Chapter 8: Geological Survey of Canada: Geological Mapping in Three Dimensions

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Introduction

The Geological Survey of Canada (GSC) has a long history of both terrestrial and offshore (marine) geological studies at local, regional and national scales. With the rise of powerful new 3D mapping methods and technologies, the GSC has increased 3D mapping activities at all scales in recent years. These efforts have built upon 25 years of outcrop-scale and subsurface 3D geological modelling in support of bedrock mapping, mineral exploration, hazard assessment, and groundwater studies. Three-dimensional mapping is recognized as a high priority by the GSC and, as such, it is highlighted by a relatively new national flagship project, Canada-3D. This project aims to develop a comprehensive 3D geological framework and associated knowledge-base for the Canadian subsurface (Figure 1; Brodaric et al. 2017; 2018). As a national mapping agency, the GSC has developed this initiative in collaboration with provincial and territorial surveys through the National Geological Surveys Committee (NGSC). The NGSC provides guidance and coordination between the 10 provincial and three territorial geological surveys and the GSC. It is anticipated that Canada-3D will become the authoritative state of knowledge for the geology of Canada at a national scale. Canada-3D is a prime example of the continuing focus on scientific innovation by the GSC in contemporary digital times. Canada-3D is a response to shifting scientific methods, emerging opportunities that favour digital techniques, as well as a response to the demands of the Canadian government’s open data strategy and global open data concerns. Such concerns are escalating alongside rising data volumes and accompanying challenges to manage new and old data. Indeed, 70 years from the initiation of the post-war acceleration in geological mapping and geophysical developments, the GSC has an enormous repository of legacy data, mostly analogue. This data volume has caused a requirement for significant resources to be allocated to data management and integration in order to fulfill goals for scientific analysis and communication. The advent of global positioning systems and the conversion of many systems to digital data capture is also rapidly expanding the geological data repositories of the GSC. This has significant impact on GSC’s 3D mapping activities, which function optimally when the data is well-structured and readily accessible. This report provides an update and an expansion on documentation in Berg et al. (2011) on 3D mapping activities at the GSC, and uses the Canada-3D initiative, to highlight ancillary GSC activities in data management, 3D model development, data visualization and related case studies.

Figure 1. Canada-3D vision as authoritative source of knowledge on the geology of Canada. Supporting elements of geological mapping, analysis and data in attribute databases with reporting and geological knowledge.
Organizational Structure and Business Model

Founded in 1842, the GSC is the oldest research agency in Canada (e.g., Zaslow 1975; Lebel 2018). It is part of the Lands and Minerals Sector of the Department of Natural Resources within which it is one of a number of branches related to earth science, geodesy and surveying, and mining. The GSC has traditionally focused on the production of geoscience knowledge to support economic development, primarily in the realm of mineral and energy exploration. More recently its mandate has expanded to include issues pertaining to geological hazards, groundwater, the environment, and climate change. Since the 1950’s the GSC has also supported Canadian strategic interests in the Arctic and offshore through targeted geoscience programs. The GSC operates in all 10 provinces and three territories on a cooperative basis with respect to federal government mandates and objectives (e.g., Lebel 2018). To fulfill this mandate, the GSC has six offices across Canada: a central office in Ottawa and 5 regional offices. A seventh office in Iqaluit, the Canada-Nunavut Geoscience Office is co-led with the territorial government. The GSC maintains a staff of approximately 400 researchers and support personnel (GSC 2018), with an annual operating budget in 2017 in the range of 74 million dollars (GSC 2018). This amount fluctuates annually depending upon the ratio of base funding and other governmental and external allocations. GSC has a matrix management framework consisting of Divisions responsible for human resource management and Programs that are designed to align with government priorities and objectives. The number of active programs fluctuates, but typically there are around 11. To supplement limited capacity, the GSC develops partnerships with provincial and territorial government geological surveys, other federal government departments, industry, universities, and other state and national geological surveys. GSC publications are available under the Canadian Government open data initiatives. It operates under a non-cost recovery basis, though it can, and frequently does, seek collaborative funding from interested partner groups from all sectors.

Overview of 3D Modelling Activities at the GSC

Prior to the advent of Canada-3D, geological modelling efforts at the GSC had been scattered amongst various programs, often reflecting dramatically different research agendas (Table 1). Modelling had been performed to address specific research questions, support derivative activities (e.g., numeric groundwater modelling) and support operational activities. To enhance regional geological and mineral deposit understanding, targeted 3D modelling has been completed in the complexly deformed areas of the Canadian Shield (e.g., Flin Flon, Schetselaar et al. 2018) and within orogenic belts (e.g., Purcell, de Kemp et al. 2016). Modelling of sedimentary basins (Carter et al. 2017) and surficial sediment (Logan et al. 2006; Nastev et al. 2016) have been completed to support groundwater and public safety geoscience programs. Offshore, high-resolution reflection seismic studies have supported 3D modelling in structural isopach studies during the 1990s (e.g., Syvitski and Praeg 1989) and

<table>
<thead>
<tr>
<th>Program</th>
<th>Geological setting</th>
<th>Area</th>
<th>Area km²</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Public Safety Geoscience</td>
<td>Surficial</td>
<td>St Lawrence Lowlands</td>
<td>72,000</td>
<td>Nastev et al. 2016</td>
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<tr>
<td>Groundwater</td>
<td>Surficial geology, buried valley</td>
<td>Spiritwood, Manitoba</td>
<td>3300</td>
<td>Logan et al. 2006.</td>
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<td></td>
<td>Paleozoic sedimentary basin</td>
<td>Southern Ontario</td>
<td>110,000</td>
<td>Carter et al. 2018.</td>
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<td></td>
<td>13 regional hydrostratigraphic 3D models across Canada</td>
<td>Distributed across Canada</td>
<td>&lt;11,000</td>
<td>Bedard et al. in prep.</td>
</tr>
<tr>
<td>Resource assessment</td>
<td>Marine estuary</td>
<td>St Lawrence</td>
<td>8000</td>
<td>Duchesne et al. 2010</td>
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<td></td>
<td>Continental shelf</td>
<td>Scotian Shelf</td>
<td>50,000</td>
<td>Campbell et al. 2015</td>
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fully digital models since the 2000s (e.g., Duchesne et al. 2010; Campbell et al. 2015). These are primarily seismo-stratigraphic models with limited integration of geological stratigraphy.

Canada-3D has emerged since 2016 as a unifying project for the integration of geological mapping in 3D. It is designed to be continuously supported ("evergreen"), multi-resolution, inter-disciplinary, collaborative, and updated regularly upon acquisition of new data both internally and from collaborators (Figure 2). To address visualization issues due to the enormous scale differences from local (i.e., 1-2 km²) scale models to the national model, and support efficient visualization, the Canada-3D framework will vary in resolution (Hillier and Brodaric 2018). Notably, scalability concerns dictate a sophisticated modelling approach that is in its nascent stages. Consequently, at this time local to regional models in blank areas are being imported into the Canada-3D database as is, while retaining provenance links to original sources. In cases where new models overlap with existing data in Canada-3D, either (1) the new models replace the existing Canada-3D model fragment, with replacement occurring in collaboration with partner agencies in cases where partner 3D models are affected, or (2) the new models will be integrated into the Canada-3D model, by treating the new models as additional control points and triggering re-modelling for the area. The resultant Canada-3D model contains full modelling provenance as well as links to detailed information on rock units, and will be visualized in desktop and online environments (Hillier and Brodaric 2018).

Resources Allocated to 3D Modelling Activities

Approximately 5 to 10 staff are involved in 3D geological modelling within individual projects. Staff are commonly geologists with an interest and experience in numeric and computer science applications. Explicit mineral deposit or groundwater model construction is accomplished by a geological expert with a geophysics team. For Canada-3D, a more structured team environment is emerging consisting of implicit modelling experts with both geological and computer science backgrounds. Geological mappers, crustal and mantle geophysicists are providing data input guidance and coordination with other government science organizations and GSC staff. Budgets vary according to program and project cycles and the scope of included costs, data collection, legacy data capture, or just interpretation and model creation.

To-date, little emphasis has been placed on public communication of models, with visualization commonly handled by viewing tools supplied by modelling software. With Canada-3D, the development of a more accessible web-based visualization environment has become a more important activity for both 2D map and 3D model presentation. To address challenges of the large size of the Canada-3D datasets, R&D is being undertaken to develop visualization methods that are hierarchical, analogous to 2D tiling in which greater resolution is seen with deeper zoom levels (Hillier and Brodaric 2018). The emerging Canada-3D web portal will enable 2D maps and 3D models to be viewed, interrogated, and portions downloaded. The 2D components are slated for release in 2019, while the 3D components are expected to be released in future years.

Overview of Regional Geological Setting

Canada spans the North American continent from the passive continental margin of the Atlantic Ocean to the active Pacific margin and from its southern extremity at 41.7 degrees northward, to include the Arctic archipelago, and the northern extremity of Ellesmere Island at 83 degrees north, plus the contiguous offshore continental shelf. It has 9,984,670 km² of terrestrial land cover and 7,100,000 km² of marine offshore.

The bedrock geology of Canada includes the oldest dated rocks in the world (St-Onge et al. 1984; Bowring and Williams 1999), and a rock record that tracks the formation and breakup of three supercontinents since the end of the Archean Eon.
The first supercontinent is referred to as either Nuna or Columbia (Piper 1976; Hoffman 1988; Park 1995). There are approximately 35 known fragments of Archean-aged crust preserved on Earth (Bleeker 2003) and these would appear to have been largely cohesive at around 1.8 to 1.7 Ga. The evidence for Nuna is based on comparative geology and is observed through alignment and synchronicity of features such as mafic dyke swarms, suture zones and orogenic belts. The existence of numerous compressional orogenic belts in the period 2.1 to 1.7 Ga (e.g., Taltson-Thelon, Wopmay, New Quebec, and Trans-Hudson in Canada; St-Onge et al. 2015) provide the evidence that amalgamation of the Archean continental fragments was near global in its extent. Reconstructions of Nuna attest to the long-lived duration of the supercontinent creating lithospheric stability for around 400 million years (between ca. 1.8 and 1.4 Ga; Evans and Mitchell 2011; Zhang et al. 2012). Breakup of Nuna is evidenced by rifting along continent margins (e.g., accumulation of the Belt-Purcell Supergroup in western Canada) and by the emplacement of mafic dyke swarms such as the 1.27 Ga Mackenzie dykes (LeCheminant and Heaman 1989).

The supercontinent cycle repeated itself during the latter stages of the Proterozoic Eon with a second supercontinent referred to as Rodinia (McMenamin and McMenamin 1990), which started to assemble from about 1200 Ma, and then dispersed again by about 700 Ma. As with Nuna, it is the global extent of compressional orogenic belts active in the period 1400 – 1000 Ma - the so-called ‘Grenvillian’ belts that include the type Grenville orogen in eastern Canada – that attest to the re-amalgamation of dispersed Nuan continents by the early Neoproterozoic (Nance et al. 2014). The supercontinent broke up episodically over a protracted period that may have exceeded 200 million years (Scotese, 2009).

The most recent supercontinent, Pangea, coalesced from the fragments of Rodinia, and assembled as Laurasia (a combination of Laurentia and Eurasia as witnessed by the Appalachian orogen in eastern Canada) and Gondwana re-united by progressive subduction of the Rheic Ocean in late-Paleozoic times. The geological, paleontological and paleomagnetic evidence for the existence of a combined landmass in late Permian-Triassic times is robust, but the details of how it was assembled are complex (Torsvik and Cocks 2013). Pangea has now dispersed and its remnants occur as 5 major continental landmases of today. Some continents are already undergoing reassembly and growth, with the impingement of Greenland and NE Canada (leading to the Eurekan orogen in Arctic Canada; St-Onge et al. 2015), and the evolution of the Cretaceous North American Cordillera and associated Western Canada Sedimentary basin.

Canada has been glaciated multiple times and little of the landscape was not glaciated during the Quaternary (e.g., Dyke et al. 2002). Most of the Canadian Shield has been stripped bare of weathered regolith exposing relatively unweathered bedrock overlain by extensive areas of glacial sediment. Sediment thickness increases dramatically over the Phanerozoic sedimentary basins where sediment thickness can rapidly increase from 10s of meters to over 200 m. The landscape is defined by extensive tracks of streamlined landforms and poorly developed juvenile drainage systems.

**Data Sources**

The GSC has a wealth of legacy data that has largely been archived through the publication process in individual reports (e.g., Open Files, etc.). In excess of 30,000 GSC documents have been scanned and are available online as PDF files. Map publications have also been scanned and captured digitally as PDF files. Little of this data has been captured in structured relational databases. Digital data capture has become progressively more common over the past 25 years and numerous databases exist for geochemical, geochronology, and geophysical datasets. Internal legacy data capture from unstructured to structured formats remains a challenge. In the 1990’s the National Mapping Program had an emphasis on digital methods and this initiated a change from analogue to digital data capture that continues to evolve (Robertson, 2010). A series of field data capture (e.g., Fieldlog, Brodaric 2004) and modelling initiatives were pursued to support structural geological interpretations, mineral exploration and groundwater studies. Projects in these domains, in addition to geophysics, have provided the framework and vision for Canada-3D to emerge. These projects and data notwithstanding, Canada-3D has a serious data gap issue, inasmuch as there are many parts of the country where the data required for 3D models is quite sparse, or inadequate for the complexity of the geology. This has required an investment in methods development to address sparse data and modelling of complex geological environments (de Kemp 2004, 2005).

Effective data management is crucial to the success of 3D programs. Because almost any geological information can impact the national model, Canada-3D has chosen to differentiate itself from core data management activities. Because the Canada-3D framework draws from several sources, the project relies on existing corporate data infrastructure and collaborative data custodians (e.g., Ontario Oil, Gas and Salt Resources Library, provincial surveys). Canada-3D manages only the 3D model data, with links to original sources (e.g., borehole data, geological maps).
Surface (2D) bedrock and surficial geological mapping continue to be a cornerstone of 3D activities at the GSC. This recognizes the accessibility of the outcrop geology of Canada, the profusion of data available and the ability to use such data to project knowledge into the subsurface. Both bedrock and surficial mapping is coordinated with provinces, with the GSC mandated to manage a national synthesis. Much of the map products only exist in raster formats and efforts are being explored as to how to capture, map polygon information, point observation and structural measurements into a structured geospatial database.

Geophysical data sets are collected in all three domains of water borne (marine), terrestrial, and airborne. Surveys may involve controlled source (seismic, electromagnetics), passive (seismic, magnetotellurics), and potential field surveys (gravity, magnetics). Datasets in each of these domains is variable in coverage, and resolution, with datasets often constrained by spatial extent or data collection parameters (line spacing). Primary (geophysical) 3D modelling of this data is not included within this review. Progressively more effort is being made to interpret and integrate geophysical signals with geological knowledge to support geological interpretations and understanding.

Terrestrial geophysical surveys have been primarily controlled source seismic and electromagnetic, most prominently those data acquired as part of the Lithoprobe program (Clowes et al. 1992; lithoprobe.eos.ubc.ca). Lithoprobe seismic reflection sections and field records are available via Open Government (https://open.canada.ca) as well as similar older and newer seismic surveys (e.g., Discover Abitibi). Seismic reflection profiles are placed section by section into 3D models to provide context for interpretation. Key aspects of published interpretations are being translated to 3D models (e.g., LITHOPROBE, http://lithoprobe.eos.ubc.ca).

Passive teleseismic and magnetoteluric field data (e.g., Roots and Craven 2017) are available through web portals Earthquakes Canada (http://earthquakescanada.nrcan.gc.ca) and Open Government respectively. Processed teleseismic data used in structural seismic studies of the lithosphere are documented in journal publications (Snyder et al. 2014) as are 3D conductivity models from magnetoteluric data. Structural interpretations of mantle discontinuities are captured and further interpreted in the 3D geological models.

Marine geophysics data is being progressive captured and documented in the Expedition database for marine seismic and swath bathymetry (Courtney 2013). Extensive marine activities mapping the continental shelf and coastal water using swath bathymetry are being completed on all Canada’s coasts, commonly in conjunction with shallow reflection seismic (e.g., Shaw and Potter 2015).

The most commonly employed data for 3D modelling are various types of drillhole datasets (water well, geotechnical, mineral, petroleum). Data quality, reliability and degree of both physical and observational data curation of these datasets is variable, as is accessibility. Issues of confidentiality, liability, industrial competitiveness, and personal privacy can limit access for periods of time and portions of datasets. For areas of surficial sediment across southern Canada provincial water well databases are the most common and accessible dataset. Lithological data and access to water wells has been coordinated through the Groundwater Information Network (GIN, Brodaric et al. 2016). In areas of infrastructure development, geotechnical data are prevalent but controlled by a disparate variety of agencies (hydro, transport, municipality, geotechnical firms) much in analogue format, and with limited record access and/or confidentiality issues. Despite early attempts to coordinate geotechnical data (Belanger 1975), such data remains difficult to access and integrate. In areas of mineral exploration and resource delineation there is abundant drillhole data; however, this data lacks public cura tion, accessibility and is considered proprietary. Documentation beyond the files of exploration companies and consultants is very limited except where submitted for mineral assessment reports.

Numerous datasets of both geological and geophysical data are collected and curated by organizations other than the GSC. Many modelling initiatives access either the primary data or through pre-existing models. For example, the most comprehensively managed drillhole datasets are in petroleum provinces of Phanerozoic basins (e.g., Alberta, Saskatchewan, Ontario). Such datasets underpin the model development in southern Ontario (e.g., Carter et al. 2017) and provincial development in Alberta (MacCormack et al., this vol., Chapter 5). The records are attribute rich with geophysical records, core samples, and drill chips. Unfortunately, this data is proprietary and accessibility is commonly through a user pay system.

3D Modelling Approaches

A range of modelling approaches have been adopted by individual studies at the GSC. Illustrative examples are provided in Table 2, but are not exhaustive. In the 1990’s modelling was completed in a range of conventional GIS platforms (e.g., MapInfo®, ArcInfoTM) and 3D modelling software (e.g., GOCAD®). Since 2015 modelling activities have been undertaken using the LeapFrog® software platform for many groundwater studies. LeapFrog® has proven to be a cost effective software option with manageable learning curve for modelling use. Conversion of geological
models into hydrostratigraphic models for numeric groundwater modelling has been completed for both internal (Benoit and Paradis 2015) and external activities (e.g., Frey et al. 2018) and use in a range of numeric flow modelling software (MODFLOW, FEFLOW, HydroGeoSphere).

In the sparse data setting of regional geological mapping, tools have been developed for interactive and implicit modelling (e.g., de Kemp et al. 2017a; Hillier et al. 2017). In contrast, mineral camps with abundant drillhole and geophysical data, including 3D seismic cubes, have enabled well-constrained 3D modelling approaches (Schetselaar et al. 2018).

The development of an efficient visualization mechanism is an integral part of Canada-3D. Visualization of such geo-models is challenged by several things: (1) massive geo-model sizes, (2) file-based data management that treats geo-models as single entities, (3) the inability of popular geo-modelling software to calculate and render massive models, (4) variability in 3D geometry structures, as key 3D data types are often unsupported; and (5) efficient and effective web-based access to large geo-models. Solutions being developed in Canada-3D include the use of hierarchical visualization to address (1), database-driven spatial decomposition and spatial indexing of geo-model files to address (2), incorporation of hierarchical sensitive streaming and rendering to address (3), the adoption of the sophisticated VTK geometry standard to address (4), and investigation into standards-based 3D web visualization systems. Integration of these results in both desktop and web-based visualization systems is ongoing.

**Clients**

The GSC supports Government of Canada priorities of economic development and public safety. To-date the principal clients for 3D geological modelling have been groundwater, mineral exploration, and public safety agencies. Clients range from watershed water managers to provincial ministries and other federal government departments.

Models are currently available through GSC publication series, as well as through the Groundwater Information Network web portal (www.gw-info.net), and are licenced for reuse through the government of Canada open data policy online. In the case of the groundwater program, models have been converted to a set of standard formats (e.g., ASCII grid, GeoTIFF, 3D PDF, GOCAD) and layers (Bedard et al. in prep). To-date no models are available for online viewing. In the past three years animations have been created to allow public previewing of model geology and applications (e.g., Russell et al. 2017b). Subsequently virtual reality and augmented reality visualizations have been developed since 2018 to enhance visualization and outreach for Canada-3D, groundwater, and mineral deposit models.

**Recent Case Study Applications of 3D Models**

The GSC is addressing the 3D geology of Canada in a hierarchal framework that is premised on an evergreen approach. In this section we overview Canada-3D and provide two applications in mineral exploration and groundwater demonstrating how regional scale models will infill a coarse resolution Canada-3D framework.

**Case Study 1. Canada-3D**

Canada-3D is consolidating GSC and provincial – territorial geological data into a seamless national geological model. Recognizing the geological complexity of Canada, as well as the diverse and commonly sparse data support in the subsurface, Canada-3D has taken an hierarchical approach, including geo-models at all resolutions, from mineral camp to national scale. It is building upon the wealth of 2D geological mapping (e.g., Wheeler et al. 1996; Fulton 1993) and emerging national compilations (St-Onge et al. 2017). The intention is not only to develop a 3D framework for Canada, but enable frequent updates as new information becomes available, making it “evergreen”.

To help prioritize and communicate the complexity of the challenge, parts of Canada and North America can simplistically be assigned to one of three broad geological domains with a thin surficial cover that is near ubiquitous across Canada (Figure 3). Canada-3D is fundamentally a geological model and thus will ingest stratigraphic interpretations from disparate data coded to provincial and national stratigraphic norms from outcrop, geophysical, drill logs, 2D and 3D geological models, and other sources.

Given the scale and sparsity of data support, a lithoframe approach, such as developed for the UK, was not
considered practical. Instead, a model of three units or four surfaces was initiated, consisting of the surficial, bedrock and mantle (and sub-mantle) layers. Initial focus is on development of surfaces separating the layers, i.e., the topographic surface, the bedrock surface, Phanerozoic-Precambrian surface, and the mantle surface (i.e., Mohorovicic discontinuity MOHO), with preliminary products created. Progress on these national surfaces is proceeding asynchronously as data support and resources permit.

The topographic surface is provided by the Canada Digital Elevation Model (CDEM; Figure 4a). This elevation surface is augmented by either the bedrock or surficial geology mapping where appropriate (e.g., Wheeler et al. 1996, Fulton 1993). The bedrock surface consists of depth to bedrock extrapolations beneath the surficial coverage (Figure 4b). This surface is a synthesis of existing provincial coverages derived from data-driven modelling integrated with a rules-based approach for shield and orogenic areas (Russell et al. 2017a). It is expected this surface will be useful in bedrock resource assessments, groundwater studies, geophysical interpretation, geohazards, permafrost degradation, and geotechnical work for infrastructure development. The Precambrian - Phanerozoic contact surface separates cover rocks of the Phanerozoic Eon and older basement rocks (Figure 4c). This surface development is being undertaken through the application of data-driven geostatistical, implicit modelling (GOCAD/ SKUA and SURFE; Figure 5) and knowledge-driven (SPARSE) methods (Figure 6; de Kemp et al. 2017a, b). It can help separate bulk rock properties into cover and basement classes useful for geophysical and mineral potential modelling. Combined with heat flow and fracture density estimates it could help develop national-scale 3D maps for geothermal energy and CO2 sequestration potential. The deepest surface is the (MOHO), corresponding to the transition in P-wave seismic velocity from 6-7 km/s to 8 km/s that commonly occurs at ±30-35 km depth (Schetselaar et al. 2017). This surface provides a first-order characterization of crustal thickness variations underneath Canada’s landmass and offshore domains. It is of increasing interest for understanding the construction of the continent and origin of certain types of mineral deposits (e.g., diamonds).

Incorporation of existing regional and local 3D models is occurring simultaneously with national surface development, to fill the volumes between the national surfaces. This largely builds on areas of simplest geology and most abundant data support, for example in order of increasing complexity and data scarcity: Phanerozoic basins, Canadian Shield, Orogenic belts and offshore. However, there remain large gaps in 3D model coverage, often coinciding with geological data sparsity. For these parts of the country with minimal data support, methods are being investigated and developed to propagate geological mapping structural information into the subsurface. Multilayer models at regional scale of 100,000s km are being integrated for Phanerozoic basins as the next phase of the initiative. Higher resolution models of <10,000s km² are being integrated for complex mineral deposit terrains, and areas of thick surficial sediment cover modelled for groundwater studies. In complex terrains mining camp scale (<10,000s km²) and Phanerozoic sedimentary basins (100,000s km²) sufficient drill holes, geophysics, geological maps may exist to construct data-driven models. In remote areas and at regional scales and depths greater than a few kilometres, sufficient observations cannot exist and model interpolation must be knowledge-
driven, with geological formations inferred by manual interpretation, mathematical down-dip extrapolation of key surfaces, or from key physical properties such as potential field properties.

**Case Study 2. Mineral Camp Models**

Early computer aided 3D methodology work was initiated at the GSC in the 1970’s with initiatives such as calculating trend surfaces with uncertainty estimates (Agterberg and Chung 1975) using 3rd order polynomials for pluton geometry estimation. Subsequently, through the 1990’s and into this century, methods have evolved using explicit interpretive tools and propagation approaches for complex folding (de Kemp 2000, Hillier et al. 2013) to implicit approaches for complete structural and stratigraphic constrained systems based on co-kriging and radial basis functions (Hillier et al. 2014). Interpretive regional models at 1:250,000 and 1:100,000 scales demonstrated 3D visualization of field-data constrained models consistent with the map products and cross-sections developed for northern Canadian regions in Baffin Island and Québec (de Kemp et al. 2001 2002; de Kemp et al. 2007; de Kemp and St-Onge 2007).

Several comprehensive 3D GIS compilations combining mine-scale and regional-scale lithostratigraphic, structural, geochemical, geophysical information have been conducted within the Targeted Geoscience Initiative Program focusing on VMS systems including the Blake River Group and Giant Horne mine in the Abitibi, Flin Flon (Schetselaar et al. 2010), Laylor mines (Schetselaar et al. 2013) in the Snow Lake belt and the Heath Steel mine in the Bathurst camp.

Other 3D models from gold mines Musselwhite (Northern Ontario) and Eskay Creek (British Columbia) (de Kemp et al. 2004), nickel PGE deposits in an Archean Ultramafic intrusive complex in the Ring of Fire (Northern Ontario; Laudadio et al. 2017), and porphyry copper systems at the New Afton Mine (Schetselaar et al. 2017; 2018) focused on seismic and geological integration for exploration using alteration signature detection (Figure 7).

One of the most comprehensive Canadian examples to date of a larger regional scale (1:100,000) bedrock model integrated with a detailed mine data set is the Mesoproterozoic Purcell Anticlinorium (de Kemp and Schetselaar 2015) and the Giant Sullivan SEDEX (Pb, Zn, Ag) (Montsion 2012). These models are now being incorporated in Canada-3D along with Lithoprobe deep seismic data and map compatible interpreted cross sections (de Kemp et al. 2016). The data along with the current well constrained Western Canada Basin basement-cover (Precambrian – Phanerozoic) surface will potentially be able to support the 3D extension of Western North American bedrock stratigraphy in the more complex faulted and folded Cordilleran geology.

The core challenge in going forward with these studies has been the fundamental lack of data in the subsurface...
for extending deposit scale structural and stratigraphic features when using solely data driven methods. In the future, hopefully it will be possible to capitalize on existing knowledge of process behaviour and new methods for simulating scenarios given the limited data and increased complexity presented to us in the deeper orogenic regions of Canada where our mineral wealth is yet undiscovered.

**Case Study 3. Groundwater Models**

The GSC groundwater program completes regional groundwater studies with an emphasis on the delineation and characterization of potable groundwater resources at municipal scales. Studies are generally completed for areas of 700 to >100,000 km² (e.g., Russell et al. 2011; Carter et al. 2017). Most exploited potable groundwater resource are hosted in surficial sediment in Canada and thus the focus of most of the program modelling has been on multilayer stratigraphic models of unconsolidated sediment which is generally <200 m thick. A small number of studies have focused on the stratigraphy of sedimentary bedrock successions (e.g., Carter et al. 2017; Pétré et al. 2015). The approach to model development has been a basin analysis approach with the collection of high-quality geological and geophysical data that would permit an analysis of the paleogeography of the basin and development of a predictive geological model (e.g., Sharpe et al. 2002). Supported by a process-based conceptual model, geological knowledge guides the interpretation and integration of disparate archival and legacy data. Three cases studies of this approach were overviewed in Berg et al. (2011) by Russell et al. (2011). Since the 2011 review, the approach to model development has not changed significantly. Data collection for surficial modelling has remained focused on integration of low-reliability water well data (Russell et al. 1998) with more rigorous seismic reflection profiling (e.g., Pugin et al. 2013), sedimentological drilling with continuous core, and downhole geophysics (e.g., Crow et al. 2015). In two pilot studies airborne electromagnetic (AEM) surveys were flown to enhance delineation of the bedrock valley geometry and the surficial stratig-
Current Challenges

The primary challenge faced by development of national 3D geological models in Canada is data scarcity or clustering – there is lack of adequate data support, such as drill holes and field observations, in many parts of the country. A coincident challenge is the lack of 3D modelling methods for regions of complex geology. Additional challenge exist with the need for interoperability and the challenge to overcome issues related to systems, syntax, structure, semantics, etc. (Brodaric et al. 2016). Combining these challenges leads to difficulties in developing 3D models in large parts of the country (e.g., orogenic belts, Canadian Shield). Canada is rich, however, with geological knowledge in the form of geological interpretations, such as geological maps, cross-sections and associated conceptual models. The challenge is to leverage this knowledge, in combination with available data, for augmented 3D model creation. This involves a three-fold approach: (1) recovering legacy data, to minimize data sparsity, (2) improving integration with related data (e.g., geophysics), and (3) investing in 3D modelling research, to build hybrid data-driven and knowledge-driven systems that can address complex geological environments. An example of the latter is GSC participation in the LOOP initiative (https://loop3d.org/; Ailleres et al. 2018), to build next-generation 3D modelling algorithms and software. This multi-agency, multinational collaboration is coordinated through OneGeology (http://www.onegeology.org/what_is/home.html). It is a collaboration of geological surveys and research institutions in Australia, Canada, France, Germany and the UK. The objective is to develop an Open Source modelling solution that will model the subsurface, characterise model uncertainty and test multiple geological scenarios (Figure 9).

Figure 7. Mine camp model of the Flin Flon massive sulphide deposit illustrating data integration with 3D seismic and modelling of faults, geological units, and ore deposit (Schetselaar et al. 2017).

Figure 8. Model of sedimentary geology of 110,000 km² area of southern Ontario with 59 layers from Precambrian to Devonian age strata. A) Inset highlighting local detail in model surface of the Silurian Guelph pinnacle reefs.
An associated challenge is the lack of well-established 3D modelling infrastructure that allows models to be managed in a rigorous way. Currently, models are file-based outputs that are largely disconnected from the input data, assumptions and methods. As files, they cannot be easily searched or compared, so model contents become opaque and not queryable. A model management approach is required, as developed in other modelling domains, that integrates models into a wider modelling lifecycle. This would allow query within and across models, and bring order to the chaos of the massive number of files. As GSOs shrink in size and competition for HR resources increases it is challenging, but essential, that organizations are able to recognize, hire and integrate skill sets required in a digital big data AI environment with traditional geological personnel. As a government research laboratory, within a large government ecosystem it is often difficult to develop the recognition and understanding of computing and IT support necessary to support research-oriented objectives. With increasing consolidation and centralization of such services this challenge is increasingly constraining and reducing the GSC’s ability to adapt to research needs.

Lessons Learned

A key lesson learned concerns the maturity of 3D modelling methods and availability of data. While 3D modelling algorithms have progressed significantly, especially with the signature advance of implicit modelling, there still remains knowledge gaps in modelling complex geology, leveraging knowledge, and in the overall management and visualization of related 3D modelling data. Thus a key lesson is the need to maintain a balance between leveraging existing technologies and methods while developing improvements. Modelling to-date at the GSC has received positive client acceptance and engagement for this type of product and highlights the need for geological survey initiatives in 3D mapping and modelling.

Next Steps

Canada-3D through the course of a two-year pilot project demonstrated the feasibility of a national scale geological model implemented incrementally and with areas of prioritization. Next steps include continued advances in all aspects of the realization of the national 3D model. Canada-3D also provides a framework for high-resolution, regional models which previously lacked context, while integration of such work provides a platform for continued engagement and dissemination to broader and new clients. There remains a continuing need for sustained funding to support data collection in the subsurface, for example geophysical surveys. There is also a real need for improved data management and accessibility across a number of sectors of the economy (e.g., mining, geotechnical, hydrogeological). Research modelling initiatives are providing the methods development (e.g., de Kemp et al. 2017a; Hillier et al. 2017) to make regional modelling more feasible. New methods and tool development are essential and initiatives such as Loop (https://loop3d.org/) will advance our ability to complete implicit modelling. Experience has also indicated that such initiatives need to be multiagency, commonly multi-national, and increasingly multidisciplinary. Canada-3D will support the New Economy for energy resources (geothermal, tidal), water resources (critical for climate change etc.), and infrastructure development (seismic zonation) by better defining broad framework for subsurface resources and hazards.

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