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# 3-D model of the Quaternary sediments in the St. Lawrence valley and adjacent regions, southern Quebec and eastern Ontario

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# 1 Contents

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## 2 Introduction

This project, carried out in collaboration with the Department of Earth and Environmental Sciences of the University of Waterloo, aims to provide a first comprehensive compilation of the surface and subsurface distribution of Quaternary sediments in the St. Lawrence valley and adjacent regions. This compilation is the first step required to produce a mapped assessment of terrain parameters for dynamic response to seismic shaking in the St. Lawrence Valley (Nastev et al., 2016a, 2016b). The thicknesses of simplified Quaternary units within the Ottawa and St. Lawrence Valleys will be integrated into a broader geohazard assessment platform (ER2, Nastev et al., 2015) used to assess casualties and damages to the built environment for a variety of seismic shaking scenarios.

In this project, a three-dimensional (3D) model is constructed to map the thicknesses of various surficial sediment units. The resulting geological model is regional in scale, extending from the Ottawa Valley to the St. Lawrence Valley and with a cell resolution sufficiently small to allow detailed analyses. In the study area, there were a number of local surficial 3D models prepared for regional hydrogeological studies (Ross et al., 2005; Girard, 2000; Logan et al., 2009; Tremblay et al., 2010; Lamarche, 2011; Caron, 2012; Légaré-Couture et al., 2017), most of them conducted under the supervision or co-supervision of the senior author. This report aims to incorporate these into a single continuous 3D model with the assistance of surficial geology maps, digital elevation models (DEM) and borehole data.

The main objective of this paper is to present the main results of this work: a simplified 3-layer regional-scale geological model of Quaternary units overlying bedrock in the St. Lawrence Valley and adjacent regions.

## 3 Study area – physiographic and geological setting

The study area is located in southern Québec and eastern Ontario (Figure 1). It extends from Ottawa to Québec City and includes Montreal, the largest city of the region. The study area covers approximately 72,800 km$^2$. While it is largely centered on the St. Lawrence valley, the study area extends over the Appalachian uplands to the southeast and covers the southern edge of the Laurentian Highlands. Elevations range greatly within the study area, the lowest being just a few meters above sea level (ASL) along the St. Lawrence River and the highest being 1 173 m ASL in the southeast Appalachians. In addition to Montreal, Ottawa and Quebec City, the study area contains a number of smaller urban centres, such as Laval, Gatineau, Sherbrooke, Trois-Rivières, St-Jérôme, Drummondville and St-Hyacinthe.

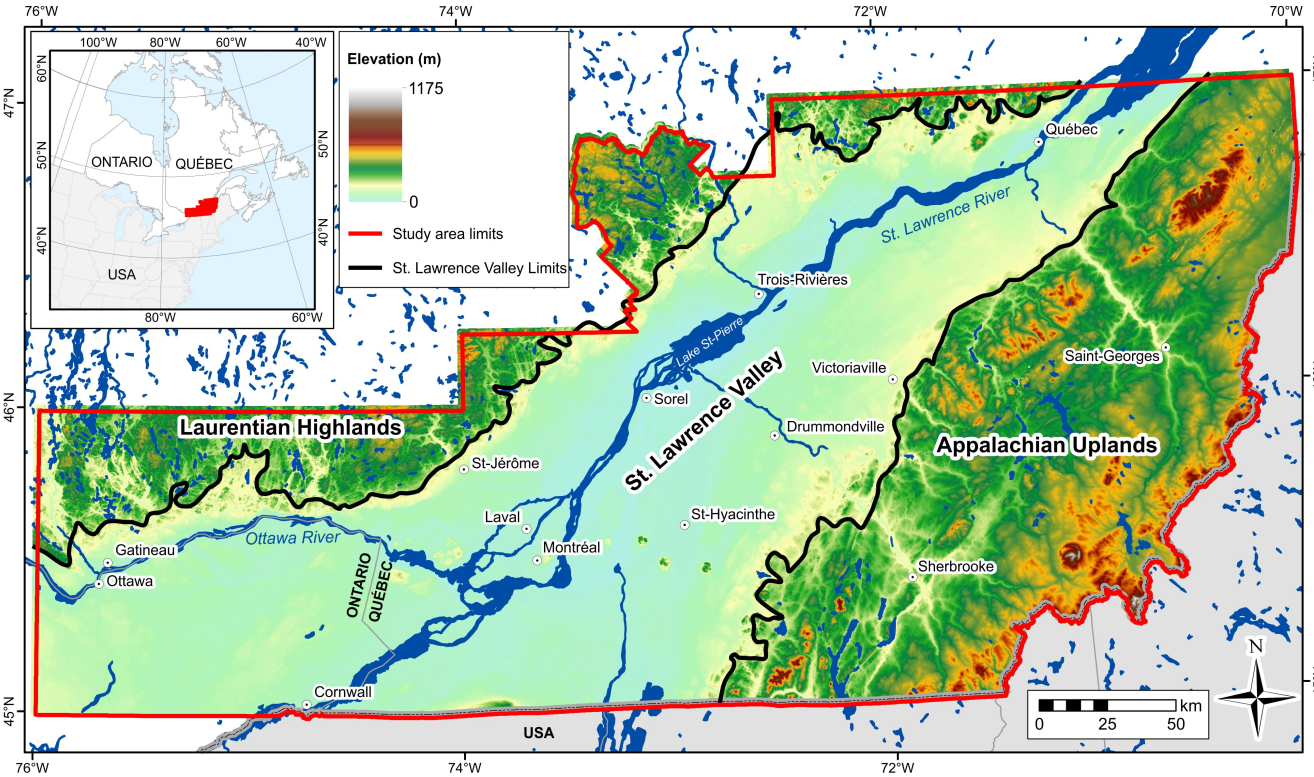


*Figure 1. Location and topography of the study area. Terrain elevations in m ASL.*

The **St. Lawrence Valley** is a relatively flat region lying below about 200 m ASL and underlain mainly by subhorizontal Early Paleozoic sedimentary rocks, known as the St. Lawrence Platform (Globensky, 1987). This platform was later intruded by alkaline magmas during the late Mesozoic (Feininger & Goodacre, 1995); these intrusions, which form a series of sharply defined hills known as the Monteregian Hills, resisted Cenozoic erosion and now stand at elevations of 200 to 400 m above the level of the valley. The valley, which also laps onto the adjacent Appalachian piedmont, is covered by relatively thick and continuous Quaternary sediments, consisting mainly of marine, deltaic and alluvial sediments but also including glacial, glaciofluvial and morainal sediments. While the lowland plain grades almost imperceptibly southward onto the Appalachian piedmont, the Quaternary sediment cover is much thinner on the piedmont than on the adjacent lowlands. The DEM (Figure 1) shows that, from a Quaternary basin point of view, not only does the valley narrow to 50 km near Québec City, but that its floor rises in elevation to almost 80 m ASL in the Quebec City narrows (Figure 1). These shoals caused Champlain Sea waters to become hydrologically disconnected from Atlantic seawaters relatively early during the isostatically-driven Champlain Sea regression (Occhietti et al. 2001; Lamarche, 2011).

The **Appalachian Uplands**, which are underlain by deformed Cambro-Ordovician rocks of the Appalachian Orogen, extend south of the St. Lawrence Valley. The rocks consist mainly of deformed low-grade metasedimentary rocks (mainly mudstone, sandstone, and wacke) but also include a few mafic metavolcanic units. The Appalachian uplands commonly consist of NE-SW trending uplands with elevations ranging from 200 to 400 m ASL and a few low mountain ranges with summits exceeding 500 m ASL, and locally up to 1175 m ASL near the Canada-USA border (Figure 1). While a major thrust fault zone, marked by a main thrust fault called Logan's Line and a subordinate fault called the Aston Fault, forms the contact between the Appalachians and the Platform (see Figure 2), the topographic contact between the two physiographic regions is so smooth that it almost escapes attention, as Figure 1 shows. The transition zone, which is underlain by a 30 km wide series of stacked thrust sheets, is commonly referred to as the Appalachian piedmont, which though not underlain by platform rocks, is considered as part of the St. Lawrence valley (Figure 1).

The **Laurentian Highlands** extend north of the St. Lawrence Valley and are underlain by Late Proterozoic igneous and high-grade metamorphic rocks of the Grenville Province, the youngest part of the Canadian Shield, The contact zone between the shield and the platform is marked by a series of en-échelon normal faults (Figure 2) and is characterized by a transitional landscape where rounded hills and hillocks underlain by Precambrian rocks protrude through the Late Quaternary marine sediment cover. This somewhat fragmented terrain is known as Laurentian piedmont. The shield hinterland is an upland region consisting of low to moderate relief hills and knobs with generally accordant summit levels at 500 to 600 m ASL (Figure 1). These were extensively scoured and rounded by Quaternary ice sheets, which also produced linear through-valley systems in weaker fracture zones.

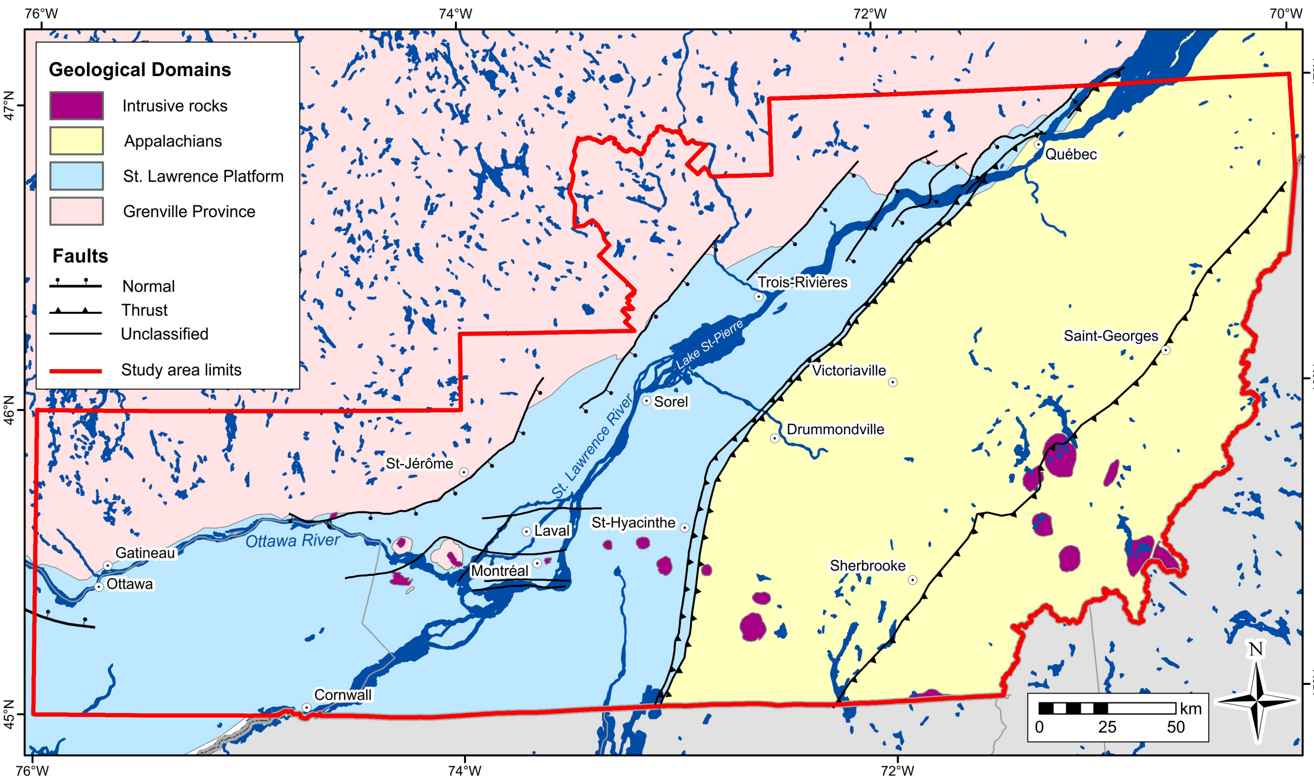


*Figure 2. Main geological provinces along with the main structural discontinuities of the study area.*

### *3.1 Quaternary context*

The study area was repeatedly glaciated and deglaciated during the Quaternary Period. However, because the ice sheets that advanced across the region were particularly erosive, the Quaternary stratigraphic record is rather fragmentary, as it contains many hiatuses and discontinuities. Building on the work of many previous workers, such as Gadd (1971), McDonald and Shilts (1971), Gadd et al. (1972) and Lamothe (1989), Occhietti et al. (1996) were able to reconstruct a stratigraphic record of glacial, interglacial and interstadial sediments ranging from at least the penultimate glaciation (Illinoian) to the last deglaciation (Figure 3). Further discussion on that stratigraphic succession is beyond the scope of this report; interested readers will find additional information in papers by Lamothe et al. (1992) and Occhietti et al. (1996). Let us simply note that the three glacial advances (Bécancour, Lévrard and Gentilly tills) recognized in the region are followed by as many successions of fluvial, glaciolacustrine and marine sediments and that individual natural sections expose only minor part of the full succession shown in Figure 3.

While the Champlain Sea was a fairly short-lived event, lasting only approximately 2,000 years (Richard and Occhietti, 2005; Parent and Occhietti, 1988), it had a huge impact on the surficial geology and lithostratigraphic record of the St. Lawrence valley. This marine incursion is responsible for the deposition of a thick blanket of soft clays overlying glacial sediments across much of the valley below about 200 m ASL on the Laurentian piedmont and below about 120 m ASL on the Appalachian piedmont. The marine clay cover constitutes a very soft layer that is not only prone to massive landslides and earthflows (Leroueil et al., 1983; Locat et al., 1984) but that also amplifies shaking intensity during seismic events (Hunter and Crow, 2015). From a hydrogeological point of view, the marine clay cover constitutes a regional aquitard across much of the St. Lawrence Platform (e.g., Beaudry et al., 2018). Large deltas and extensive beach complexes along Champlain Sea shorelines were emplaced as relative sea level fell quickly because of high rates of glacial isostatic rebound.

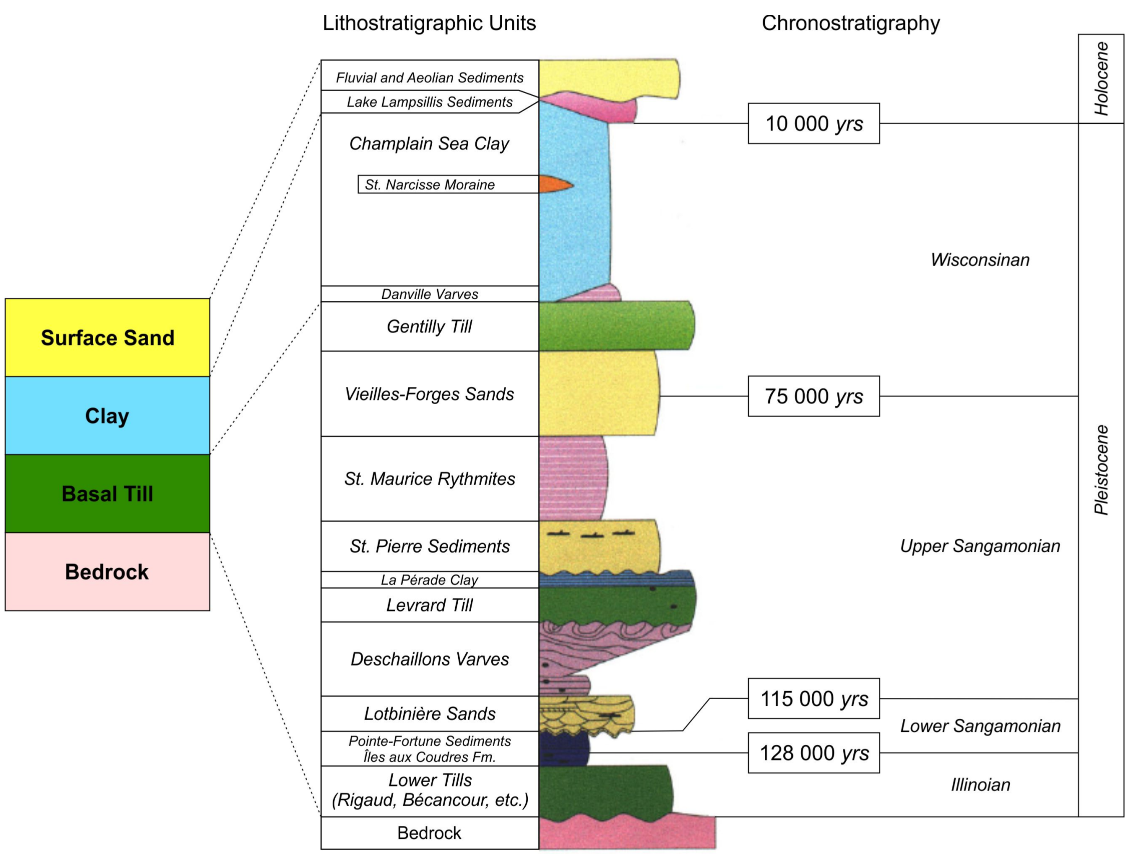


*Figure 3. Complex lithostratigraphic units of the St. Lawrence Lowlands (right; modified from (Occhietti et al., 1996) combined on the basis of their physical properties to form a simplified 3 unit stratigraphic column (left), permitting development of a regional scale model.*

# 4 Methodology

## *4.1 Conceptual model*

To determine the distribution and thickness of the major surficial units across the entire Québec-Ottawa region, we developed a simplified 3D geological model. It is a deterministic realisation of the subsurface stratigraphy and of the interfaces separating the broad geological units. In the study area, several 3D geological models were already available; most of them had been developed for hydrogeological characterization in various regions: Portneuf (Girard, 2000), Mirabel (Ross et al., 2005), South Nation watershed (Logan et al., 2009), Chateauguay watershed (Tremblay et al., 2010), Québec City (Lamarche, 2011), Chaudière River watershed (Caron, 2012), Trois-Rivières region (Légaré-Couture et al., 2017). The process leading to the development of these models included a thorough review of borehole and geophysical databases with emphasis on geological consistency or interpretation, an exercise deemed too time-consuming to repeat in the current study. Interested readers are referred to the publications and reports listed above for details on database quality control, on the development of these geological models and on associated interpretations. The models were simplified for the purpose of this study (see below), but the main task was to fill the gaps between the existing models. Various data sources provided the necessary input parameters to develop the regional model needed for this study. For the purpose of this study, a seamless surficial geology map was created first with a standardized legend (Parent et al., 2021). A regional digital elevation model with 90 m resolution (CGIAR-CSI Shuttle Radar Topography Missions, 2006) was used to drape the surficial geology. The existing geological models were simplified and the main task was to fill in the gaps between the models. To this end, various data sources provided the necessary parameters for the development of a continuous and seamless regional model. For example, borehole descriptions from a public database (gw-info.net) were interpreted/ simplified and coded. All data were imported into the Gocad software suite (www.pdgm.com/products/gocad/), which was used to build the final seamless 3D geological model.

To avoid unnecessary details as well as the complexities of the regional stratigraphic record, the diverse surficial units with similar lithofacies, physical properties (e.g. density, compactness, shear strength) and depositional environments were aggregated into three broad categories which were deemed adequate for the purpose of the project (see Nastev et al, 2016a, 2016b). From top to bottom (Figure 3), these informal simplified units are: sandy surface sediments (herein referred to as sand), intermediate clayey sediments (clay), and glacial sediments and older Quaternary units (basal till).

- ***Sandy surface sediments*** consist mainly of littoral and sublittoral sand that overlie fine-grained marine or glaciolacustrine sediments, or that overlie glacial sediments at elevations closer to the marine limit. This group includes fluvial and aeolian sands whose thickness ranges from 1 to 10 m, similar to that of littoral sands. It also includes deltaic sands that are much thicker, commonly on the order of 20 to 40 m. In addition, this unit includes glaciofluvial deposits (sand and gravel) and undifferentiated non-marine sand and gravel in areas above the marine limit. Spatially most of the sand units of this group occur as extensive shallow sheets or as long and narrow belts along streams and ancient beaches.

- ***Intermediate clayey sediments*** consist almost entirely of silty clays and clayey silts deposited on the floor of the glaciomarine and glaciolacustrine water bodies that inundated vast parts of the Quebec-Ottawa corridor during the last deglaciation. The soft clayey sediments of this group are the main unit of concern due to their physical properties making them susceptible to ground shaking and to landsliding. While this unit includes certain units of glaciolacustrine or lacustrine origin, the thickest and most widespread are the Champlain Sea clays that consist mainly of low density, soft, usually saturated silty clay sediments and which may be geotechnically highly sensitive. As reported in a number of publications (e.g. Gadd, 1971; Leroueil et al., 1983; Locat et al., 1984; Parent and Occhietti, 1999), the clay content of these marine muds is commonly above 50 % and may be as high as 90 %. Certain Champlain Sea muds lose much of their strength when disturbed and behave like a viscous fluid. Their sensitivity is generally correlated with high natural water content, flocculated fabric of clay particles, low electrical attraction between clay-size particles, low overburden pressures during deposition, and post-depositional leaching of salts (Locat et al, 1984; Torrance, 1988). As a consequence, retrogressive earthflows are widespread throughout the study area. Characterised by rapid lateral expansion, earthflows encompass large areas of almost horizontal terrain, with slope angles on the order of one degree or less (Quinn et al., 2010; Brooks, 2103)

- ***Basal glacial and older non-glacial sediments***, though comparable in terms of compactness and stiffness, are rather heterogeneous in terms of origin and particle size distribution (Figure 3). This ubiquitous unit consists mainly of glacial and glaciofluvial sediments deposited by the Laurentide Ice Sheet during the last regional glacial advance and recession (Late Wisconsinan). It also includes undifferentiated sub-till sediments commonly exposed in a series of lowland sections, notably in the Trois-Rivières, Bécancour and Richelieu-Yamaska regions (Occhietti et al., 1996; Gadd, 1971; Lamothe, 1989; Parent et al., 2014) and in the upper Chaudière Valley (Shilts, 1981). The glacial sediments included in this unit are heterogeneous in nature and usually contain pebbles, cobbles and boulders enclosed in a compact silty or sandy silt matrix. Their density, compactness and stiffness are elevated in comparison to the overlying clay and sand units; their stiffness is such that drillers are sometimes uncertain as to whether bedrock is encountered, particularly in the Lowlands and Appalachians. The sub-till sediments included in this unit are much more discontinuous than the overlying till but their thickness locally exceeds 30 m, with an observed maximum of 150 m in Trois-Rivières (Légaré-Couture et al., 2017). As shown in Figure 3, these units include a variety of clayey, sandy and diamictic sediments that are sporadically observed in riverbank exposures and boreholes; their detailed distribution is not easily resolved and is clearly beyond the scope of this report. While the sub-till units consist of a variety of lithofacies, their relative stiffness, shear strength and density, often as high as those of the overlying tills units, are due to overconsolidation caused by the large effective pressure exerted by the 2 to 3 km thick glaciers that overrode them during the last glaciation (Peltier et al., 2015).

### *4.2 3D model construction*

There are many approaches to develop 3D geological models, and part of the difficulty in creating a regional 3D model is choosing the most suitable method for the project. In this particular project, stratigraphic simplifications, and sometimes re-interpretations, were necessary, keeping in mind the model needs to capture bedrock topography and the internal geometry and thickness of the overlying sediment units. To this end, the Geological Framework Model (GFM) strategy to determine the stratigraphic architecture was employed (Ross et al., 2005). The GFM ultimately displays the unconsolidated sediments overlying a varying regional bedrock topography. The internal stratigraphy is defined by continuous surfaces that represent the tops of lithological units. Discrete triangulated surfaces are created in Gocad from points and curved lines, and then modified with the Discrete Smooth Interpolation (DSI) algorithm, which minimizes roughness while still honouring hard and soft constraints (Ross et al., 2005). The DSI algorithm ultimately smoothens a surface while honouring control points precisely, and less reliable data less exactly. It can take into account thickness constraints in a specified direction, as well as border constraints to refrain from extending or compressing a surface. The modeled surfaces therefore represent boundaries for lithological units.

Because the units within the Quaternary succession in this study area are in reality very discontinuous, the modeled surfaces are continuous and span the entire region for the purpose of this study. However there will be no vertical separation between the respective upper and lower modeled surfaces and the thickness of that unit is nil (0 m).

#### *4.2.1 Available data*

The data sources for this project include a seamless surficial geology map produced by the Geological Survey of Canada (GSC) (Parent et al., 2021), a Digital Elevation model (DEM) derived from the Shuttle Radar Topography Mission (SRTM) dataset (CGIAR-CSI, 2006), public borehole data (SIGEOM, N/Aa) (SIGEOM, N/Ab), and simplified local 3D models extracted from Girard (2000), Ross et al. (2005), , Logan et al. (2009), Tremblay (2010), Lamarche (2011) and Caron (2012). The data used to create the 3D model are shown in Figure 4 and Figure 5.

This project uses the NAD83, UTM zone 18N coordinate system to integrate all the data in the same environment. The surficial geology for the study area and the DEM also had to be preliminarily edited. The surficial geology was saved as separate lithological unit shape files in ArcGIS and then imported into Gocad as curves. The DEM, originally a raster file, was converted to a point set in ArcGIS and then imported into Gocad as a point set. A surface was then created from this point set and represents the topographic surface.

The borehole logs indicate the thicknesses of each unit, although the majority of them only indicate depth to bedrock. Due to the large number of boreholes, the borehole data were imported into Gocad as a point set, representing the tops of each simplified lithological unit. There were 60 832 boreholes for the study area, with the highest borehole density in and around urban areas.

The simplified already existing 3D geological models of smaller regions were also imported into Gocad as point sets due to the great number of data points. These models were sampled at a regular interval of 250 m and this distance was retained for the point set spacing.

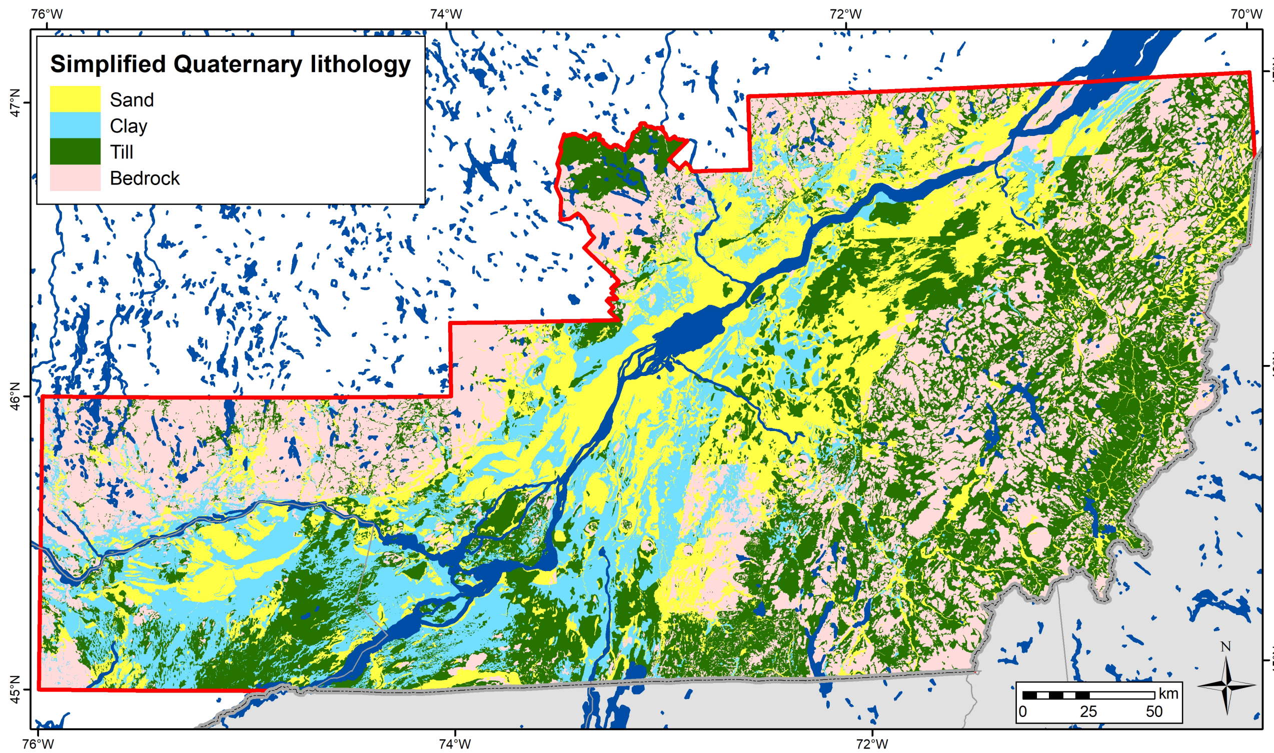


*Figure 4. Simplified Quaternary lithology map of the study area. Modified from an early version of the surficial geology map (Parent et al., 2021 (in prep).*

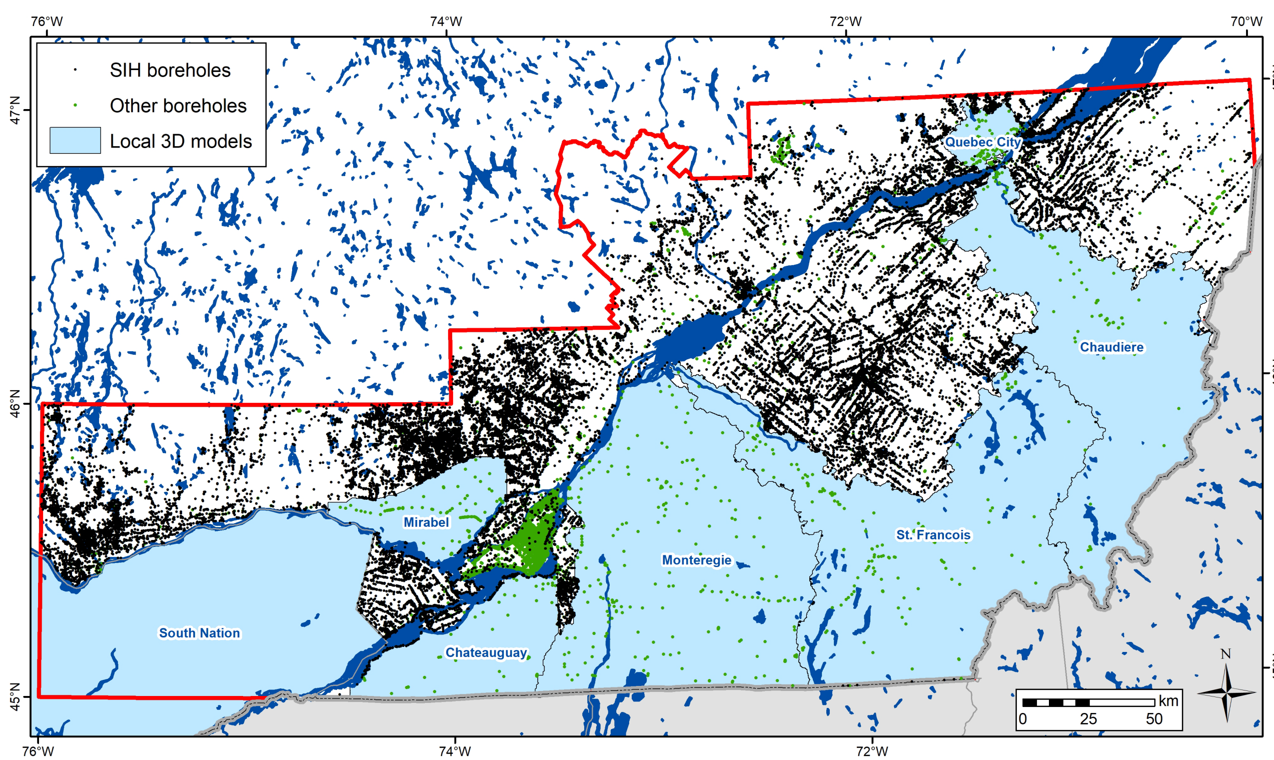


*Figure 5. Data used for the 3D model construction.*

### *4.2.2 Surface creation*

The first surface to be created for the 3D model is the topographic surface. A triangulated surface with a regular mesh (200m x 200m) is created from the DEM point set.

Next, the surficial geology is imported into Gocad as curves for each lithological unit. Irregular triangulated surfaces are created from these curves. Editing of the surficial geology map is a time consuming process as the study area is vast and contains complex surficial geology patterns. Once the editing is completed, the surficial geology is displayed properly as a geological map with an elevation of 0 m ASL.

The lithological information is then projected or transferred to the nodes on the topographic surface (Figure 6). The surface mesh contains nodes that are regularly spaced at 200 m and connected by line segments forming a pattern of regular triangles. This approach of creating a regular surface mesh was preferred in this project to facilitate the transfer of properties and creation of stratigraphic grids. The downside is that it slightly modifies the shape of geologic contacts, but this was considered as a reasonable limitation given the scale and purpose of this project. Nodes capture the information for the surface, including coordinates (X, Y, Z) and any other given properties such as the simplified lithologic units (SLUs): Surface Sand, Clay, Basal Till, and Bedrock. To account for discontinuities, no data values are assigned to SLUs in areas where they do not occur at the surface. The nodes with the geological properties indicate where a specific SLU outcrops in the study area, to which we can infer that younger lithological units are absent as well. Using the simplified stratigraphic column, it can be inferred that, when Bedrock is outcropping, all of the other units are absent; that, when Basal Till is outcropping, Clay and Surface Sand are absent; and that, when Clay is outcropping, Surface Sand is absent. The nodes within each lithological region are used to determine when the top of the corresponding surface is equal in elevation to the topographic surface, therefore indicating the above lithological units have a thickness of 0 m.

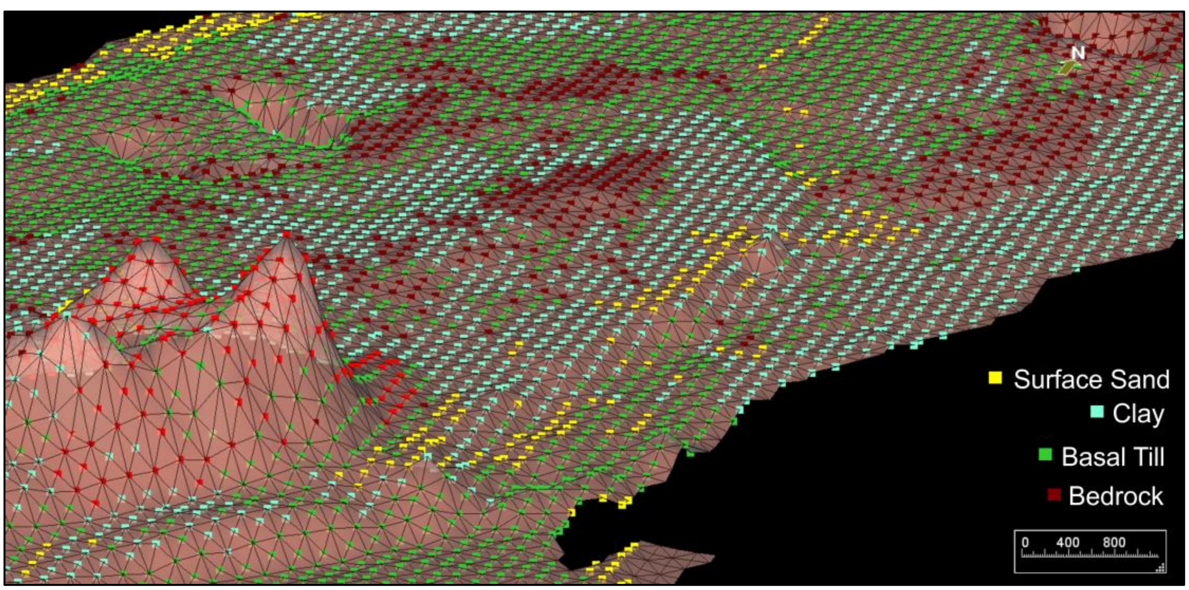


*Figure 6. Topographic surface with a regular mesh that hold information or properties such as lithology.*

The surface of the top of the Bedrock is the next surface to be created after the topographic surface. The surface of the top of the Basal Till is created next and then the surface of the top of the Clay unit. The top of the Surface Sand, which is the youngest unit, corresponds to the topographic surface as the unit always starts at the topographic surface elevation. The underlying lithological units outcrop in some areas, leaving the Surface Sand unit with 0 m thickness. The order of surface creation is executed in this 'sandwich pattern' as it is easier to edit the inner surfaces to remain within the boundaries of the outer surfaces.

The mesh structure of the topographic surface is replicated to keep the same structure for the bedrock top surface. The nodes within the regions where the bedrock surface crops out are set as "control nodes". These ensure that those areas are not moved from their present locations while the surface elevation is being edited or interpolated. This step forces the bedrock surface to outcrop exactly in these areas while allowing the other unconstrained nodes to be pulled downward to match other constraints (e.g. borehole markers).

The borehole logs indicate the top of specific SLUs. As mentioned earlier, some boreholes only contain depth-to-bedrock information while others contain information about the whole stratigraphic column. The borehole data are displayed as a point set due to the large number of data points or markers. The markers indicating the top of the Bedrock unit become control points. During interpolation, a surface is displaced vertically to honour the control points as closely as possible while honouring roughness criteria to produce a smooth surface. The surface does not have to honour control points, as these are "soft" constraints; however, it must strictly honour control nodes which are "hard" constraints. Setting a Z-directional constraint on the border ensures that the surface does not stretch or compress at the edges but merely move upwards or downwards.

Once all of the constraints are in place, a discrete smooth interpolation (DSI) routine is applied to the surface to create the Bedrock surface (Figure 7) The preliminary Bedrock surface is edited to exclude problematic boreholes or further interpret areas with little to no borehole data.

The finalised Bedrock surface is then duplicated to constitute the starting point of the Basal Till surface. The same constraints are applied and the surface is interpolated. Editing this surface also includes ensuring that it is constrained within the limits of the Bedrock surface and the topographic surface (e.g. the Basal Till surface does not dip below the elevation of the Bedrock surface). The fact that all surfaces share the same mesh structure greatly reduces crossover issues, especially for this type of model where some units are thin and discontinuous.

When the Basal Till surface is finalized, it is duplicated to constitute the starting point of the Clay unit surface. The same steps used to construct the Basal Till surface are applied to the Clay surface as well. The Clay surface must be constrained within the limits of the Basal Till surface and the topographic surface.

# 5 Results: regional 3D model

## *5.1 Elevation of bedrock surface*

As indicated earlier (section 3.3.1), the hypsometric map of the top of bedrock (Figure 7) constitutes the base of the 3D surficial geology model and it is thus important to verify its geomorphological coherence, particularly the valley patterns of the main tributaries of the St. Lawrence River. As shown in Figure 7, the bedrock floor patterns of the St. Lawrence, Richelieu and Yamaska rivers upstream of Lake St-Pierre show accordant levels at about -25 m ASL grading down to about -50 m ASL along the north shores of Lake St-Pierre and St. Lawrence River downstream of Trois-Rivières. These low elevations are recorded further downstream to the vicinity of Deschaillons and St-Pierre-les-Becquets, where the classical exposures of Early Wisconsinan and Illinoian sediments are located (Gadd, 1971; Lamothe, 1989; Occhietti et al, 1996). This suggests that the St. Lawrence and its tributaries formed a relatively well-integrated fluvial system grading down to a base level as low as -50 to -75 m ASL, presumably during the Early Pleistocene. The latter sub-epoch was a protracted period of oscillating sea levels below present (Hansen et al., 2013; Toomey et al, 2016), prior to the maximum development of midlatitude ice sheets (Clark et al., 2006). Although this was a relatively short interval (less than 2 Ma), rapid entrenchment of the ancestral St. Lawrence River was possible because the underlying platform rocks consist of soft shales and sandstones. Further downstream, traces of this fluvial system are also recorded in the buried valley underlying the lower town in Québec City, where the top of bedrock lies at -78 m (Lamarche, 2011; Lamarche et al., 2008). While the well-organized fluvial system recorded by the bedrock topography shows that glacial over-deepening was not a factor in the central valley, Figure 7 also shows that the lower reaches of the St-François, Nicolet, Bécancour, Chaudière and Etchemin paleovalleys have not been captured in the current reconstruction. This may be an artefact resulting from an insufficient dataset. In the case of the Chaudière and Etchemin rivers, this certainly seems to be the case as both valleys definitely run in an epigenetic course in their lower reaches, as shown by the many bedrock-controlled rapids and falls near their confluence with the St. Lawrence River, notably the 35 m-high fall on Chaudière River.

The hypsometric map (Figure 7) also shows that the bedrock floor of the St. Lawrence Platform lies regionally at elevations ranging between -25 and +25 m ASL and rises sharply by about 50 m as the thrust faults marking the northern edge of the Appalachian piedmont are crossed. This sharp rise of the bedrock floor is not apparent in the regional DEM (Figure 1) while on the north side of the valley, the contact zone between the Shield and the platform is generally conformable with the surface topography. In eastern Ontario, the irregular surface of the platform reaches elevations of about – 25 m, which suggests that glacial erosion and over-deepening may have played a major role along the southern edge of the Shield in that region, a situation resembling that of the Shield edge in Great-Lakes region.

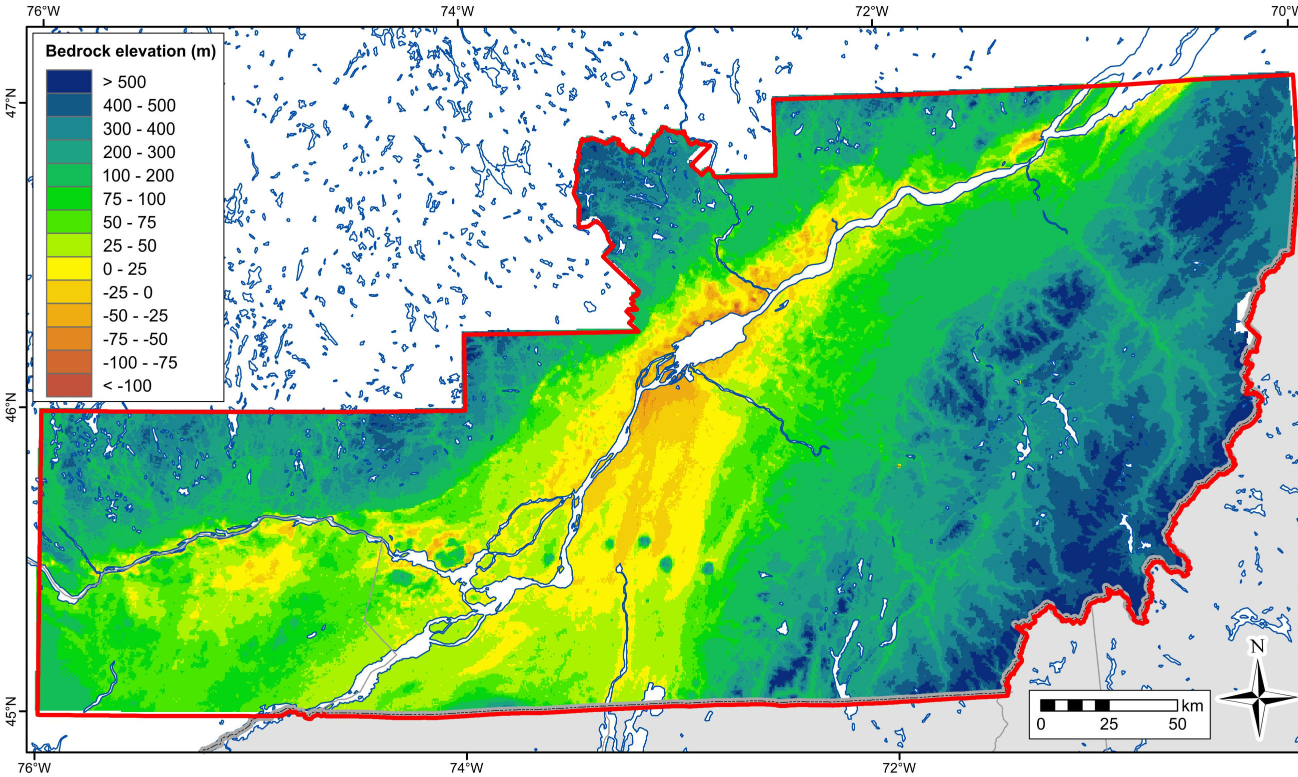


*Figure 7. Hypsometric map of the top of bedrock in the St. Lawrence valley and adjacent regions.*

### *5.2 Total thickness map/model*

Together with the map of the top of bedrock, the total thickness map of Quaternary sediments (Figure 8) is probably the most accurate of the maps produced in the course of the present study (Figure 7, Figure 8, Figure 9, Figure 10 and Figure 11), largely because depth-to-bedrock is generally recognized as the most reliable dataset that can be extracted from archived subsurface records. This is particularly important in the case of water well records in which Quaternary sediments descriptions are generally considered as low reliability data (Ross et al., 2005). The relative accuracy of the total thickness map also stems from the key horizontal (X, Y) control exerted by surficial geology maps which bring fairly accurate constraints through the distribution of bedrock outcrops and mapped thin till units, particularly in the Appalachians and Laurentians.

As expected, Figure 8 shows that surficial sediments are generally less than 2 m thick on the Appalachian Uplands and Laurentian Highlands, except for a sizeable area along the upper Chaudière valley where total thickness can reach as much as 50 m. In the St. Lawrence Valley, there are two main areas of thick surficial sediments. The first one is a large region around Lac St-Pierre where observed total thickness reaches 25 to 50 m over a large area and as much as 100 m in the vicinity of Trois-Rivières. The area of thickest surficial sediments underlying the city of Trois-Rivières is the combined result of thick deltaic sands of the St-Maurice delta (see Figure 11) and of well-known thick pre-LGM (Last Glacial Maximum) glacial and non-glacial sediments (Légaré-Couture et al., 2017; Occhietti, 1977; Hardy and Lamothe, 1997; Occhietti et al., 1995; Lamothe, 1989), as shown in Figure 9. The other one lies in the valley east of Ottawa, where a large area of Quaternary sediments exceeding 25 m in thickness (Logan et al., 2009) is observed, largely because of thick Champlain Sea clays (Figure 10) recorded in a sizeable basin, called the Ottawa Basin by Gadd (1986).

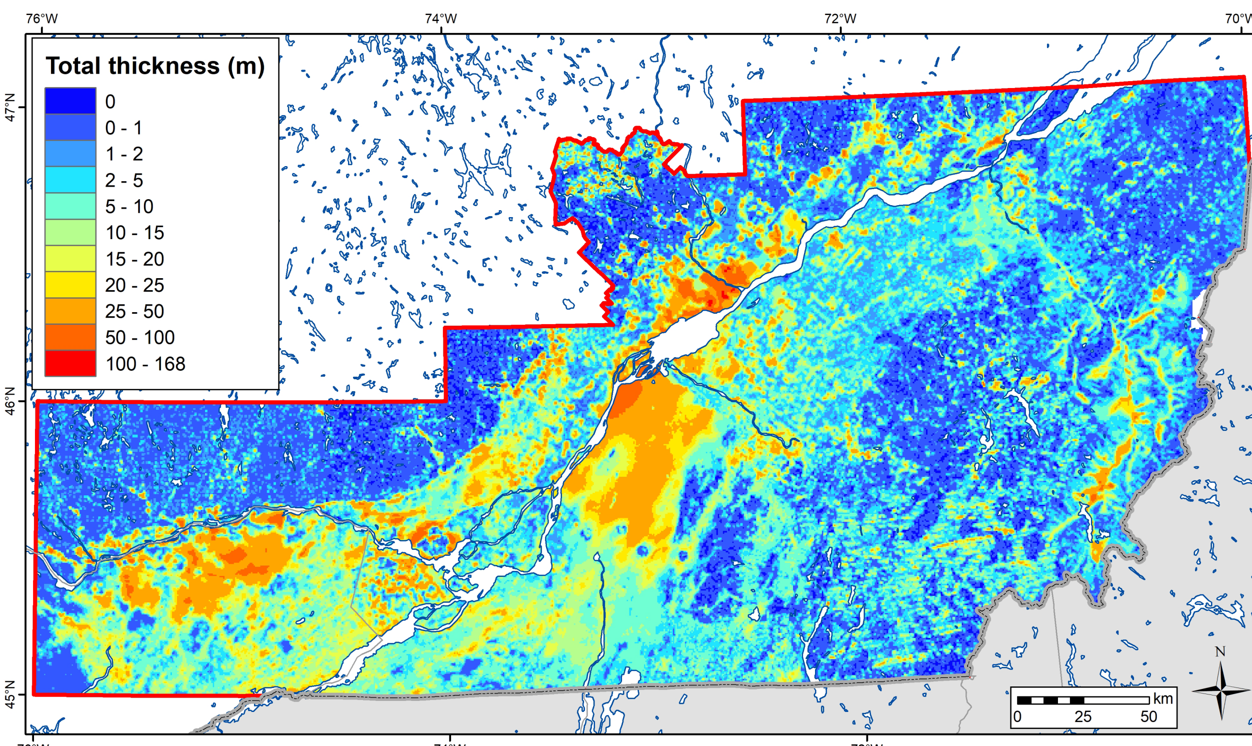


*Figure 8. Map of the total thickness of Quaternary sediments in the St. Lawrence valley and adjacent regions between Québec City and Ottawa.*

### *5.3 Till thickness map/model*

As explained above in Section 3.1, Figure 9 presents the thickness distribution of a basal composite unit consisting of undifferentiated glacial and non-glacial Quaternary sediments deposited during the interval preceding and including the last regional glacial advance (Late Wisconsinan). This composite unit is generally a few meters thick on the Laurentian Highlands and Appalachian Uplands where it consists essentially of glacial sediments, with the notable exception of the upper Chaudière valley. There, thick Early to Mid-Wisconsinan sediments underlie the Lennoxville Till, which is the regional surface till emplaced during the last glacial advance across the southern Quebec Appalachians (McDonald and Shilts, 1972; Shilts, 1981).

In the St. Lawrence valley, the thickness distribution of this basal composite unit displays a seemingly undulating pattern ranging from a few meters up to about 25 m. While a diffuse triangular area of thick till lies east of the St. Lawrence River and north of the Monteregian Hills (Parent et al., 2014), the main areas of thick glacial and non-glacial sediments are found underlying the city of Trois-Rivières (Légaré-Couture et al., 2017) and in a few buried valleys in the region west of Montreal (Ross et al., 2005) and in Quebec City (Lamarche, 2011). Noticeable along the northern edge of the valley is an arcuate suite of small bodies of thick glacial and glaciofluvial sediments outlining the St-Narcisse Moraine (Occhietti, 2007).

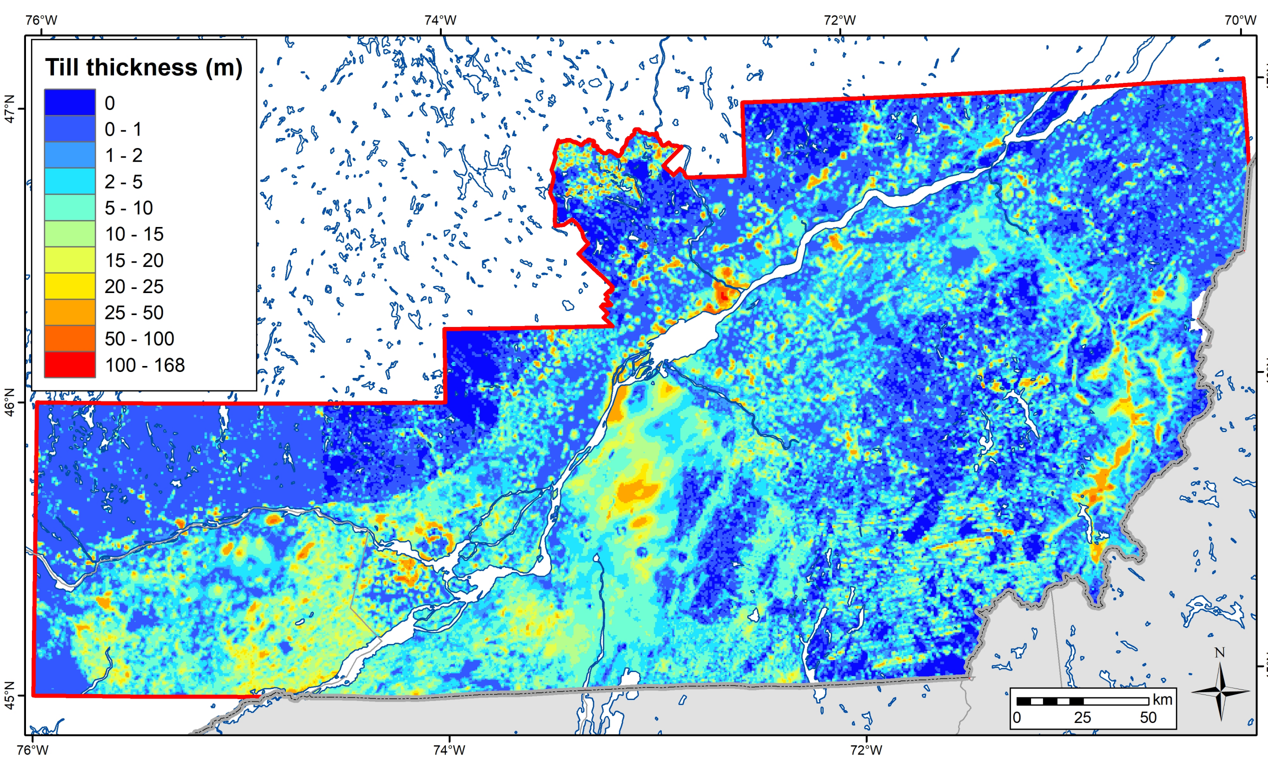


*Figure 9. Thickness map for the composite unit of stiff glacial and non-glacial sediments in the St. Lawrence valley and adjacent areas between Québec City and Ottawa.*

### *5.4 Clay thickness map/model*

The spatial distribution of marine clay thickness (Figure 10) shows that while Champlain clays are rather ubiquitous below 200 m in the St. Lawrence Valley, they are concentrated in two distinct basins where they usually are 20 to 30 m thick, but occasionally reaching 50 m in thickness. One basin is centered in Eastern Ontario and has been labelled the Ottawa Basin by Gadd (1986). The other is centered in a large area surrounding Lake St-Pierre and extends southward to the Monteregian Hills; for convenience, we will call it the Yamaska Basin. Secondary smaller and shallower depocenters can be observed in the Châteauguay River watershed south of the Montreal region and in the L'Assomption River watershed just north of the Montreal archipelago.

Figure 10 also shows that the marine clay thickness decreases rapidly to almost nil on the Appalachian Piedmont where the clayey sediments are generally thin and discontinuous, except in a few valleys where they may reach 5 to 10 m in thickness. Also noticeable are the general thinness and discontinuity of clayey sediments in the Montreal archipelago; this is due mainly to fluvial erosion by the Proto-St. Lawrence River as it re-established its course following the Champlain Sea – Lake Lampsilis episodes. A similar situation also occurred in the Quebec City region, with the additional effect of the depositional hiatus of fine-grained marine sediments on the Appalachian piedmont.

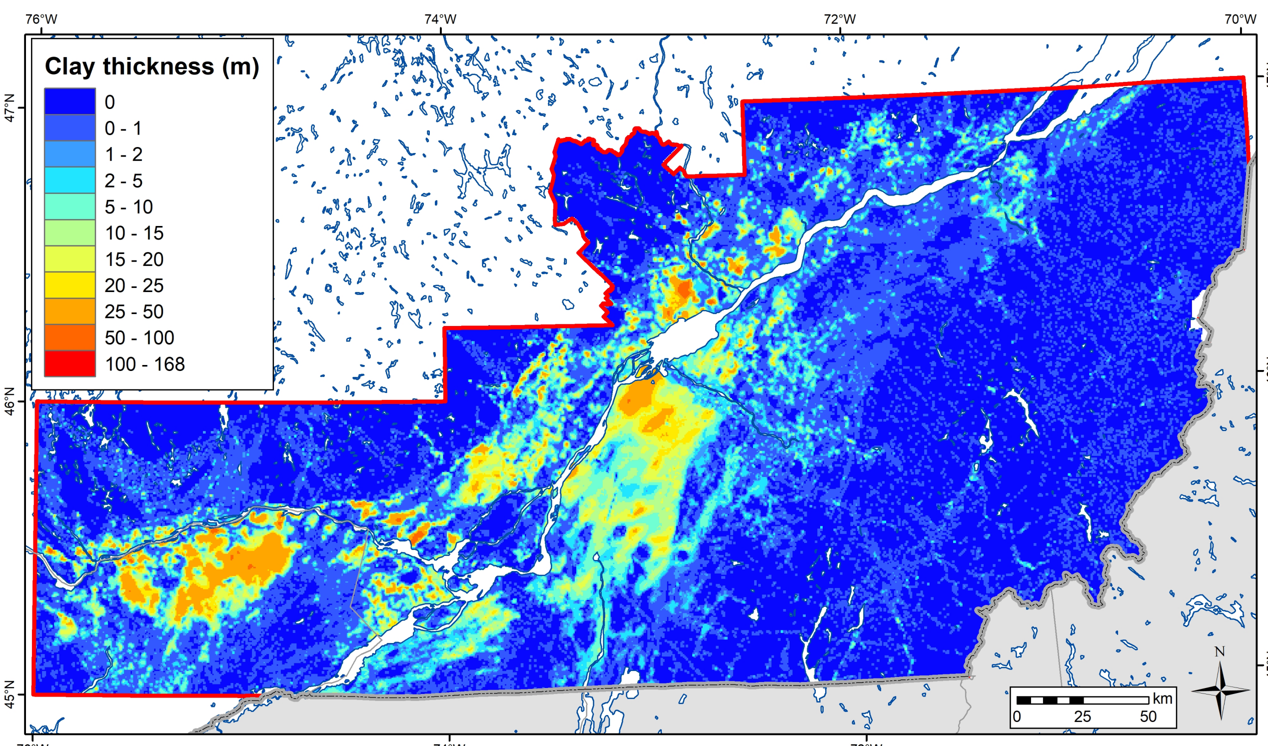


*Figure 10. Thickness map for clayey sediments in the St. Lawrence valley and adjacent areas between Québec City and Ottawa. Note the two basins, one in Eastern Ontario (Ottawa Basin), the other in southern Quebec (Yamaska Basin).*

### *5.5 Sand thickness map/model*

The surface sand isopach map (Figure 11) shows that the main areas of thick surface sand consist of deltaic sediment bodies emplaced at the mouth of large rivers discharging into the Champlain Sea. The largest and thickest of these are the St-Maurice River delta in Trois-Rivières (Légaré-Couture et al., 2017), the St-François River delta near Drummondville, and the St. Lawrence River delta near Sorel. The partly buried delta of the St. Lawrence River in Quebec City (Lamarche et al., 2008; Lamarche, 2011) is noticeable, even at the scale of this map. Deltas emplaced by smaller rivers (L'Assomption, Sainte-Anne, Jacques-Cartier) discharging into the Champlain Sea can also be observed along the southern edge of the Shield. Noticeable is the absence of a large delta for the Chaudière River near the northern edge of the Appalachian Highlands; this is attributed to important longshore drift on the southern Champlain Sea shore in that region (Paradis et al., 2014). Elsewhere in the valley, the surface sand unit is thin and discontinuous, consisting mainly of beaches and bars formed during Champlain Sea regression and alluvial sands deposited along the tributaries of the St. Lawrence River.

At low elevations (below about 25 m ASL) along the St. Lawrence River and Lake St-Pierre, between Montreal and Trois-Rivières, the surface sand unit consists of fairly continuous sheets of alluvial sands; these are particularly thick near Sorel, where the St. Lawrence River discharges into Lake St-Pierre.

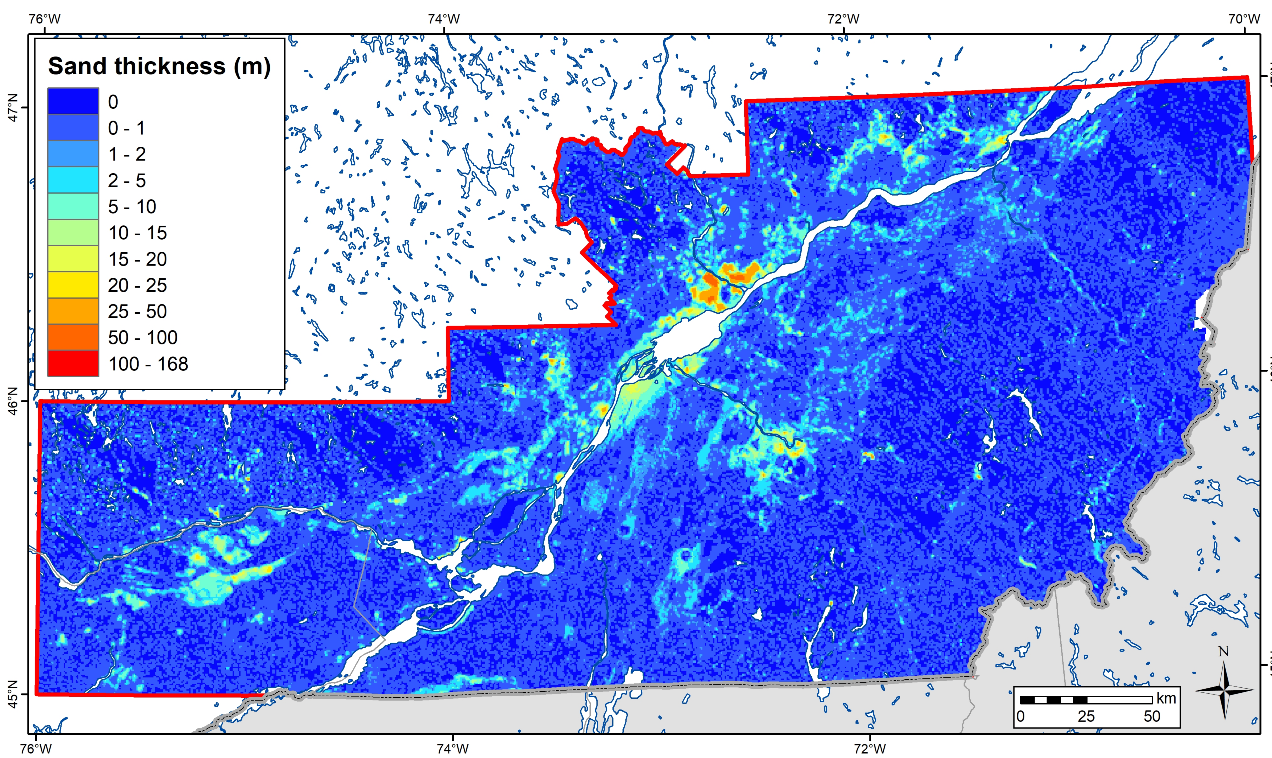


*Figure 11. Thickness map for sandy surface sediments in the St. Lawrence valley and adjacent areas between Québec City and Ottawa. Notice the thick delta of the St-Maurice River in Trois-Rivières and the continuous blanket of alluvial sands bordering the St. Lawrence River between Montreal and Trois-Rivières.*

## 6 Metadata

| | |
|---|---|
| Title | 3D model of the Quaternary sediments in the St. Lawrence valley and adjacent regions, southern Québec and eastern Ontario |
| Organisation | Government of Canada; Natural Resources Canada; Geological Survey of Canada |
| Dataset creation date | 2013 |
| Dataset publication date | 2021 |
| Presentation form | Digital model |
| Dataset status - Update frequency | Completed - Not planned |
| Dataset language | English |

**License**



**Constraints**



**Abstract**

A thorough geohazard evaluation requires an understanding of the surface and subsurface geology. The thickness of unconsolidated sediments and their physical properties greatly impacts how a region will likely behave during a seismic event. Three-dimensional (3-D) geological models are being used to determine areas most susceptible to earthquake disturbance. This project used ArcGIS and Gocad softwares to create a 3D geological model of the region between Québec City and Ottawa, bordered by the United States to the South and the Laurentian Highlands to the North. For the purpose of this study, the geology has been simplified into three basic units: 1) Surface Sand, 2) Clay and 3) Basal Till. This simplified three unit stratigraphy is typical of a regional scale model, which in this study area covers 72,800 km$^2$. The regional geological model was developed using a variety of data sources including a Digital Elevation Model (DEM) of the study area, borehole data from public databases, existing local geological models, and a surficial geology map.

**Goals**

The goal of this project is to produce a simplified 3-layer regional model of the Quaternary deposits over bedrock of the region between Ottawa and Québec City in the context of a geohazard evaluation.

**Keyword(s)**

3D Model, Geohazard, Quaternary, Southern Québec, Eastern Ontario

**Spatial reference**

| | |
|---|---|
| Extent | Southern Québec and Eastern Ontario |
| Spatial extent (Lat/Long) | X Min: -76.1 X Max: -69.9<br>Y Min: 44.8 Y Max: 47.2 |
| Reference system code | EPSG:26918 |
| Reference system name | UTM NAD 83 Zone 18 |
| Spatial representation | Text table (CSV) |

**Lineage**

- 3D model creation

  1) Stratigraphic simplification to obtain 3 Quaternary layers

  2) Data cleaning and preparation

     a. Boreholes
     b. Surficial geology map
     c. Local 3D models

  3) Surface creation in Gocad

     a. Topographic surface
     b. Bedrock top
     c. Basal Till unit top
     d. Clay unit top

  4) Unit thickness calculation

- Data source

  - Surficial geology map
  - Digital elevation model (DEM)
  - Public borehole data
  - Local scale Quaternary 3D models

**Dataset content and structure**

The dataset is available in text file and in ESRI Shapefile. The different column/attribute information is described as:

| **Column/attribute** | **Description** | **Unit** |
|---|---|---|
| x | X coordinate | UTM NAD 83 Zone 18 |
| y | Y coordinate | UTM NAD 83 Zone 18 |
| sand | Thickness of the sand layer | Meters |
| clay | Thickness of the clay layer | Meters |
| till | Thickness of the basal till layer | Meters |
| Total_quat | Total thickness of the Quaternary sediments | Meters |
| Z_DEM | Elevation of the Digital Elevation Model | Meters |
| Z_top_clay | Elevation of the clay layer top | Meters |
| Z_top_till | Elevation of the basal till layer top | Meters |
| Z_top_br | Elevation of the bedrock top | Meters |
| D_top_clay | Depth of the clay layer top | Meters |
| D_top_till | Depth of the basal till layer top | Meters |
| D_top_BR | Depth of the bedrock top | Meters |

**Dataset contacts**

| | |
|---|---|
| **Principal investigator** | Michel Parent<br>Government of Canada; Natural Resources Canada;<br>Geological Survey of Canada - GSC Quebec<br>490, rue de la Couronne, Québec, Québec, Canada |
| **Originator** | Danielle Howlett<br>Waterloo University |

## 7 Conclusions

This report presents the first comprehensive compilation of the surface and subsurface distribution of Quaternary sediments in the St. Lawrence valley and adjacent regions. It also presents an original method to incorporate Quaternary sediments into a regional scale 3D model with the assistance of surficial geology maps, digital elevation models and borehole data.

The resulting 3D model is actually a simplified model of Quaternary units that constitutes the first step required in producing a mapped assessment of terrain parameters and response to seismic shaking for the St. Lawrence Valley (Nastev et al., 2016a, 2016b), a region where the presence of soft Champlain Sea clays may lead to significant amplification of seismic shaking (Hunter and Crow, 2012). The thicknesses of simplified Quaternary units within the Ottawa and St. Lawrence Valleys has already been integrated into a risk assessment tool (ER2, Nastev et al., 2015) used to estimate human casualties as well as damages to exposed buildings and infrastructure for a variety of seismic shaking scenarios.

This 3D model also shows that a well-integrated drainage system grading down to a sea level of – 25 to -50 m below present had developed on the St. Lawrence Platform, presumably during the Early Pleistocene. The model is also being used as a simplified hydrostratigraphic model used in coupled surface water – groundwater modeling for the Yamaska River watershed.

## 8 Acknowledgements

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