compilation project (Brodaric, et al., 2015). This database provides information about a specific bedrock unit, compiled from many sources of literature, enabling sophisticated querying of the units. The communication, standardization and client delivery of data has been implemented at a national scale by the Groundwater Information Network (GIN) which is serving disparate data from 8 provincial water well databases along with time series monitoring data from a number additional provincial and international data sources including the USGS (Brodaric, et al., 2014). Through the work of various participants there is also a strong integration with international geological standards for delivery of geological information via web protocols (Sen & Duffy, 2005).

## Parsing geological complexity

The geology of Canada is diverse, the data support ranges from surface mapping to extensive subsurface datasets, and the knowledge framework has similar diversity in understanding. The 3D mapping of Canada needs to address these differences by integrating support across the provincial and federal levels. Consequently it is unlikely that one approach will work for the entire country. It is also, equally unlikely, that progress will be advanced for all geological layers, domains, and jurisdictions with equal timing. It is thus necessary to consider how to parse the geological complexities into manageable and as geologically homogeneous entities as possible, both vertically and horizontally. The extensive physiographic, and geological mapping along with subsurface studies completed to-date provides insight into this issue. The

### Table 3. Examples of public domain regional surficial modelling in Canada.

<table>
<thead>
<tr>
<th>Jurisdiction</th>
<th>Size km$^2$</th>
<th>Layers</th>
<th>Data support</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Abitibi, Quebec</td>
<td>9,200</td>
<td>11</td>
<td>water wells</td>
</tr>
<tr>
<td>2 Oak Ridges Moraine</td>
<td>12,000</td>
<td>6</td>
<td>water wells, core, seismic</td>
</tr>
<tr>
<td>3 S Ontario</td>
<td>72,000</td>
<td>2</td>
<td>water wells</td>
</tr>
<tr>
<td>4 Mackenzie valley</td>
<td>~1,600,000</td>
<td>2</td>
<td>seismic shot holes</td>
</tr>
<tr>
<td>5 Manitoba, SE</td>
<td>45,000</td>
<td>17</td>
<td>water wells</td>
</tr>
<tr>
<td>6 Alberta</td>
<td>131,000</td>
<td>4 - 8</td>
<td>water wells</td>
</tr>
<tr>
<td>7 Manitoba, SW</td>
<td>176,225</td>
<td>35,</td>
<td>water wells, seismic</td>
</tr>
</tbody>
</table>
9 volume Geology of Canada (e.g., Wheeler and Palmer, 1993) provides a guideline on how to approach the problem with its division of Canada into shield, orogenic belts, cover rocks, and Quaternary (Fig. 2). Both the shield and orogenic belts are structurally complex with extensive folding and faulting resulting in stratigraphic reversals and abrupt lateral and vertical changes in rock units. These two elements are thus the most complicated domains in which to complete 3D mapping. Each is nevertheless composed of large structural domains that have some elements that can be conceptualized in consistent manners and likely delimited by available data support. Sedimentary cover rocks whether on the shield (Athabasca Basin) or one of the numerous Phanerozoic basins generally have limited structural complexity with predominately subhorizontal and only modest normal and reverse fault offsets of strata (e.g., Southern Ontario, Fig. 3). For large parts of the country where petroleum resources are exploited there is extensive data support for regional 3D mapping (e.g., Carter and Castillo, 2006; Mossop and Shetsen, 1994). The Quaternary cover of Canada is an element on its own but the distribution, thickness and character of glacial sediment is also closely correlated with the bedrock domains. Consequently across areas of extensive cover rock surficial
sediment is commonly thick (e.g., Gao et al., 2006), whereas for much of the Shield and orogenic belts of the Appalachians and western Cordillera, particular in areas of high relief, sediment is thin and restricted to intra montane and alluvial valleys.

Large infrastructure tasks require systematic workflow models that allow for the realization of progress at smaller scales while advancing toward a long-term objective. This is the case for a Canada wide 3D mapping initiative. Individual geological mapping and basin studies will continue to advance our knowledge and contribute datasets with legacy data being integrated into a suitable framework.

When envisioning a model for > 1,000,000 km² it is easy to succumb to the thought that the model will be nothing more than a cartoon realization of the geological complexity of the country. As data support and geological complexity is highly variable, and to minimize computational issues of a large model, it is likely to both vary in resolution and contain higher resolution embedded models of local interest. To ensure scientific rigour of 3D mapping an initial step is ensuring the accessibility and integration of high quality geological information that will be available for interrogation within a model framework. To access the broadest datasets possible for model generation, and to meet the challenges of a large model domain considerable generalization will be required. For example, modelling of the Quaternary commonly relies on water well records that lack information to support stratigraphic assignments other than by lithostratigraphy. Locally, however, the Quaternary stratigraphy may be defined by one or more of a number of stratigraphic approaches (e.g., lithostratigraphy, seismic stratigraphy, chemostratigraphy, biostratigraphy, radiometric dating). Integration of the index benchmark stratigraphic data ensures a connection between the science and the generalization of large scale regional modelling. In the sedimentary basins there is commonly a subset of stratigraphic boreholes that are considered as benchmark reference data (Fig. 3). Furthermore, data input cannot be limited to a black box approach where the backward accessibility to input data is lost. In this regard a seamless national compilation of the bedrock and surficial geology is critical, one that consists of not only lithological or chronostratigraphically coded polygons but a full wealth of structural measurements that can inform subsurface data projection (e.g., de Kempt et al., 2015). Given the scarcity of subsurface data for country beyond the petroleum provinces, modelling will require methods to exploit geophysical data and interpolate structural and lithological trends from surface to subsurface.

Figure 3. Perspective views of proof of concept model for approximately 150,000 km² of Southern Ontario straddling Shield - Phanerozoic region of Southern Ontario. A) Perspective view to the northeast of three layer model of Quaternary (yellow), Phanerozoic (grey) and Precambrian (red). B) Perspective view from south of Phanerozoic model volume populated with 66 stratigraphic control boreholes.
To facilitate data interrogation - mapping refinement requires visualization and access to the primary data and a simple means of regionalizing data limited to geographic point and line format. One possible model for this realization is the Macrostrat model (Peters et al., 2015) that uses Delaney Polygons to parse the country into neighborhoods for individual data points. Such an approach assumes the default status that the geology of a region is represented by the centroid of the polygon such that synthetic regional stratigraphic columns form the underpinning of the model; for Canada a similar approach could be adopted or it could be populated with real data both in terms of the surface areas chosen (e.g., unit boundaries) and subsurface columns (e.g., from sections or derived from geologic relations stored in databases). It is efficient as no interpolation is required and there are no issues of whether the correct stratigraphic - structural geometries have been maintained during model interpolation.

Another approach is a national four layer model of principal geological domains from the surface to Moho comprising surficial sediment, Phanerozoic cover rock, orogenic belts, Precambrian and crystalline rocks, and lower crust. In this approach the geology of respective bounding surfaces simplify to the most general geological scenario possible, issues of inverted or disrupted stratigraphy are eliminated. The simplified mega block model also affords an opportunity for the nesting of visualization approaches and models. Within the respective mega-block volumes data can be presented in point and line form as drill hole data and cross-sections (e.g., Hammer et al., 2011). An approach similar to that adopted by the National Lithoframe model of Great Britain (e.g., Mathers et al., 2014). This permits visualization of geological variability without the challenge of dealing with issues of stratigraphic interpolation.

Summary

To-date limited work has been completed in development of a national 3D model of Canada. The GSC is exploring the feasibility, has held internal workshops, and developed working groups for such a project (Snyder et al., unpublished) and is communicating with provinces. In some provinces 3D modelling programs are already well advanced and construction of regional scale models of 10,000 to 100,000s kms scales is in progress. Development of a 3D framework for the geology of Canada is also a necessary initiative to ensure the preservation and access to a wealth of subsurface data collected by geological survey organizations in Canada during the past 50 years. In the 21st century a national 3D model should be viewed as an underpinning infrastructure element, similar to other national infrastructure frameworks. It is also a potential natural successor to delivering the knowledge framework and successor to benchmark publications such as the 9 volume Geology of Canada contribution to the The Geology of North America (e.g., Wheeler and Palmer, 1993). Furthermore, a continental scale 3D model of Canada could support investigations into a host of science orientated (e.g., Fan et al., 2014) and economic development issues.

References


Geoscan, http://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/geoscan_e.web


