Development of a 3-D geological model towards natural hazards mitigation, St. Lawrence River Valley, Eastern Canada

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Abstract: As part of the Canadian Government's main goals to ensure safe and strong communities for its citizens, the Geological Survey of Canada has recently undertaken the development of a 3-D geological model and a seamless surficial geology map of the St. Lawrence River valley in Eastern Canada. This paper summarizes the initial phase of this project, which consists of gathering, validating, and integrating existing geological and geotechnical data through a geographic information system. It presents the preliminary results towards the development of a 3-D geological model of unconsolidated sediments in the St. Lawrence Valley, based on digital elevation model, surficial geology map and subsurface information. A preliminary map of the thickness of unconsolidated sediments in the St. Lawrence Valley is presented for the first time. This map shows deeply buried bedrock zones with sediment thickness in excess of 160 m. These deep zones are critical areas with respect to regional mapping of ground susceptibility to earthquake disturbance. The potential influence of such deep zones on earthquake-induced landslides is examined. Geoscience data quality issues and problems encountered in data validating and integrating are also discussed, and potential solutions suggested.

Résumé: Afin d'offrir à ses citoyens des communautés fortes et sûres, le gouvernement du Canada, via la Commission géologique du Canada, a récemment entrepris le développement d'un modèle géologique en trois dimensions (3D) et d'une carte continue de la géologie de surface de la vallée du Saint-Laurent (situé dans l'est canadien). Cet article résume la phase initiale de ce projet, lequel consiste à la collecte, la validation et l'intégration de données géologiques et géotechniques existantes à l'aide d'un système d'information géographique et de bases de données cartographiques associées. On y présente brièvement les résultats préliminaires du développement d'un modèle géologique 3D des sédiments non-consolidés dans la vallée du Saint-Laurent basé sur un modèle numérique d'élévation numérique, de cartes de dépôts de surface et des données de dépôts souterrains. Une carte préliminaire de l'épaisseur des sédiments non-consolidés est présentée pour la première fois. Cette carte montre des zones profondes de la roche en place recouvertes, à certains endroits, par plus de 160 m de sédiments. Ces zones profondes sont des aires critiques dans le contexte de la cartographie régionale de la susceptibilité de perturbation des sols suite aux séismes. On examine aussi l'influence de ces zones profondes sur l'occurrence de glissements de terrain induits par des séismes. On y discute également des problèmes de qualité des données géoscientifiques et de ceux rencontrés dans la validation et l'intégration de ces données. Des solutions potentielles sont suggérées.

Keywords: 3D models, geographic information systems, geological hazards, mapping, and sediments.

INTRODUCTION

The recent, rapid development in information technology and the acquisition of large amounts of numerical geoscience data, and/or the increasing data transfer towards numerical format through digitization, has lead to the production of new mapping products such as 3D geological models of the subsurface (e.g. Culshaw 2005). These models are increasingly used to better understand the subsurface and also move towards a better land-use management status in urbanized areas. Geoscientific information pertaining to urban geology is more commonly and widely used as a response to growing concerns about the lack of geoscientific analysis in urban development (Heiken et al. 2003; McCall et al. 1996; ESCAP 1989). Relevant information on geomorphology, bedrock (e.g. composition, fracturing, faults), surficial geology (e.g. texture, grain size distribution) and hydrogeology (e.g. water table depth) compiled in geodatabases and easily accessible helps geoscientists, engineers, and planners in increasing the capacity of better development communities.

Background

Urban Geology in Canada

Urban geology studies have more than a century-long history in Canada. One pioneering work is the paper by Ami (1900) entitled "On the Geology of the Principal Cities in Eastern Canada". A later paper by Burwash (1918) dealt with Vancouver. In more recent times, Legget (1973) published "Cities and Geology" which remains one of the best known on the subject. In 1982, R.F. Legget edited a Geological Society of America's Reviews of Engineering Geology series in which two Canadian cities (Edmonton: Rutter & Thompson, 1982; Toronto: White, 1982) were included. Boyer et al. (1985) wrote an extensive paper on the urban geology of Montreal in the Bulletin of the

Association of Engineering Geologists. In 1998, Karrow & White edited a GAC Special Paper on urban geology of nineteen Canadian cities.

Urban Geology of the National Capital Area (Ottawa)

"Urban Geology of Canada's National Capital Area" was a pilot project aimed at developing approaches, methodologies and standards that can be applied to other major urban centres of the country, while providing the geoscience knowledge required for sound regional planning and environmental protection of the National Capital Area (Ottawa). A first phase of the project occurred in the 1970's and had lead to a reference document "Regional Geoscience Information: Ottawa-Hull" extensively used for regional planning (Bélanger & Harrison 1980). The database and accompanying location maps were of little use because of limitations related to the mainframe computers available at that time (Bélanger 1998). Responding to interests by local governments and the private sector, in 1994 the federal Government launched a second phase of the Urban Geology Project (Moore 1998). The purpose of that new initiative was to provide flexible on-line geoscience information, in formats compatible with user needs, based on cutting-edge technology to compile, process and display geoscience information (Bélanger 2004).

Goal of the project

The aim of the St. Lawrence Valley project is to provide geoscience information for sound regional planning. This includes sustainable development of natural resources, mitigation of natural hazards, identification of vulnerable soils and aquifers to anthropogenic input, and identification of best environmental practices in developing regional and urban infrastructure.

Private and public agencies have compiled an enormous amount of geoscientific information in the form of geological and topographic maps, stratigraphic information (derived from engineering and waterwell logs), remote sensing images, and numerous geoscientific reports describing the physical environment of the St. Lawrence Valley. The availability of geoscience information in digital format, and the use of universal standards for information management, along with the possibility of analysing multiple layers of geospatial data, using Geographic Information Systems (GIS), provide the possibility of integrating various sources of information. From these derived documents, such as thematic maps, stratigraphic sections and three-dimensional geological models can be produced.

This paper summarizes the initial phase of this project, which consists of gathering, validating, and integrating existing geological and geotechnical data through a geographic information system and the associated geo-database. It briefly presents the preliminary results towards the development of a 3-D geological model of unconsolidated sediments in the St. Lawrence Valley. A preliminary map of the thickness of unconsolidated sediments in the St. Lawrence Valley shows deeply buried bedrock zones with sediment thickness up to 160 m in some places. These deep zones can be critical areas with respect to regional mapping of ground susceptibility to earthquake disturbance and earthquake-induced landslides (Aylsworth *et al.* 2003; Hunter *et al.* 2003).

STUDY AREA

Location

The study area covers the St. Lawrence River valley from Kingston to the St. Lawrence estuary, for a total length of 1180 km (Figure 1). It also includes the Ottawa Valley to the west, the Saguenay-Lac St. Jean region to the north, and the Gaspesie Peninsula to the east. To the south and southeast, the study area is bounded by the borders of the USA and the province of New Brunswick. The study covers a total area of 287 847 km^2 and includes six of the 39 largest Canadian urban communities.

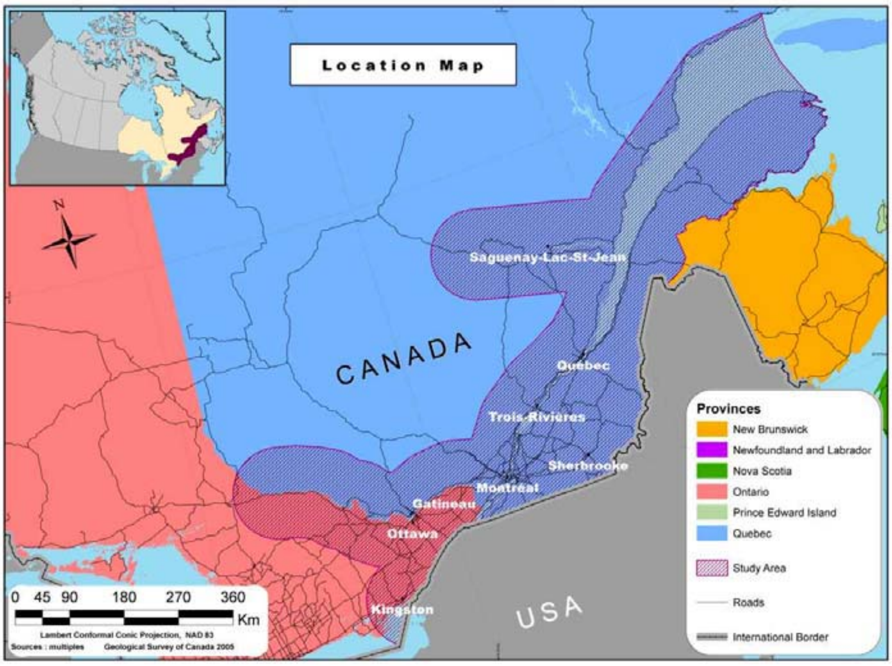

Figure 1. Location map.

Population and economical significance

Historically, the St. Lawrence Valley was the main entrance to Canada (formerly Nouvelle-France) in the 16th and 17th Centuries. Initially, the first cities were founded along the St. Lawrence and the Ottawa Rivers. As the population grew, it expanded along smaller tributaries and inland. Today, more than half of the Canadian population lives in the St. Lawrence River valley and Great Lakes Lowlands Region. Of these around 8 million people, i.e. one fifth of the total population of Canada, live in the study area (Statistics Canada 2001). Montreal, Ottawa-Gatineau region, Kingston, Quebec City, Sherbrooke and Trois-Rivières are the largest cities with a population density >50 people per square kilometre (Figure 2). The study area was, and still is, the hub for the development of the economical life in Canada. Industries (e.g. aerospace, computers, "technological know-how"), forestry and agriculture are the main economic activities in the study area.

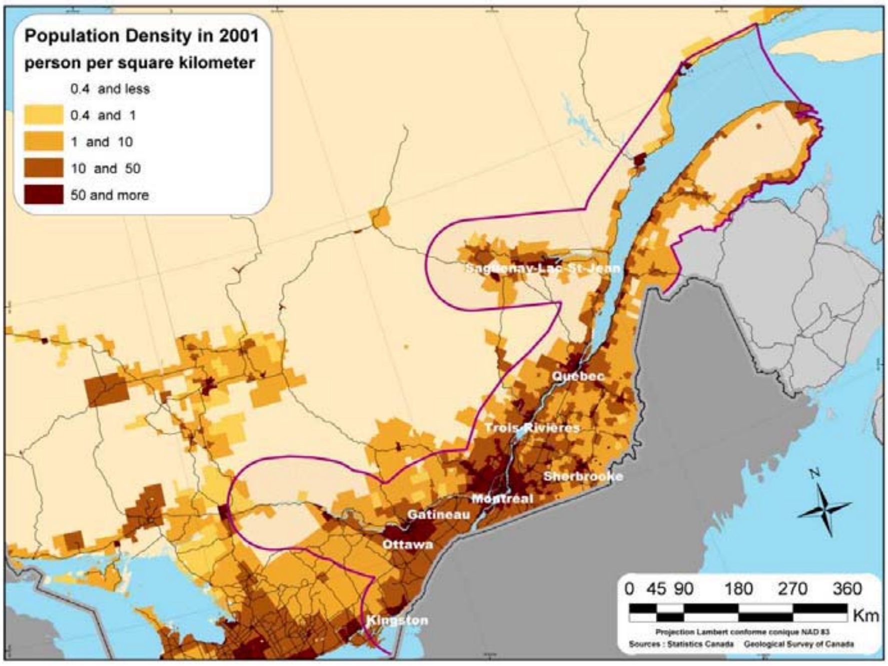

Figure 2. Population density map for the study area (Data from Statistics Canada 2001).

Geomorphological and geological settings

The study area intersects 3 main geological provinces (Figure 3a). The thin central portion of the study area lays on a slightly inclined 2300 m–thick Paleozoic sedimentary platform that occupies an ancient rift zone (Houde & Clark 1961; Wilson 1964). The area also includes part of the Appalachian Mountains in the south and southeast, which are composed of folded and faulted sedimentary and metamorphic rocks (Fig. 3b). To the north, it includes metasedimentary, intrusive and gneissic rocks from the Precambrian Grenville Province of the Canadian Shield (Figure 3a; Davidson 1989). These two regions have a moderate relief with a variable thickness of Quaternary deposits, whereas the St. Lawrence Platform shows a low relief and a vast Quaternary deposit cover usually varying between 30 and 60 m in depth (Occhietti, 1989). The Appalachians have a typical ridges and depressions relief severely modified by glacial erosion. The Canadian Shield shows a hummocky relief resulting from numerous faults and structural lineaments and intensive glacial erosion.

The geomorphology of the Quaternary deposits in the study is mainly affected by post-glacial fluvial and coastal erosion processes that created a series of terraces and step-shaped plains while the Champlain Sea was retreating (about 12 k years B.P.). The latter deposited thick silty clay sediments, which are often greater than 100 m thick in the central part of the St. Lawrence Valley, in the Ottawa River valley, and in several buried valleys. Generally, Champlain Sea deposits are less thick on valleys sides and in hilly areas (Occhietti 1989). Pro-glacial deposits, such as moraines widely cover the Appalachian and Canadian Shield region (Figure 4). Karrow & Occhietti (1989), Occhieti & Karrow (1989), and Occhietti (1989) summarized the Quaternary history of the study area and Figure 4 gives more detailed information on the surficial deposits.

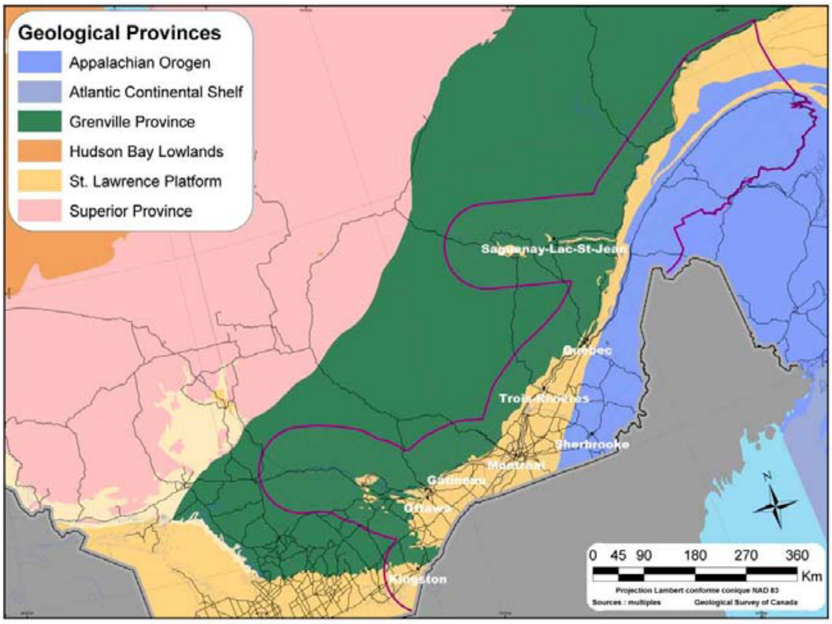

Figure 3a. Principal bedrock geology provinces (After Wheeler *et al.* 1996).

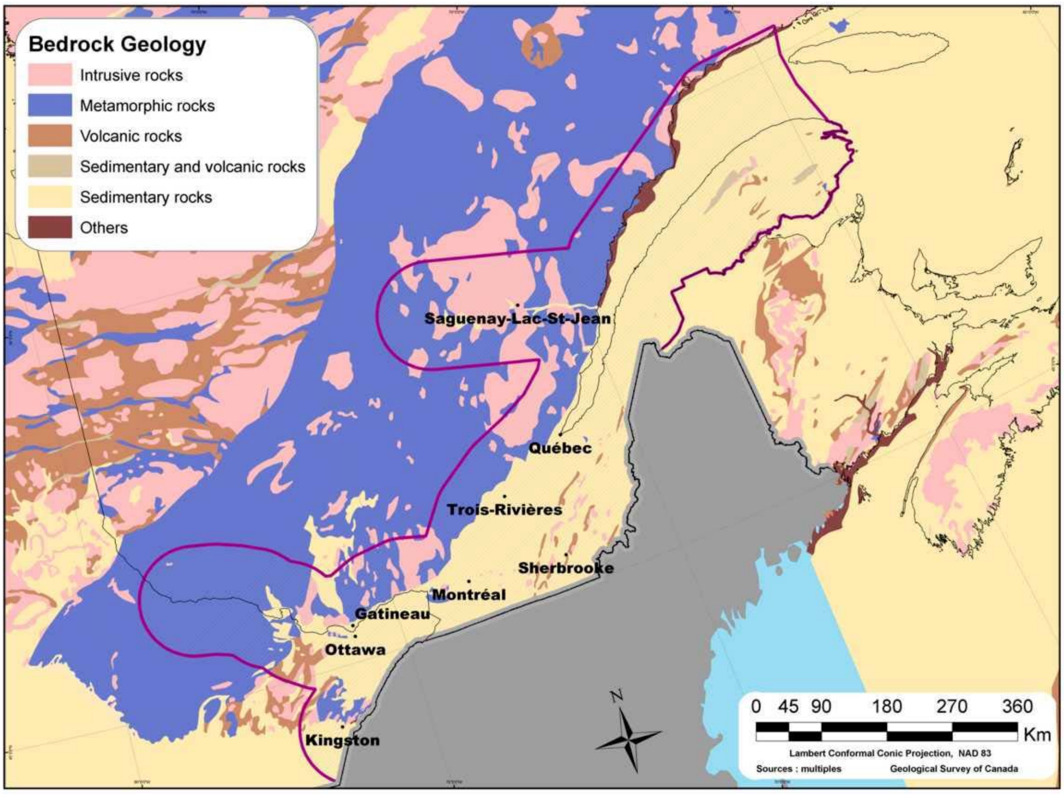

Figure 3b. Simplified bedrock geology map (After Wheeler *et al.* 1996).

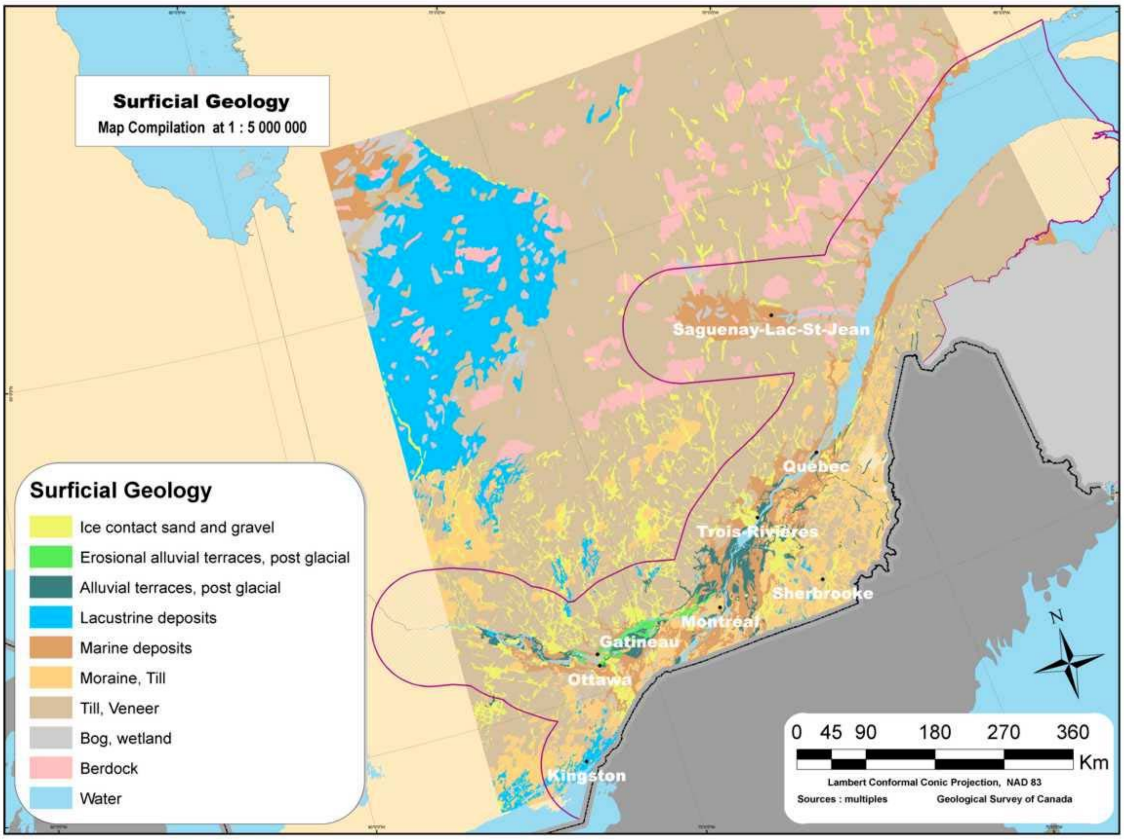

Figure 4. Surficial geology map at 1:5000000 scale (After Fulton 1995).

Natural Hazards

Earthquakes are frequent in eastern Canada (Figure 5) (Basham et al. 1979; Lamontagne & Ranalli 1997; Lamontagne 1998). Earthquakes greater than Magnitude 6 have occurred in the last three centuries (Lamontagne 2000). The origin of these seismic events are various: i) tectonism of lithospheric plates; ii) glacio-isostatic rebound following the last deglaciation; and iii) neotectonism associated to stress relief of zones weakened by, for example, meteoric impact in Charlevoix area 350 Ma ago (Rondot 1968). One of the most significative recent seismic event was the November 25, 1988 M 6 earthquake in Saguenay region (Lamontagne 2000).

The Quaternary history and the associated deposits and processes make the study area prone to mass movements. Some 90 people were killed by landslides in the area during the past 150 years (Locat & Chagnon 1989). Most of the landslides occurred in the Champlain Sea silty clay deposits, which often show sensitive clay behaviour or quick clay behaviour, especially in the clayey silt deposits on the north shore the St. Lawrence River (Quickley 1980; Torrance 1983). The most spectacular landslides in these clay deposits were the 1971 St-Jean-Vianney landslide (32 ha; Figure 6), the 1908 Notre-Dame-de-la-Salette landslide (40 ha), and 1955 Nicolet landslide ($190x10^3 m^3$) in which 31, 33 and 3 people respectively lost their lives. Rock avalanches and rock falls are probably the least frequent landslide types occurring in the study area because of the low relief. Nonetheless, between 1836 and 1839, such processes have claimed about 100 lives along the Quebec City Promontory while this city was booming (Chagnon *et al.* 1979).

The natural processes of erosion and floods are very frequent in the study area. The St. Lawrence north shore coasts are prone to coastal erosion as they are exposed to strong winds and currents (Morisset *et al.* 2004). The study area receives large amounts of precipitation (often associated with the passage of declining tropical storms), including intense spring rainfall events, which once combined with snow melt, bring a large volume of water into the ground. Floods also result from ice dams on the St. Lawrence River and its main tributaries.

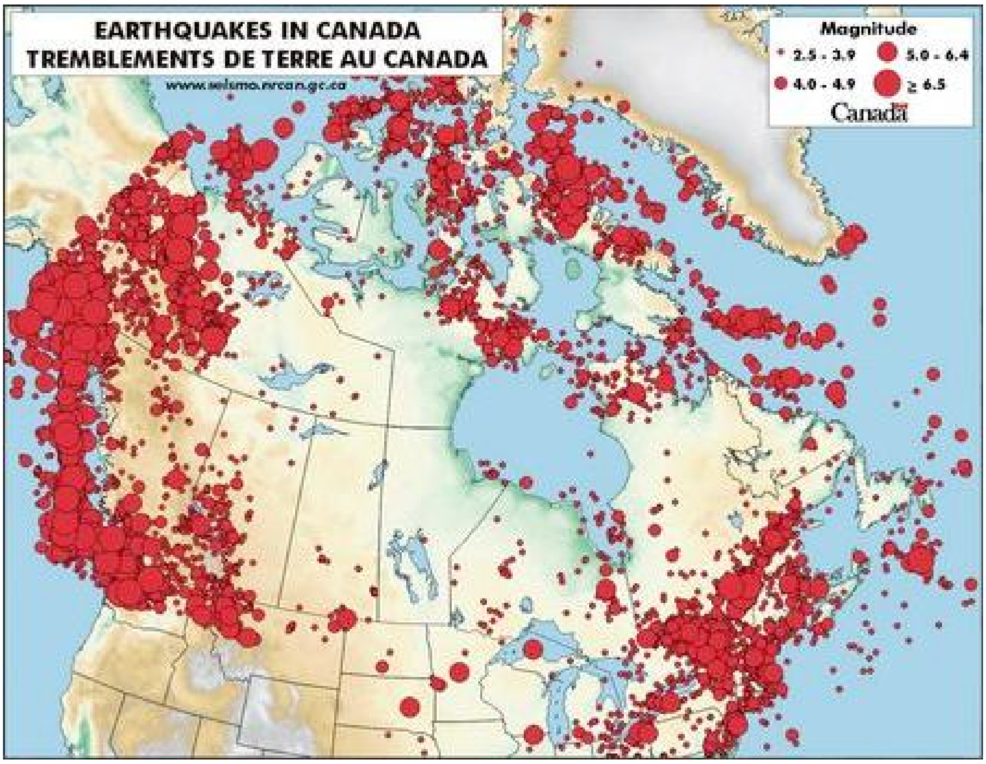

Figure 5. Earthquakes map of Canada (Source : http://www.seismo.nrcan.gc.ca/eqinfo/caneqmap_e.php).

Figure 6. Photo of the 1971 St-Jean-Vianney earthflow, Saguenay region (Source :Société Historique du Saguenay, Collection Ellefsen).

METHODOLOGY

Data acquisition and compilation

Bélanger (1998) developed a methodology of acquiring, storing and processing (manually and automatically) the data for a regional urban geology project in the Canada's National Capital Area. The same methodology has been applied by the authors to this current project in the St. Lawrence River valley. Data acquisition is one of the most important tasks within an urban geology project as the data quantity and quality strongly affect the final results and the relevant information that can be illustrated by derived mapping products. The requested data can be prioritised this way into: essential (e.g. borehole data, surficial geology, bedrock geology) and secondary (e.g. population, transportation and any other types of infrastructure).

Borehole databases

Within the framework of this project, water well databases were acquired from the Ministère du Développement Durable, de l'Environnement et des Parcs du Québec and the Ministry of Environment of Ontario. The number of water well logs acquired for this project are respectively 160000 and 28000 for Quebec and Ontario. These water wells logs contain the following information: depth, brief soil and rock stratigraphic description, water table depth, and depth of refusal. In this initial phase of the project, only the depth to bedrock was used. However, it is important to note that the stratigraphic description has to be used with caution since soil and rock description is often obtained by using crushed samples from destructive drilling techniques. Furthermore, for most of the time, the soil and rock description is not done by well-trained geologists. In addition to the water well logs, geotechnical borehole logs were obtained from public and private agencies for specific areas. For example, 100 geotechnical databases and borehole logs were provided by the Administration Portuaire de Québec and Hydro-Québec for the vicinity of Quebec City. The large portion of the borehole datasets is situated along the St. Lawrence River and the Ottawa River where urbanization has been more intense in the past fifty years (Figure 7). In total, there are 136000 entries in the main borehole database that were used to create preliminary mapping products. About 52000 data entries were rejected for the following reasons: i) wells do not go down to the bedrock; ii) several boreholes at the same locations; and iii) no stratigraphic description provided.

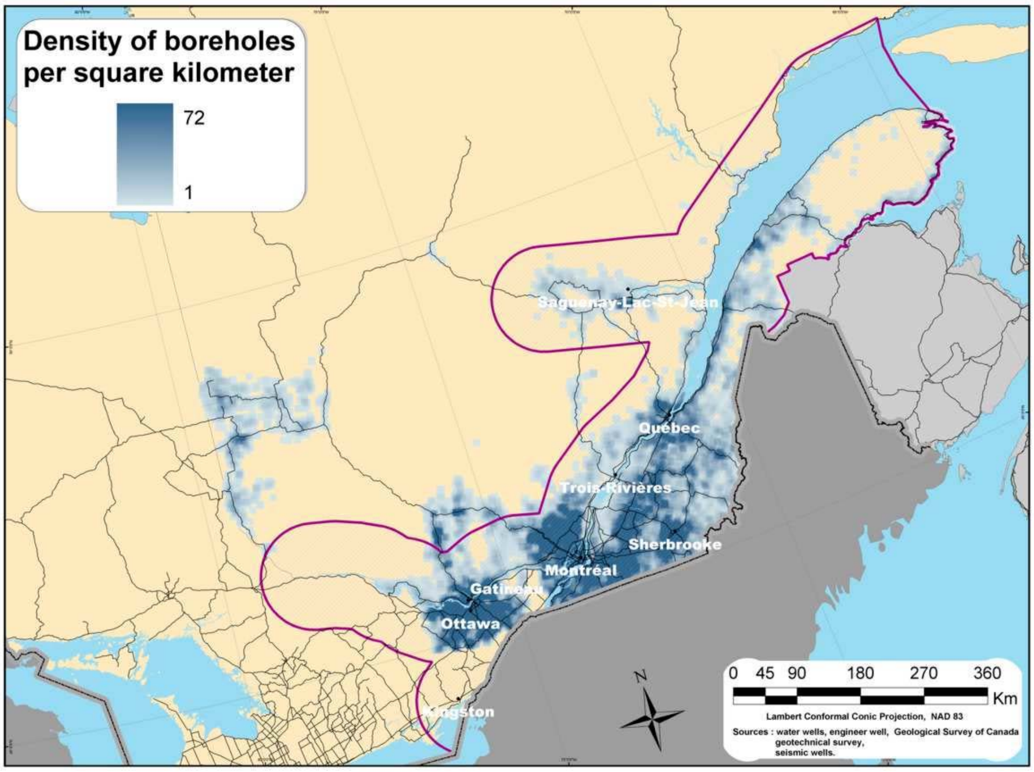

Figure 7. Boreholes density map.

The borehole databases used came in various formats such as MS Excel spreadsheets, text files, or MS ACCESS databases. A main database structure has been created to standardize the data compilation and storage. The structure was partially based on the detailed geotechnical database obtained by the Ministère des Transport du Québec. In its current format a complete set of geotechnical information can be stored for every borehole record (e.g. XY coordinate, stratigraphy, piezometric parameters, vane shear test values, etc.). The information from all these various databases was entered into the main database by Visual Basic programming through the development of a data input form. Considering the large amount of borehole data, automatic data transfer from original databases to the main database had to be programmed.

Surficial and bedrock geology

The surficial geology database consists of a compilation of existing digital surficial geology maps for Ontario and Québec produced by the Geological Survey of Canada. As the scale varies from one map to the next and no seamless map exists, a multi-scale approach had to be taken to cover the entire study. For example, the coverage of surficial maps at a scale of 1:100000 and 1:50000 is incomplete in the study area, whereas 1:1000000-scale maps cover more than 90% of the entire study area. Therefore, the integration of surficial geology maps at various scales was needed. An existing compilation map at a scale of 1:5000000 has been used for the present study (Figure 4, Fulton 1995). This dataset has been mainly used to identify the unconsolidated deposits and bedrock terrains. The latter is given a depth to bedrock equal to zero since bedrock crops out at the surface. In a subsequent data-processing phase, we envisage the integration of all the surficial geology maps available at 1:50000 and 1:100000 scale into a seamless coverage map. Additional paper maps will also be transferred into the digital format.

The bedrock geology map for the study area was obtained from the Eastern Canada geological map(s) already published by Wheeler *et al.* (1996). No special data compilation was been performed on the bedrock geology data yet. This dataset will be used in subsequent development phase of the 3D model.

Data processing

A methodology has been developed to continually update the main borehole and surficial geology database. Figure 8 shows a flow chart that lists the various actions related to data cleaning, structuring and formatting processes. The first step is to list and compile all the borehole databases and maps available for the study area. At this stage, partnership is developed with data providers and data sharing agreements are implemented. The data collection can be divided into two types of information: i) surficial geology (planimetric) and ii) borehole information (3rd dimension). The structuring and cleaning processes are different from one to the other. For the boreholes data, the cleaning process involves many steps. The first step is to create a MS ACCESS database into which the raw data is imported. Because of the heterogeneity of the data, custom programming has to be made to correctly input data. Once the data input is completed, a first cleaning phase can be performed using SQL commands. For example, our primary goal was to determine the depth to bedrock in the study area. In order to achieve this, all the boreholes that do not contain any information on bedrock and bedrock depth are deleted. At the end of this first cleaning phase, only the boreholes going down to bedrock remain in the database. The next step is to transfer this data into the main database and to create a boreholes location map. Duplicate information can be found at the same borehole location because, for example, of the merging of databases, and therefore some deletion has to be carried out by the GIS specialist in consultation with the geoscience expert to keep the relevant data in the database. Although time consuming, this second cleaning step is crucial in maintaining a good quality database. Thus a new boreholes location map can be created and used for data interpolation.

The integrating process of surficial geology maps is less complicated. The first step is to inventory all the surficial geology maps available (at any scale), compile them, transfer the non digital maps into numerical format, and integrate them into a GIS platform to obtain one uniform map. Maps available in hard copy have to be digitized and transfered to numerical format. Maps already available in numerical format have to be converted into the software-specific format in order to be merged and used in the GIS platform (ESRI's ARCGIS). For the St. Lawrence Valley case study, the spatial integration has been done through by "GIS edge-matching" techniques. The surficial geology coverage is not continuous in the study area. This is because several maps are still in paper format and have not been digitised, and because surficial geology mapping was carried out using different geological classifications. The surficial geology classification has changed over the years and, for example, two adjacent maps can have the same spatial boundaries for a specific polygon but may have two different geology classifications.

PRELIMINARY RESULTS

Deposits thickness map

Various thematic derived products can be extracted and created from the GIS database. Specific maps or graphics derived from integrated information, such as the locations of landslide areas, or sources of granular materials can easily be produced (Bélanger 1998).

Another method of producing derived maps is by the Inverse Distance Weight interpolating method between point data. An example of such a product is the unconsolidated deposits thickness map as shown in Figure 9. This map was created using an interpolation map of the depth of surficial material (from borehole database) and the surficial geology map covering the study area. The thickness of unconsolidated deposits at each site was calculated and thickness values were interpolated between sites. Such a map is for the first time presented for the St. Lawrence River valley.

As expected, thicker surficial deposits are found above the bedrock platform in the central part of the study area along the St. Lawrence River valley (Figure 9). The deposits thickness map shows very thick areas of unconsolidated sediments ranging up to more than 100 metres, or even 160 m at some locations (e.g. near Trois-Rivières). Locally, smaller areas of thick unconsolidated deposits (50-75 metres) can be observed west of Montreal and on the north shore of the Lac St. Jean. In the St. Lawrence River and Ottawa River valleys, the thickness of deposits varies in general between 10 to 50 metres.

The surficial deposits are generally less than 10 m thick in the surrounding Appalachian and Canadian Shield regions. This is in accordance with previous works (e.g. Occhietti 1989).

Similar derived unconsolidated sediment thickness maps were published for much smaller areas within the study area (Bélanger 1998), but this is the first time that such a regional thickness map has been published for the St. Lawrence River valley and its adjacent valleys.

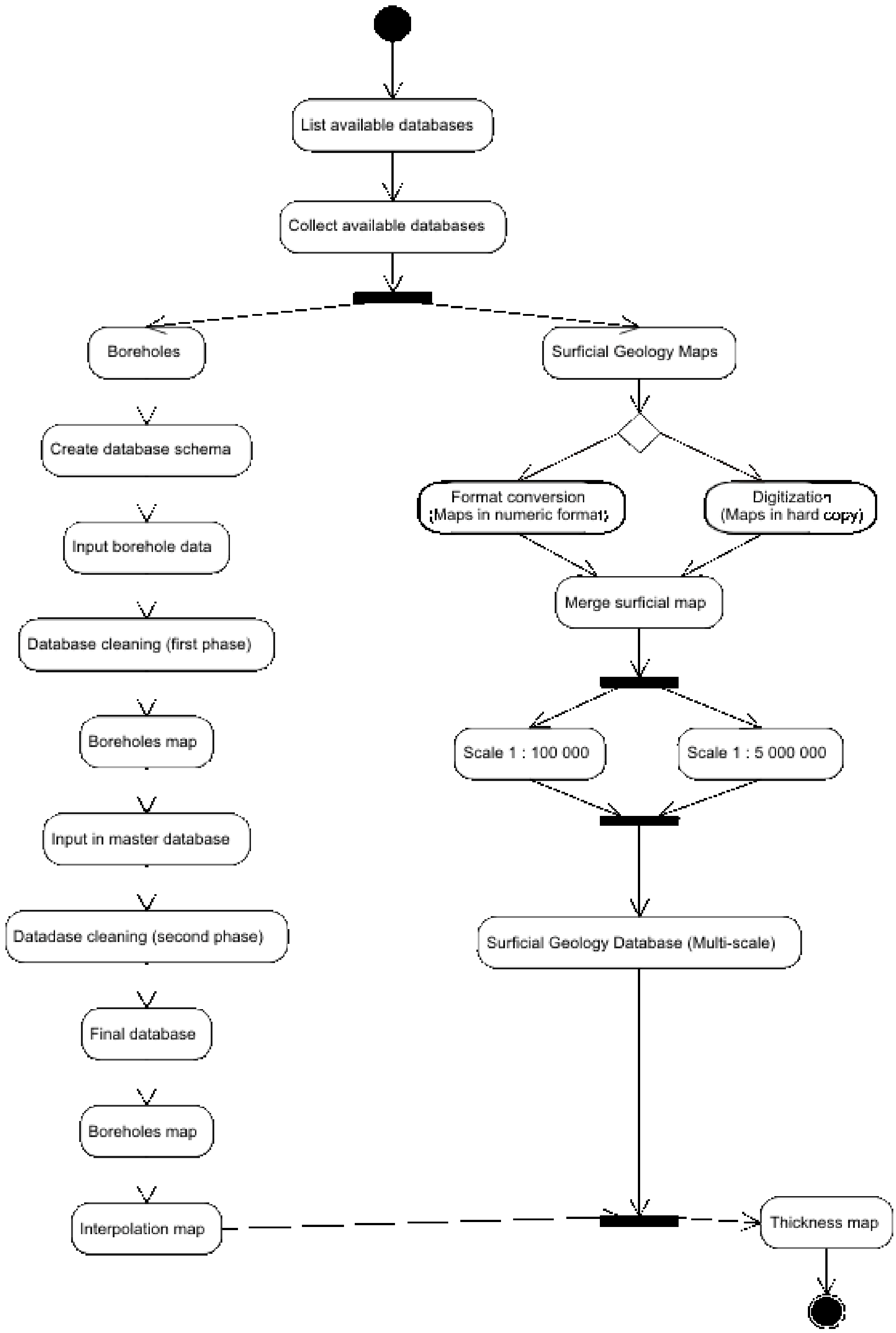

Figure 8. Data analysis flow chart.

Other products

Using various GIS applications, other derived mapping products can be obtained from the databases. An example is stratigraphic sections, i.e. cross-sections along a terrain segment in which a geological model is developed. Other types of derived mapping products include 3D models, bedrock topography (by interpolating the depth of unconsolidated sediments down to the bedrock) and bedrock aquifers by combining the bedrock topography, the faulting system, and the rock porosity values.

DISCUSSION

Integrating the data

The use of GIS permits the integration of various types and sources of information to produce derived mapping products and 3-D geological models. It also goes beyond statistical analysis by integrating geographical parameters, such as stratigraphy, spatial distribution of geological formations and geotechnical parameters, to produce models closer to reality (Bélanger 1998). However, it is very challenging to produce a stratigraphy of an area with data coming from various sources and different formats. These include point data (e.g. water wells, geotechnical boreholes), polygon data (e.g. surficial geology formations), and contour or interpolated lines (e.g. surface elevation, bedrock topography).

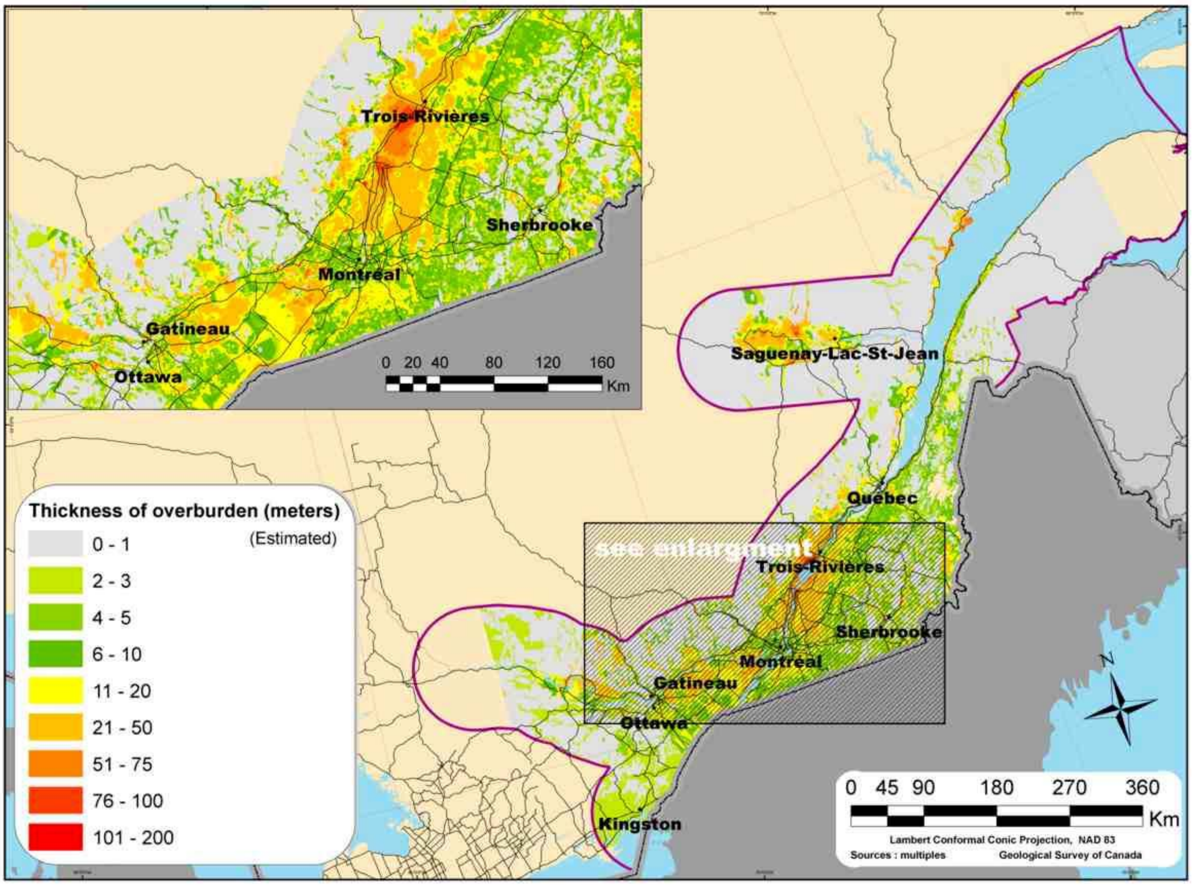

Figure 9. Unconsolidated deposits thickness map.

Two main difficulties are encountered when integrating data from various sources. The first difficulty is the method used to describe surficial material. As this project shows, the description of the same material differs according to the purpose of the source document and on the training of people describing the material. For example, engineers, geologists and well drillers have their own way of describing the same material. For drillers, the drilling equipment is an important limiting factor, as the equipment does not provide adequate samples to identify complex materials. Engineers may describe the material according to its geotechnical properties as opposed to geologists who describe materials according to their composition and origin. Therefore, it is often useful, if not essential, that at least one common field in databases links the various material descriptions, for example the grain size distribution. Another example is the fact that no seamless surficial geology map is available for the study area. In the future, it will be difficult to integrate the maps because they are at various scales, were published at different times, have different classifications, symbology and legends. (e.g. feet *versus* meters; 1:30000 *versus* 1:1000000 etc).

A second difficulty comes from the nature of the original dataset or document. For example, the surficial geology maps used in our study provided a relative accurate geographic extent of deposits but did not provide local minor variations. For large-scale study (1:50000 and greater), boundaries between different units are often not precisely defined, whereas to the contrary, borehole logs provide a stratigraphy at a very precise location without taking into consideration the surrounding deposits (Bélanger 1998).

Combining surficial geology maps and borehole data cannot be done automatically. The two types of data can give different interpretations of the surficial deposits at the same location. The judgment of the geoscientist is then required to correctly interpret the stratigraphy and to reach a certain form of standardization or agreement in the data.

Deposits thickness map

About 72% of the 188 000 borehole logs used to create the unconsolidated sediments thickness map are water wells. As explained above, the quality of this dataset can vary considerably from one to the next. Caution must be taken in using this preliminary deposits thickness map since it is more reliable where there is a high density of data (Figure 7); in areas of sparse data the map is less reliable. Nevertheless, the spatial distribution of these boreholes is more than acceptable. The 136000 boreholes are widely distributed within the study zone, at least within inhabited zones (see Figure 2) where deposits thickness maps are meaningful. However, some critical zones are lacking data, such as the area between Ottawa and Montreal on the south shore of the Ottawa River and in the vicinity of Trois-Rivières. The zones of thick unconsolidated deposits are critical with respect to regional mapping of ground susceptibility to earthquake disturbance. Work by Aysworth *et al.* (2003) and Hunter *et al.* (2003) in the Ottawa River valley showed that localised zones of thick Champlain Sea unconsolidated sediments can be associated with strongly disturbed clay deposits and the presence of numerous landslides probably due to the local shear wave amplification during large seismic events. For example, slope failures were observed in the Trois-Rivières region following the 1988 M6 earthquake in Saguenay, where the epicentre was situated more than 300 km east of Trois-Rivières. Once combined with peak horizontal ground acceleration and peak horizontal ground velocity maps, deposits thickness maps can be used to assess the regional potential ground disturbance susceptibility. In the same way, it can be used for landslide hazards susceptibility mapping.

CONCLUSION

This paper summarizes the initial phase toward the development of a 3-D geological model and a seamless surficial geology map of the St. Lawrence River valley in Eastern Canada. It is achieved by gathering, validating, and integrating existing geological and geotechnical data through a geographic information system and the associated geodatabase. It briefly presents the preliminary results from the development of a 3-D geological model of unconsolidated sediments in the St. Lawrence Valley, based on a digital elevation model, surficial geology map and subsurface information. For the first time a preliminary map of the thickness of unconsolidated sediments in the St. Lawrence Valley is presented. The deposits thickness map shows areas of very thick unconsolidated sediments that are greater than 160 m thick in some locations. Such a map, in combination with seismic parameters and landslide hazards maps, can be used as a tool for a better land-use planning and management. Difficulties were encountered in integrating various sources and types of datasets. Finally, better quality point, polygon and interpolated data (e.g. detailed geotechnical borehole logs and ground studies) are necessary in order to have a complete coverage of the St. Lawrence River valley and its adjacent valleys, as well as to validate the current borehole information.

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