Chapter 20: Ontario Geological Survey Three-Dimensional Mapping Activities

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Introduction

The Ontario Geological Survey (OGS) is mapping southern Ontario’s Quaternary deposits in 3D by developing interactive models that can: 1) aid in studies involving groundwater extraction, protection, and remediation; 2) assist with the development of policies surrounding land use and nutrient management; and 3) help to better understand the interaction between ground and surface waters. The goals of each project are to reconstruct the regional Quaternary history, assemble standardized subsurface databases of new and legacy geological and geophysical information, build 3D models of regional-scale sediment packages, and generate both technical and user-friendly products. Understanding the architecture and inherent properties of the Quaternary sediments that overlie bedrock will assist in the development of provincially-mandated source water protection plans and with geoscience-based management plans for groundwater resources. Guided by the Places to Grow Act (2005), priority 3D mapping areas are identified with advice from local conservation authorities who are knowledgeable of local water issues and long-term pressures facing groundwater resources.

Organizational Structure and Business Model

The OGS is a provincial organization that is within the Mines and Minerals Division of the Ministry of Energy, Northern Development and Mines. The OGS is the principal government organization responsible for the collection, documentation, and distribution of regional geoscience data. The OGS is funded by the provincial government and our operating budgets are set on an annual cycle. As the steward of Ontario’s public geoscience data and information, the OGS provides public access to this information free of charge.

There are 4 administrative units within the OGS, and each provides specific core functions. These are:

- **Director’s Office**
- **Geoservices Section**: chemical and physical analyses of inorganic geological materials; cartographic, editorial, and publication services; library services and warehouse services
- **Resident Geologist Program**: local area geologic knowledge and expertise as it applies to mineral resource assessment
- **Earth Resources and Geoscience Mapping Section**: geoscience data collection, interpretation, and dissemination

The mapping section conducts field-based geological surveys aimed at better defining and understanding geological processes and earth resources to support the minerals industry and clients engaged in science related to the environment, natural hazards, public health and safety, and climate change adaptation. While the collection of geoscience data pertinent to understanding groundwater has been ongoing for over 125 years, the pace has accelerated in the years since the 2000 Walkerton contaminated water tragedy. In that time, we have migrated from adhoc projects to an integral, Ontario Public Service Amethyst Award winning initiative that includes 3D sediment and Paleozoic bedrock mapping, as well as ambient groundwater geochemistry.

Overview of 3D Modelling Activities

OGS led 3D sediment mapping activities are concentrated within the densely populated southern regions of the province (Figure 1). In 2002, a pilot project was initiated in the Regional Municipality of Waterloo (Bajc and Shirota 2007). This area was selected for the initial study as it is one of the leading municipal users of groundwater in Canada and is within an area of intense population growth where pressures on the groundwater resource are expected to increase significantly. Protocols for 3D sediment mapping were established as part of this project, guided by experiences gleaned from national, state, and provincial geological surveys doing similar work across the globe, including collaboration with the Geological Survey of Canada on a 3D study of the Oak Ridges Moraine Planning area (Sharpe et al. 2007). To date, the OGS has released 4 Groundwater Resources Studies – the culminating
products of sediment mapping projects – as part of its 3D sediment mapping program (Figure 1, Table 1) with one nearing completion and another two studies in progress (Bajc et al. 2012; Bajc and Dodge 2011; Bajc and Shirota 2007; Burt 2013; Burt and Dodge 2011, 2016; Mulligan 2014). The total area covered by these surveys exceeds 26 000 km², which is over 20% of the populated area of southern Ontario. Future studies are planned for both the extreme southwestern corner of the province as well as within the Ottawa-St. Lawrence lowlands where municipal, agricultural, and industrial pressures on both the surface and groundwater resources are mounting. The OGS is additionally collaborating with the Geological Survey of Canada on the development of a regional model of Quaternary sediments and bedrock for southern Ontario (Carter et al. 2018).

**Resources Allocated to 3D Modelling Activities**

Staff availability is an important consideration when initiating a new 3D mapping project. There are typically 2-3 concurrent projects, each run by a Quaternary geoscientist. Each project is both time and labour intensive, taking approximately 5 years from inception to final reporting assuming a one-year project overlap. The geoscientist is responsible for collaboration with core client groups to identify geoscience gaps, the compilation and standardization of legacy data, the collection of new geological data (one reconnaissance field season and 2 to 4 drilling programs), geological interpretations and development of conceptual geologic models, creation of the 3D model, and delivery of interim and final products.

The geoscientist is assisted by additional staff on a part-time basis as required. Summer field assistants are drawn from local colleges and universities. An OGS geophysicist reviews existing geophysical data, works with the geoscientist to develop a strategy for collecting new data, directs the procurement process for data acquisition, oversees the survey and product generation in conjunction with the successful contractor, and provides interpretations and advice to the lead geoscientist. A GIS applicationist assists with the assembly and management of legacy and newly collected data as well as with the creation of gridded surfaces and Google Earth products for the final data release. A drafter is responsible for ensuring that figures and posters meet publication standards.
OGS projects require robust budget allocations for the acquisition of new high-quality geophysical and geological datasets. Sample analysis (grain size, geochemistry, mineralogy, paleoecological analysis, dating) further increases project costs.

**Overview of Regional Geological Setting**

Southern Ontario is bounded by the Algonquin Highlands of the Canadian Shield to the north and low-lying (commonly overdeepened) basins of the Great Lakes and St. Lawrence River to the west, south, and east. Paleozoic strata overlie the crystalline basement rocks and consist of gently south and southwest-dipping carbonate, clastic, and evaporite strata (Figure 2; Armstrong and Dodge 2007). Prominent bedrock cuestas, particularly the Niagara (200-300 m high) and Onondaga (20-30 m high) escarpments, exist where resistant strata (primarily dolostone) overlies softer shale or evaporite successions (Brunton et al. 2009). Inset into the broader regional bedrock topography are a series of bedrock valleys, locally buried by up to 260 m of Pleistocene sediments (Figure 2; Gao et al. 2007). Large re-entrant valleys along the Niagara Escarpment commonly mark the surficial expression of more significant buried bedrock valley features extending into thick drift areas, which locally host pre-Late Wisconsin sediments, some of which consist of productive aquifers (Russell et al. 2004; Bajc et al. 2018; Burt 2018; Steelman et al. 2018).

Sediments overlying Paleozoic bedrock in southern Ontario span at least the last two glaciations (marine oxygen isotope stage (MIS) 1-6; Eyles 1987; Dreimanis 1992; Karrow et al. 2000; Mulligan and Bajc 2018). Sediment successions that pre-date the Late Wisconsin (MIS 2) glaciation are rarely exposed and preferentially occur within bedrock depressions or within interlobate zones where glacial lakes were present during the build up and retreat of ice sheets resulting in their burial and protection from erosion. They consist of a series of tills capped by interglacial and interstadial deposits, that in turn can be overlain by thick successions of predominantly

<table>
<thead>
<tr>
<th>Study</th>
<th>Area (km²)</th>
<th>OGS Boreholes</th>
<th>Geophysical Survey</th>
<th>Database Records</th>
<th>Picks</th>
<th>Layers</th>
<th>Block Size</th>
<th>Release Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waterloo Region</td>
<td>1385</td>
<td>15</td>
<td>Shallow seismic, downhole, ground penetrating radar, Radarsat</td>
<td>17 023</td>
<td>38 629</td>
<td>19</td>
<td>100 m</td>
<td>2007</td>
</tr>
<tr>
<td>Barrie-Oro Moraine</td>
<td>1290</td>
<td>32 holes 2375.25 m</td>
<td>Shallow seismic, downhole</td>
<td>7 155</td>
<td>28 272</td>
<td>23</td>
<td>100 m</td>
<td>2011</td>
</tr>
<tr>
<td>Brantford-Woodstock</td>
<td>2715</td>
<td>36</td>
<td>None</td>
<td>15 106</td>
<td>42 026</td>
<td>20</td>
<td>100 m</td>
<td>2011</td>
</tr>
<tr>
<td>Orangeville-Fergus</td>
<td>1550</td>
<td>43 holes 1918.54 m</td>
<td>Ground gravity</td>
<td>11 117</td>
<td>46 208</td>
<td>20</td>
<td>100 m</td>
<td>2016</td>
</tr>
<tr>
<td>South Simcoe</td>
<td>1455</td>
<td>25</td>
<td>Ground gravity, airborne time-domain electromagnetic, regional shallow seismic, downhole</td>
<td>24 939</td>
<td>70 926</td>
<td>18</td>
<td>100 m</td>
<td>In progress</td>
</tr>
<tr>
<td>Niagara Peninsula</td>
<td>5000</td>
<td>99 holes 3192.1 m</td>
<td>Ground gravity, regional shallow seismic, downhole</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>In progress</td>
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<tr>
<td>Central Simcoe</td>
<td>1375</td>
<td>33 holes 2942.75 m</td>
<td>Ground gravity, regional shallow seismic, downhole</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>100 m</td>
<td>In progress</td>
</tr>
</tbody>
</table>
Figure 2: Regional setting of completed and in-progress OGS 3D sediment mapping projects. 
A) Digital elevation model draped over a hillshade. Note the large elevation change at the Niagara Escarpment (arrow). The Onondaga Escarpment is much more subdued and is often buried. B) Drift thickness map (Gao et al 2007). C) Summary bedrock geology (Armstrong and Dodge 2007). The Niagara Escarpment is at the contact between Ordovician shale, dolostone, limestone (purple), and Silurian dolostone and limestone (green). The Onondaga Escarpment is at the contact between Silurian dolostone and limestone (green) and Devonian limestone and dolostone (blue). D) Surficial geology (OGS 2010).
glaciolacustrine deposits recording the evolution of extensive lakes developed in southern Ontario during the build-up and advance of ice during the Late Wisconsin (MIS 2). These deposits are of interest as they locally host significant confined aquifers (Burt 2018; Mulligan and Bajc 2018; Gerber et al. 2018).

Thick regional till sheets cover older sediments and bedrock and record the main phase of Laurentide Ice Sheet advance southwestward into the northern United States during the Late Wisconsin (MIS 2). During deglaciation, thinning of the LIS resulted in the reorganization of the ice sheet into distinct lobes and/or ice streams (Barnett 1992; Sookhan et al. 2018) due to topographic funnelling into the low-lying Great Lakes basins (Eyles et al. 2018). Initial break-up was associated with extensive meltwater production and (predominantly coarse-grained) sediment deposition into growing interlobate areas, promoting the deposition of large, sandy stratified moraines including the Waterloo, Orangeville, Oak Ridges, and Oro moraines (Barnett 1992; Bajc and Shirota 2007; Burt 2018; Mulligan et al. 2018a; Sharpe et al. 2018). Subsequent re-advances and/or readjustments of ice lobe/stream margins partially overrode the flanks of the moraines and deposited younger, primarily fine-grained till sheets (Arnaud et al. 2018; Burt 2018). As ice lobes withdrew from southern Ontario, extensive lakes developed, locally covering the surface tills with deposits of sand, silt, and clay, with local gravelly sediments deposited near former shorelines (Barnett and Karrow, 2018; Mulligan et al. 2018b).

**Data Sources**

The OGS’ 3D models are based on legacy data sets further informed by new geophysical and geological data (Figure 3). Legacy data sets have a highly variable spatial distribution (Figure 3), resolution, and quality. Water well records are the most plentiful, but also of the lowest quality. The data are publicly available and can be downloaded for free from the Ministry of Environment, Conservation and Parks (MECP) as a Microsoft Access database that includes well location, material, well screen, and pumping test information. Scanned well submission records can also be downloaded from the same site. As

![Figure 3: Distribution of legacy datasets (orange, blue and grey dots), new geological information (purple and green dots), and geophysical surveys (black and pink lines) on the Niagara Peninsula. Note the lack of water wells (blue) in areas with large numbers of oil and gas wells (grey). Geotechnical records are concentrated along the major highways, the Welland Canal, and in some urban areas. Note the records with obviously incorrect location information plotting outside of Ontario. Sources: Water wells https://www.ontario.ca/data/well-records accessed December 3, 2018. Oil and gas records http://www.ogslibrary.com/ accessed December 3, 2018.](image-url)
expected, the data are concentrated in the populated southern portions of the province where groundwater is used for domestic, industrial, and agricultural purposes. The water well database is standardized using a two-step translation process before it is used for 3D geological mapping (Burt and Bajc 2005). Some detail is lost during this process, but this is justified in a regional-scale modelling project.

The remaining databases vary in accessibility and coverage and range in quality from low to high depending on the original purpose, drilling method, and material descriptions. Each database is prepared as described above. Oil and gas records are publicly available, but a subscription fee is required. The records are focused on specific bedrock formations and have limited use for sediment models with the exception of depth to bedrock information. Geotechnical records range from low to high quality and are generally shallow, targeting the first significant load-bearing unit. They can be publicly available or privately held by consultants. It is often necessary to manually enter the records into a database from scanned logs. This is labour intensive but does provide the opportunity to better interpret the original descriptions. The Urban Geology Automated Information System was created for 11 urban centres in Ontario during the 1970’s and 1980’s. Although recent data is missing, these databases provide geotechnical data in an accessible digital format. The Ministry of Transportation geotechnical records from road building and inspections (typically only 1-2 m in depth), as well as clusters of deeper records from bridge and overpass construction, are available for use as well. Finally, partner conservation authorities and municipalities generally make proprietary and/or confidential geotechnical records obtained by consultants available for modelling. Archived OGS reports and field notes, university theses, and rarely journal publications are sources of high-quality data. Unfortunately, the data are typically of limited coverage and rarely penetrate the full sediment cover.

A variety of geophysical methods have been used to identify drilling targets and to define the lateral extent and geometry of sediment packages. Ground-based gravity surveys are completed under contract to the OGS before drilling commences. The surveys help to identify the location of buried-bedrock valleys and escarpments but do not differentiate between infilling sediment types. A pilot project is underway to evaluate the possibility of converting residual Bouguer gravity profiles into depth to bedrock profiles. Additional geophysical work has been completed in several project areas by the Geological Survey of Canada’s (GSC) Near Surface Geophysics Section as part of a 5-year collaborative effort (Russell and Dyer 2016). Seismic reflection lines ranging from 4.5 to 21.5 km in length have been acquired to define the bedrock surface and provide insight into the architecture of overlying glacial sediments (Figure 4) (Pugin et al. 2018). Downhole geophysical surveys were conducted by the GSC in monitoring wells located adjacent to the seismic lines and in representative sediment packages. Downhole compression (Vp) and shear (Vs) seismic logs are used to calibrate the seismic data and convert two-way travel time profiles to true depths. Apparent conductivity and magnetic susceptibility logs are used to characterize lithological variations within and between sediment packages (Crow et al. 2017a, b). In some locations, regional groundwater temperature variations were determined from high-resolution fluid temperature logs (Crow et al. 2017a, b). A pilot time-domain airborne electromagnetic survey was undertaken within a portion of one of the 3D mapping project areas to assess its use for mapping lithostratigraphic units of varying resistivity in the subsurface. The method proved to be useful for defining the bedrock surface, especially in areas of shale, but failed to effectively discriminate overlying aquifer and aquitard units because of the limited range of conductivities of the Quaternary sequence that was present.

The highest quality data in each project area is collected by the lead geoscientist. A reconnaissance field season focuses on the examination of surficial, natural, and man-made exposures. The overall quality of existing surficial mapping is assessed and where necessary, new surficial maps may be produced with the assistance of high resolution elevation models. The goal of this reconnaissance field season is to allow the geoscientist to gain an appreciation for the Quaternary history and sediment-landform relationships of the project area. During subsequent field seasons, drilling targets are selected to refine the stratigraphic relationships of tills and associated stratified sediments, establish sediment-landform associations, and determine the nature of bedrock valley fills (Figure 5). The number of boreholes and metres of core retrieved, varies across and between project areas (Table 1). Track or truck mounted mud-rotary drills with 1.5 m samplers retrievable by wireline are used to continuously core the Quaternary sediment cover and upper 1.5 to 5 m of bedrock. The 8.5 cm diameter core is logged, photographed at 0.25 m increments with representative samples collected every 1.5 m or when significant changes in lithology occur for grain-size analysis, carbonate and heavy mineral content, radiocarbon dating, and paleoecological analysis. In clay-rich areas, a pocket penetrometer is used to perform field penetration tests. The resulting high-quality dataset allows the lower-quality legacy datasets to be interpreted more accurately. Monitoring wells (2.5-inch diameter threaded, flush-joint polyvinyl chloride (PVC)) with 1.5 or 3 m long slotted screens are installed in some boreholes by conser-
Figure 4: a) and b) High-resolution CHIRP sub-bottom profile displaying the sediment architecture in the eastern part of Kempenfelt Bay (submerged eastern extension of the tunnel valley forming the northern boundary of the south Simcoe study area; see Figure 1; modified from Mulligan, in prep); c) uninterpreted and d) interpreted S-wave seismic reflection profile across the Cookstown tunnel valley (CV) and adjacent uplands collected by the Geological Survey of Canada (data from Pugin et al., 2018) with borehole logs and surficial mapping as geologic constraints. SS-11-07 is 200 m south of the profile and SS-12-06 is projected from 2.7 km south for reference. Vertical red line shown where an intersecting seismic reflection profile intersects the displayed line (figure from Mulligan et al. 2018).
Figure 5: Conceptual geological framework for Central Simcoe County illustrating the stratigraphic architecture and facies variability within Newmarket Till across the physiographic regions and subglacial environments in the study area. No scale implied but typical thickness ranges are provided at the left of each log. Arrows denoting paleo-ice flow directions are interpreted from clast provenance, till sheet morphology, clast faceting/striae orientations and/or substrate deformation features. TV=tunnel valley. Figure from Mulligan et al. 2018c.
viation authorities and municipal partners for ongoing monitoring of groundwater levels and potential changes in water chemistry (Campbell and Burt 2015).

3D Modelling Approach

The OGS uses an implicit approach for regional-scale 3D modelling. As a first step, a conceptual framework subdividing the Quaternary sediment cover into regional-scale hydrostratigraphic units and typically one undifferentiated bedrock unit is developed (Table 1). These units are identified based on age and the sediment characteristics resulting from deposition in different environments (Burt and Dodge, 2016). Although the number of units varies between projects, an effort is made to correlate units from adjoining mapping areas. Bedrock is only subdivided where both crystalline Precambrian basement and overlying Phanerozoic sedimentary formations occur within the study area. The conceptual geologic framework functions as a guide for the interpretation of legacy data sets.

The 3D models are generated using commercially available Datamine Studio 3® software adapted to regional-scale modelling using a series of scripted routines commissioned by the OGS (Bajc and Newton 2005). Location and geological material tables, created from the master subsurface database, are used to generate borehole traces that can be viewed as 2D cross-sections or in 3D space. A static water depth table defines the depths of water well-screens and static water levels. When plotted beside the borehole traces, the data can aid in aquifer correlation.

Three-dimensional points, referred to as picks, identifying the top of a given hydrostratigraphic unit are manually digitized onto the borehole traces. The number of picks made on an individual borehole trace is dependent on the number of hydrostratigraphic units that can be interpreted from the primary material types. In many cases, it is only possibly to identify one or two units on the lowest quality traces whereas all units present in an area can be identified on the highest quality continuously cored boreholes. The picking process automatically generates a new table containing the borehole identifier, X, Y, Z coordinates of the pick, the hydrostratigraphic unit, and the quality rating of the borehole trace. Additional picks are digitized off the borehole traces to refine the geometry of the modelled surfaces. Wells that appear to be in the wrong location (i.e. dubious elevations, sediment thicknesses, or bedrock elevations) are either ignored or removed from the project database throughout the modelling process. The number of picks varies according to the size and complexity of the model area, and this has resulted in 28 000 to 71 000 picks made on completed models (Table 1).

Once a preliminary set of picks has been made, the scripted routines use the picks and a high-quality surface material database derived from the digital seamless surficial geology map to generate interpolated wireframe surfaces representing the tops of each hydrostratigraphic unit. The interpolation method used for OGS 3D modelling is isotropic inverse power of distance cubed (Bajc and Shirota, 2007). First, the picks are validated to ensure that the hydrostratigraphic units are in the correct sequence. Out of order picks are flagged for correction and then ignored by the software during the current run. In an attempt to reduce problems with overlapping wireframe surfaces, especially in data sparse areas, hydrostratigraphic unit elevations are interpolated onto a grid of virtual boreholes. The grid size can be adjusted throughout the modelling process: 200 to 500 m cells can be used to quickly generate surfaces early in the process whereas 100 m cells are used to refine the model and to generate final products.

During the interpolation process, each hydrostratigraphic unit is considered individually. A search radius, defined by the geologist to reflect the perceived extent of the unit, is drawn around each virtual borehole. An interpolated elevation is then assigned to the virtual borehole when a minimum of one high-quality, two medium-quality, or three low-quality picks are found within the search radius. If there are insufficient picks, the unit is considered absent and the elevation is automatically set as equal to the underlying unit. This process results in all hydrostratigraphic units being represented in each virtual borehole although units may have zero thickness at some locations.

Finally, a continuous set of wireframes are generated from the interpolated elevations and a set of rules are applied to remove any overlaps. Pinch-outs are accommodated by draping units on top of each other. These continuous surfaces are a requirement of most groundwater flow modelling software packages. A second set of wireframes are created by comparing the elevations for each triangular element. Locations where any unit had zero thickness are identified and those triangular elements were removed. This introduces holes, or pinch-outs, into the surfaces and more accurately represents the spatial extent of the units.

A 3D block model is then created by filling the space between each modelled wireframe surface with blocks of variable thickness (Figure 6). The planar dimensions of the columns match the virtual borehole grid size and the vertical dimension of each column is calculated automatically to fill in exactly between the surfaces. The resulting block model is used to calculate the volume, thickness, and surface contour of each unit.

Once a model run is complete, the results are visually compared with the borehole traces. Out of order picks are corrected, interpretations are re-
fined, and additional off-trace picks are added. The model is then re-run.

Each modelling project is released as a Groundwater Resources Study containing:

- A detailed report describing the geologic setting, protocols developed for the construction of the model, the distribution and properties of each hydrostratigraphic unit, and important recharge areas as well as aquifer vulnerability.
- Portable document format (.pdf) versions of structural contour and isopach maps of all modelled units, west-east and south-north cross-sections at 2 kilometre intervals, and depth to aquifer maps that can be used to assess aquifer vulnerability and recharge areas.
- Logs and analytical data from continuously cored boreholes.
- A stripped-down version of the subsurface database (.mdb) containing borehole location and stratigraphic information, data picks and static water level and screen depth.
- Comma-delimited text (.csv) files of both continuous and discontinuous surfaces designed as inputs to other software packages such as hydrogeological modelling, or visualization software.
- ESRI® ArcInfo® structural contour grids of discontinuous surfaces.
- A hypertext mark-up language (.kml) file that portrays transparent overlays of the structural contour and isopach maps as well as borehole locations and lithologic logs in a web-based (Google Earth™ mapping service) environment allowing for enhanced user interaction with the spatial data.

**Clients**

The OGS 3D sediment mapping team serves a diverse range of client groups who utilize different interim and final products for different purposes. These include:

- Conservation Authorities (responsible for protecting Ontario’s groundwater resource as part of Source Water Protection planning)
- Towns and municipalities (groundwater quantity and quality concerns and land-use planning)
- Geoscience consultants (contracted to produce groundwater flow models and water budget assessments for Conservation Authorities, towns, and municipalities). Also studies involving remediation of contaminated sites.
- Provincial and federal government agencies (for example internal OGS clients, Ministry of the Environment, Conservation and Parks, Ministry of Natural Resources and Forestry, Ministry of Municipal Affairs and Housing)
- Academia
Conservation authorities, towns and municipalities have firsthand knowledge of local issues, pressures and emerging concerns involving water, other resources, and associated planning scenarios. These client groups are instrumental in establishing model area priorities through yearly project proposal submissions that are evaluated by OGS geoscientists and management. Once a region has been selected for study, topics pertinent to that area are identified and updated during the life-cycle of the project. The project geoscientist acts as a go-to person for expert geological knowledge during data collection, the modelling phase, and then following completion of the project. OGS clients facilitate access to drill sites, partner to install long-term monitoring wells, and provide access to legacy datasets.

Reaching an audience that goes beyond primary contacts at project area conservation authorities or local municipalities and cities can be a challenge. The OGS has adopted a range of strategies that target different audiences. Since 2014, the Geological Survey of Canada and Conservation Ontario have collaborated with the OGS to offer a free yearly open house event featuring overview and project-specific talks and posters for conservation authority practitioners, policy makers, planners, municipal water specialists, consultants, and academics. The open house is a popular networking and educational opportunity. The OGS also participates in an annual conservation symposium, offering workshops, program and project-specific talks, and a corporate booth. Field visits and tours have proven popular with groundwater professionals from sister ministries, municipalities, conservation authorities, and project area consultants. Topical presentations at colleges and universities and working with faculty to provide topical and geographically relevant teaching material provides an excellent opportunity to reach a young technical audience. Hiring students from universities within or close to project areas facilitates student learning and encourages future collaborations, including thesis work. Working with museums and local interest groups has great potential for reaching the general public. The OGS has provided presentations to staff, donated core, and helped develop displays and material for exhibits and educational programming.

Recent Jurisdictional-Scale Case Study Showcasing Application of 3D Models

OGS 3D sediment mapping products have been used as model inputs and to inform groundwater and planning decisions at pan-provincial to sub-watershed scales. Some examples of these are:

- **Southern Ontario 3D model**: The OGS is collaborating with the Geological Survey of Canada to produce a provincial scale 3D model that summarizes the Quaternary sediment cover into seven layers (Figure 7). OGS cored boreholes and geological interpretations from completed and ongoing projects were incorporated into the model.

- **Municipal water supply studies**: Many clients require an improved understanding of the internal architecture of large stratified moraines to address concerns over water quality and quantity. Several early projects identified windows through regional aquifers and the locations of untapped aquifers with the potential to support future needs (Figure 8; Bajc and Shirota 2007; Bajc and Dodge 2011; Burt and Dodge 2011, 2016). Several clients are interested in whether buried-bedrock valley aquifers are capable of meeting municipal demands and how much groundwater is entering and leaving their watersheds along the valley system. In Waterloo Region, a secondary project was initiated that involved installing monitoring wells in logged boreholes, and drawing cross-sections delineating valley aquifer systems. In the Town of Erin, a large pumping station and associated infrastructure was decommissioned due to aquifer contamination. They needed to know whether a buried valley ran under the facility and whether it hosted an aquifer. In this case the OGS completed a ground gravity survey and drilled a borehole as part of the Orangeville moraine project.

- **Improved monitoring well network**: On the Niagara Peninsula, clients required a geologic framework, as well as monitoring wells, to improve groundwater flow models and to better understand surface water – groundwater interactions within several subwatersheds. Drill sites suitable for monitoring wells were prioritized and 29 wells, several later converted into nested wells, were installed.

- **Stressed watersheds and drought management**: Whitman’s Creek, a world-class cold-water fishery with groundwater dependent base flows, is under stress. An OGS 3D model, watershed specific cross-sections, and interpretations and recommendations for further study were used to assess and manage water withdrawals. The Innisfil Creek watershed has high groundwater usage for agriculture and golf course irrigation and in recent years, base flow in Innisfil Creek temporarily fell to extreme low levels. An OGS conceptual model and borehole data was used for a subwatershed-scale Mike-SHE hydrological model and development of a drought management plan.

- **Green Belt Expansion**: Several ministries required information on the subsurface extents of important aquifers contained within hydrologically significant moraines in the Greater Golden Horseshoe surrounding the Greater Toronto Area.
of southern Ontario. OGS contributions included surficial maps, moraine delineation, karst mapping, and the geological expertise required to interpret the datasets. This information was used to inform decisions on the location of future growth of the Green Belt, an area of restricted development aimed at protecting important water features (cold water streams and wetlands), as well as the geology that supports its uninterrupted health.

Current Challenges

Like most provincial surveys, the OGS is facing changing government priorities, increased demands for projects and deliverables, and limited resources. This is forcing the OGS to find new and creative solutions to ensure that we limit impacts to client interactions, data collection, and product delivery.

There are many challenges related to computer software and hardware. Replacing aging hardware would result in new operating systems necessitating expensive software upgrades. Scripted routines were originally written for Datamine Studio 2® and later revised to operate with Studio 3®. Upgrading to newer versions of the software would require these time-saving scripts to be rewritten. This means that the OGS is generally not able to benefit from advancements in computer processing speed or improvements in the software without significant cost and impact to productivity.
Changing technology has already impacted product delivery. Previous projects included a cross-section viewer capable of drawing sections along user-defined lines drawn on a Virtual Earth base map. These sections could be saved, and then imported into Google Earth™ mapping service in conjunction with overlays of structural contour and isopach maps and this allowed for enhanced user interaction with the spatial data. The section viewer used Microsoft® Virtual Earth® which is now Bing Map and the coding and links have changed. This will require a rebuild of the cross-section viewer, and a possible migration to another platform.

Discoverability and data retrieval are a constant challenge for ministry staff and clients alike. OGS clients have difficulty finding the correct page on our ministry website, and once there, it is difficult to find project specific publications. OGS Earth, a web portal that allows geoscience data collected by the Mines and Minerals Division to be viewed and downloaded using Google Earth, has proven to be an effective solution. However, many products are large and are downloaded as a series of .zip files that must be merged. This is cumbersome, and errors often occur.

Figure 8: Example of a simple depth to aquifer vulnerability map generated for the Orangeville-Fergus area of southwestern Ontario. The map depicts the depth below the surface of sand- and gravel-rich 3D model units (Burt and Dodge 2016).

Field programs and analytical work result in large-scale, rapid data collection. Collaborating with other surveys, ministries, and academia can be an effective way to ensure that data reaches its maximum potential.

Lessons Learned

One of the most important things that the OGS has learned is the value of communication and active collaboration throughout the life cycle of a project. Discussions with experts at sister ministries, conservation authorities, and municipalities during project planning provide an excellent opportunity to find out whether there are specific areas of concern, emerging issues, and/or future development projects. Conservation authorities and municipalities can facilitate site access and provide legacy datasets from consultants. Early communication also increases the potential for converting boreholes into monitoring wells to gain additional useful information for modelling efforts. Partner funding can take months and it can also take months for permits for permanent infrastructure to be approved (especially during summer holiday periods). Communication ensures that clients have a realistic idea of what they are going to get, can identify opportunities for releasing interim products, and provide input as to how products can be improved. Communication with local universities and colleges will identify common areas of interest. Collaborating with university graduate students can be an excellent way of conducting site-specific studies or addressing scientific questions that are beyond the scope of the project.

Critical to the success of the program is ensuring that the geological and hydrogeological information presented within the reports is delivered in a manner that can be understood by both technical experts and non-technical users. Derivative and value-added maps, such as those that estimate aquifer recharge or vulnerability, are
particularly useful. An attempt has been made to produce standardized products that allow for models to be merged and this also facilitates the creation of a provincial-scale 3D model of Quaternary geology. This is balanced with the development of new products, such as interactive drilling data and borehole maps, that take advantage of advancements in technology (Burt and Webb 2013; Burt and Chartrand 2014).

Communicating the uncertainty of geological maps and reports to their users is a relatively new venture for geoscience and a variety of approaches are being trialled. The OGS is currently using a visual approach to address uncertainty in 3D hydrostratigraphic mapping projects (Burt and Dodge 2016). Each isopach or structural contour map is complemented by a dot map that indicates the location and the quality of picks used to interpolate the surface (Figure 9). The dot maps provide an estimate of the reliability of the source data and give an immediate visual indication of the distribution of data across the study area. Clients find this visual representation intuitive and the 3D team can focus on interpreting and mapping geology rather than mapping uncertainty.

**Next Steps**

OGS 3D sediment mapping activities have been well-supported by our senior management and divisional leadership team and core client base who recognize the importance of OGS data and products. The OGS team provides the regional geologic framework for hydrogeological modelling and policy decisions in areas where 3D sediment mapping studies have been completed. Proposals for future projects have been submitted that would expand our efforts into southeastern Ontario as well as infill gaps in coverage in the southwest. The future challenges are to improve the ease of data retrieval, address technological changes that impact product delivery, and expand uptake beyond our core client base to ensure that high-quality geoscience data remains a government priority.

**References**


Bajc, A.F., and Dodge, J.E.P. 2011. Three-dimensional mapping of surficial deposits in the Bradford-Woodstock area,


