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CONTEXT

This guidebook was originally prepared for a fieldtrip that was organised and presented jointly by the Geological Survey of Canada and the Institut national de la recherche scientifique (INRS) during the GeoMontreal2013 Conference. The conference was the 11th Joint Meeting of Canadian Geotechnical Society (CGS) and the Canadian National Chapter of the International Association of Hydrogeologists (IAH-CNC) held in Montreal from September 29 to October 3, 2013. This version of the guidebook has been slightly adapted from the original to make it a more useful reference document and to incorporate minor editorial changes.

The objective of the fieldtrip was to present the results of a regional hydrogeological project, for which most of the work had been completed in March 2013. The study area extends over ~9000 km^2 in southern Quebec, and includes the watersheds of the Richelieu and Yamaksa rivers, and the watershed of Missisquoi Bay on Lake Champlain.

Each fieldtrip stop was strategically selected in order to discuss features of the five hydrogeological contexts defined for the project to better describe and understand the regional aquifer system. Because of time and distance constraints, only five stops were planned. Material presented to the participants included conceptual models for geology, as well as quantitative and qualitative hydrogeology, geological cross sections and several figures drawn from the final project report and the hydrogeological atlas of the project, all printed in poster format to facilitate the explanation and description of the hydrogeological system to participants. Given the context of the project and the informal nature of the fieldtrip, several figures contain legends and text in French.

On the morning of October 3rd, 2014, the bus left downtown Montreal on a sunny warm day, perfect for a fieldtrip, with fifteen participants from Canada, the United States and Brazil. Some of the photos taken during the fieldtrip are presented in the Appendix.

We wish to thank the GeoMontreal2013 conference organising committee, especially Dr. Marie Larocque, for inviting us to organise the fieldtrip.

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1. Introduction

Aquifers of the Richelieu/Lake Champlain and Yamaska watersheds were recently characterised in the course of a regional groundwater assessment (Carrier et al., 2013a and 2013b). The project, a joint INRS[1] / GSC[2] / OBV Yamaska[3] / IRDA[4] collaboration, was conducted as part of both the "National Groundwater Inventory" of the GSC Groundwater Mapping Program and the "Programme d'acquisition de connaissances sur les eaux souterraines du Québec" (PACES), which is funded by the Department of Environment of Quebec and aims to assess groundwater resources of populated regions of Québec. The project began in April 2009 and ran until March 2013. The current year (2013-2014) is devoted to scientific publications and to the completion of Ph.D. theses.

The project objective was the development of an efficient integrated and multidisciplinary characterisation approach using geological, geophysical, geochemical and hydraulic methods. The study area of 9000 km^2 in Quebec, extends from the St. Lawrence River southward into northern Vermont and New York (Figure 1). In Quebec the regional population is 577 000 inhabitants, of which about ~20% use groundwater as a water supply. In municipalities of less than 5000 inhabitants, however, this percentage reaches 58%. The poor quality of surface water in this rural area was well known prior to the project, but little information was available on the quality of groundwater. One M.Sc. thesis (Beaudry, 2013) dealt with regional hydrogeochemistry, and another (Thériault, 2013) studied the cycling of nitrogen in two small agricultural watersheds representative of the study area.

The St. Lawrence Platform underlies much of the western half of the study area and its elevation is below about 60 m (Figure 2). The Appalachians underlie the eastern part of the region, with elevations up to 800 m, but these uplands typically lie at elevations of 200 to 300 m. The seven Monteregian Hills, which are aligned along an east-west axis roughly across the middle of the study area, have maximum elevations varying between 210 and 540 m.

The region is characterised by a cold humid continental climate. Total annual precipitation in the region varies from 955 to 1275 mm, 20 to 25% of which occurs as snow. Mean annual temperature ranges from 4.3 to 6.7 °C, the coldest month being January (with mean temperature between -9 and -12 °C) and the warmest being July (19 to 21 °C). Precipitation is slighter higher (+170 mm/y) and temperature slightly colder (-0.6 °C) in the Appalachians than in the St. Lawrence lowlands. Evapotranspiration is estimated to range from 530 to 600 mm/y (Carrier et al., 2013a).

For the Quebec portion, existing data (mainly from the provincial databases and consultants reports) were supplemented with targeted fieldwork, which included seismic reflection profiling, TDEM surveys, drilling into bedrock, borehole geophysics, CPT/SMR soundings

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and sonic drilling in Quaternary sediments, water and soil sampling and hydraulic testing. Due to budget constraints, fieldwork was not carried out in the U.S. portion of the study area.

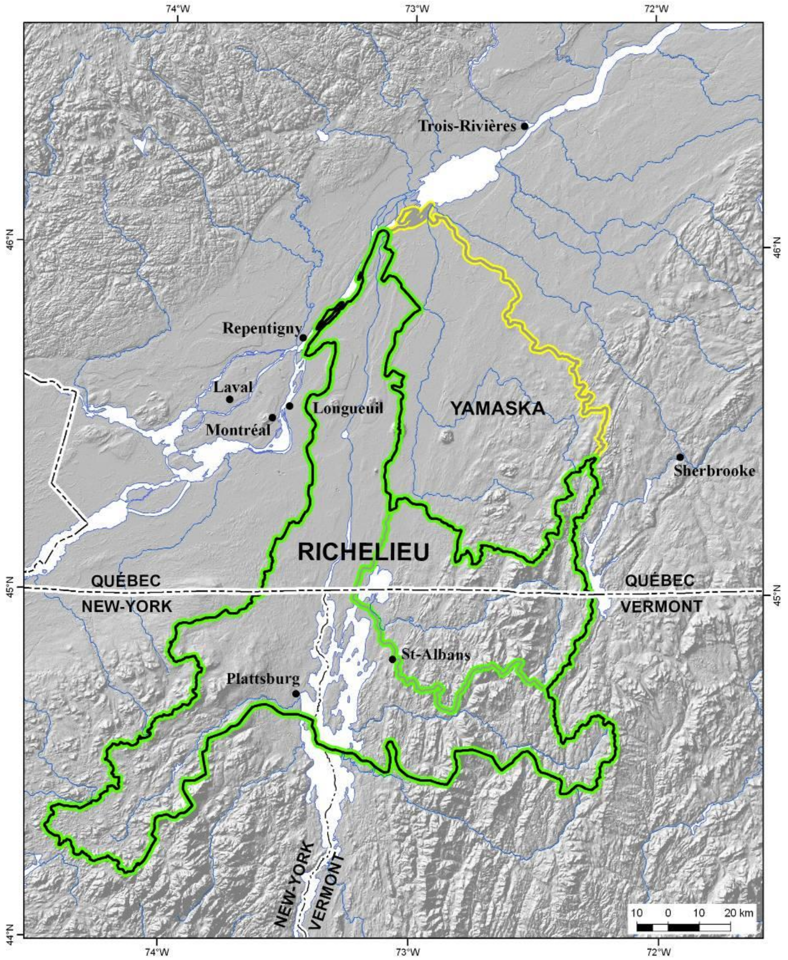


Figure 1: Location of the study area. Richelieu / northern Lake Champlain basin (4000 km^2 in Québec and 7500 km^2 in the US) and Yamaska basin (4800 km^2). Only the Canadian side has been extensively characterised by our workgroup, hence the focus of this fieldtrip.

For this fieldtrip, five stops were selected in Quebec in order to discuss features of the different hydrogeological contexts that were defined within the framework of the project to better describe and understand the hydrogeological system. They are presented in Figure 2.

The analysis and interpretation of new and archival data allowed us to better understand the groundwater flow dynamics of this aquifer system, to delineate and characterise the main hydrogeological contexts, to quantify regional recharge, to assess the hydrogeological and hydrogeochemical properties of the different geological units and to characterise regional fracture patterns. At the end of the project, three M.Sc. and two Ph.D. theses will have been completed.

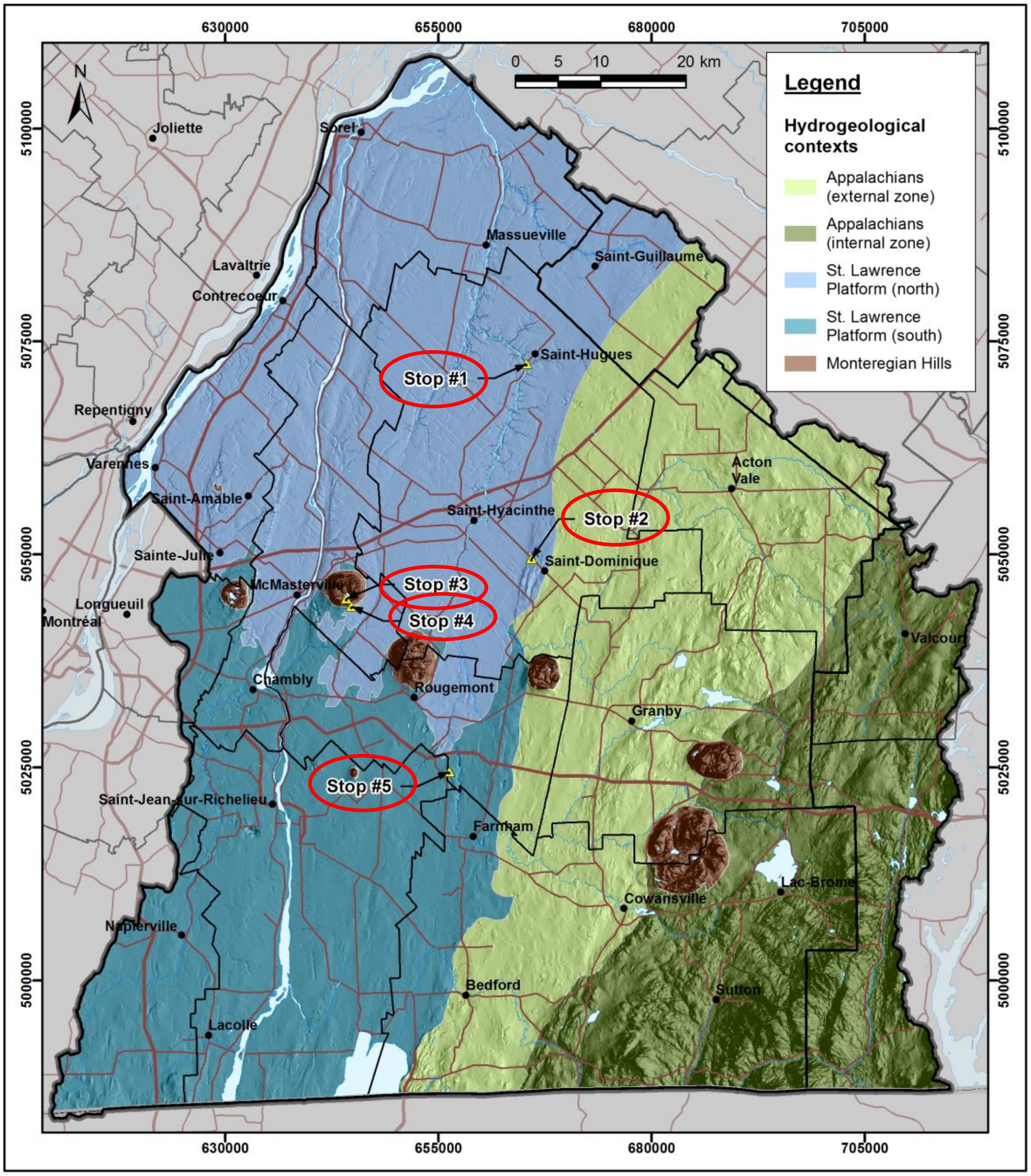


Figure 2: Location of the five stops selected for the 1-day fieldtrip in Montérégie Est. Background colours correspond to the five hydrogeological contexts (see section 3).

2. General bedrock and Quaternary geological contexts

Four geological contexts were defined in the study area (Figure 3). The **Adirondack Mountains** are composed of crystalline rocks, which are the oldest rocks of the study area (Archeozoic/Protozoic to Pre-Hadrynian) and consist of metamorphic and intrusive rocks (gneiss, migmatite, gabbro, anorthosite and syenite). The **St. Lawrence Platform** is underlain by flat-lying sedimentary rocks of Cambrian and Ordovician age. They mainly consist of red and black shale, dolostone and limestone. The platform unconformably overlies igneous and metamorphic rocks of the Grenville Province (Precambrian basement). In the study area, **Appalachian** rocks, also Cambro-Ordovician in age, mainly consist of deformed low-grade metasedimentary rocks (sandstone, mudstone, limestone) but also include a few volcanic rock units. These rocks were intensely deformed, faulted and fractured during the Taconian and Acadian orogenies. The Appalachians are composed of two zones: the External zone (corresponding to the Piedmont physiographic region) and the Internal zone (corresponding to the Uplands physiographic region). Rocks of the External zone in Quebec are slightly less metamorphosed than those of the Internal zone. Logan's Line, a major fault zone, separates the St. Lawrence Platform from the Appalachians. **Late-stage intrusives** in Quebec are mainly Cretaceous alkaline intrusives of the Monteregian Hills. Contact metamorphic aureoles (hornfels) surround these intrusives and associated dykes and sills have been observed locally. Although these late intrusives do not constitute a geological context that is as important as the Platform and the Appalachians, they are, nonetheless, considered separately since they show distinctive characteristics compared to the other contexts and because they play a distinct and key role in the regional hydrogeology of this study area.

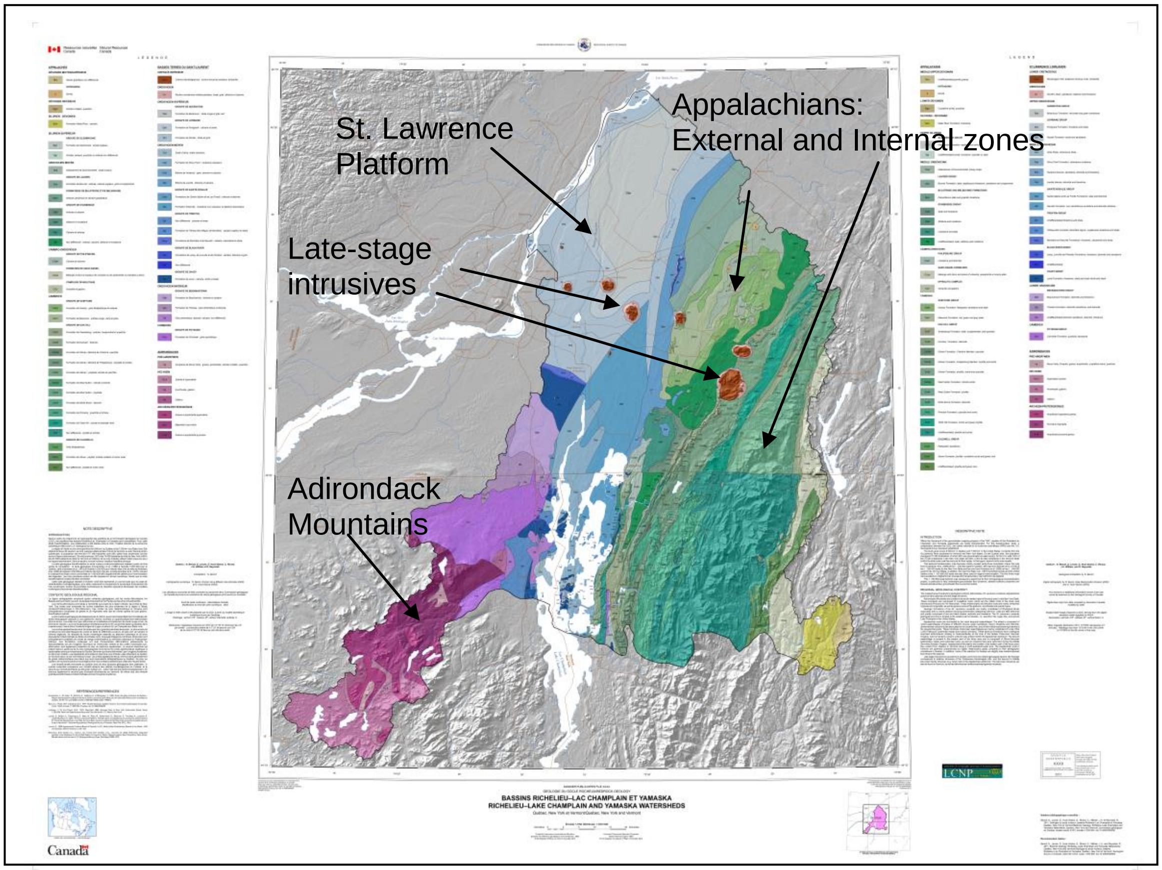


Figure 3: Canada/U.S. bedrock map at the 1: 250,000 scale (Benoit et al., 2013).

The surficial geology map presented in Figure 4 is a generalized version of the 1:50 000 maps prepared by Dubé-Loubert et al. (2014). As shown in Figure 4, till is the most extensive Quaternary unit in the study area. In the northern part of the **St. Lawrence Lowlands**, the regional till is generally covered by a 20 to 30 m thick blanket of marine muds that were deposited in the Champlain Sea, an arm of the Atlantic Ocean that inundated the isostatically depressed St. Lawrence valley up to almost 200 m ASL for almost 2 000 years at the close of the last deglaciation. The marine unit locally overlies fine-grained varves that had been deposited during the preceding Glacial Lake Candona episode (Figure 5) (Parent and Occhietti, 1988 and 1999). Lake Candona shorelines lie about 40 to 60 m above Champlain Sea shorelines and have been observed on the Appalachian Piedmont and valleys as well as in the Lake Champlain and Upper St. Lawrence valleys. In the southern part of the lowlands, the marine clay unit is thinner and much more discontinuous. Here, except in local mud-filled bedrock lows, the surficial units are relatively thin (< 10 m) and consist of a mosaic of wave-reworked till and littoral sands and gravels. Regionally, the marine muds grade upward into freshwater muds that were deposited in Lake Lampsilis (Figure 5), a body of freshwater water that replaced marine waters as relative sea level fell below about 60 m in the Québec City region. Continued uplift led to further emergence and to the deposition of a discontinuous blanket of alluvial sands by the Proto-St. Lawrence River. This offlap fluvial unit increases in thickness near the modern St. Lawrence River and Lake St-Pierre.

In the **External zone (Appalachian Piedmont)**, the Quaternary sediment cover is thin and rock outcrops are quite common. The top 1 to 2 meters of the surface till was vigorously reworked and winnowed by waves and currents of the Champlain Sea and is therefore coarser and more permeable than the underlying compact till. Littoral sands and gravels along with reworked tills are the most widespread surficial unit of the Piedmont. Champlain Sea muds are restricted to the main valleys, such as the Yamaska and Rivière Noire valleys. In the **Internal zone (Appalachian Uplands)**, the till cover is generally thin and discontinuous on topographic highs and rock outcrops are abundant. In mountainous terrains, such as in the Sutton Hills, coarser melt-out tills commonly cover bedrock and compact basal till. Glaciofluvial sands and gravels occur almost exclusively in valleys where glacial meltwaters were concentrated. Glaciolacustrine sediments, including varved silt and littoral/deltaic sand, are common in the main Appalachian valleys (e.g., Upper Missisquoi and Sutton).

To graphically portray the surficial stratigraphy, a schematic cross-section is presented (Figure 5) for the northern part of the Richelieu-Yamaska region that extends from the St. Lawrence River to the Appalachian uplands. In addition to the distribution of Champlain Sea and post-Champlain Sea sediments, the cross-section presents a schematic view of the architecture of the underlying glacial and non-glacial sediments. Archival well data together with new borehole data and multiple CPT soundings show a nearly continuous, though sometimes thin, till sheet. A cored borehole (RS-02) has intersected a lower thick till overlain by subaqueous outwash sand, then by thin till. A similar stratigraphic context can also be observed near St-Césaire at Stop #5. Borehole RS-04 of the project intersected plant-bearing alluvial sands between two till units. Selected plant debris from the alluvial sand were dated at 31 270 ± 200 years BP (Beta-343397). This alluvial unit thus predates the last glacial maximum but appears as significantly younger than the classical St-Pierre Sediments that are older than 65 000 years BP (Gadd, 1971; Lamothe, 1989; Occhietti, 1990).

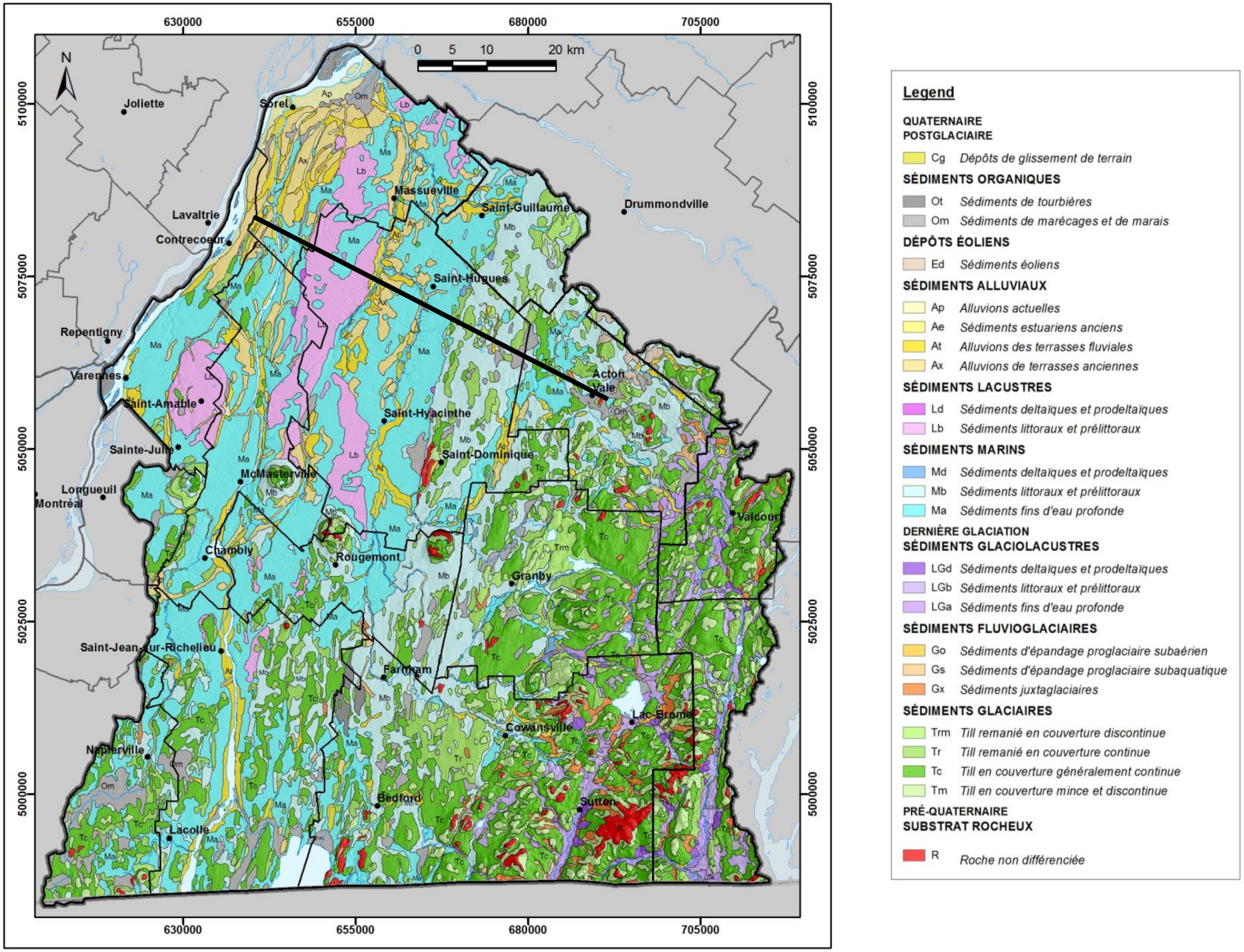


Figure 4: Surficial geology map (generalized at a scale of 1:500 000 from detailed 1:50 000 map sheets) (Carrier et al., 2013b). Approximate location of the schematic cross-section of Figure 5 is shown by a black line.

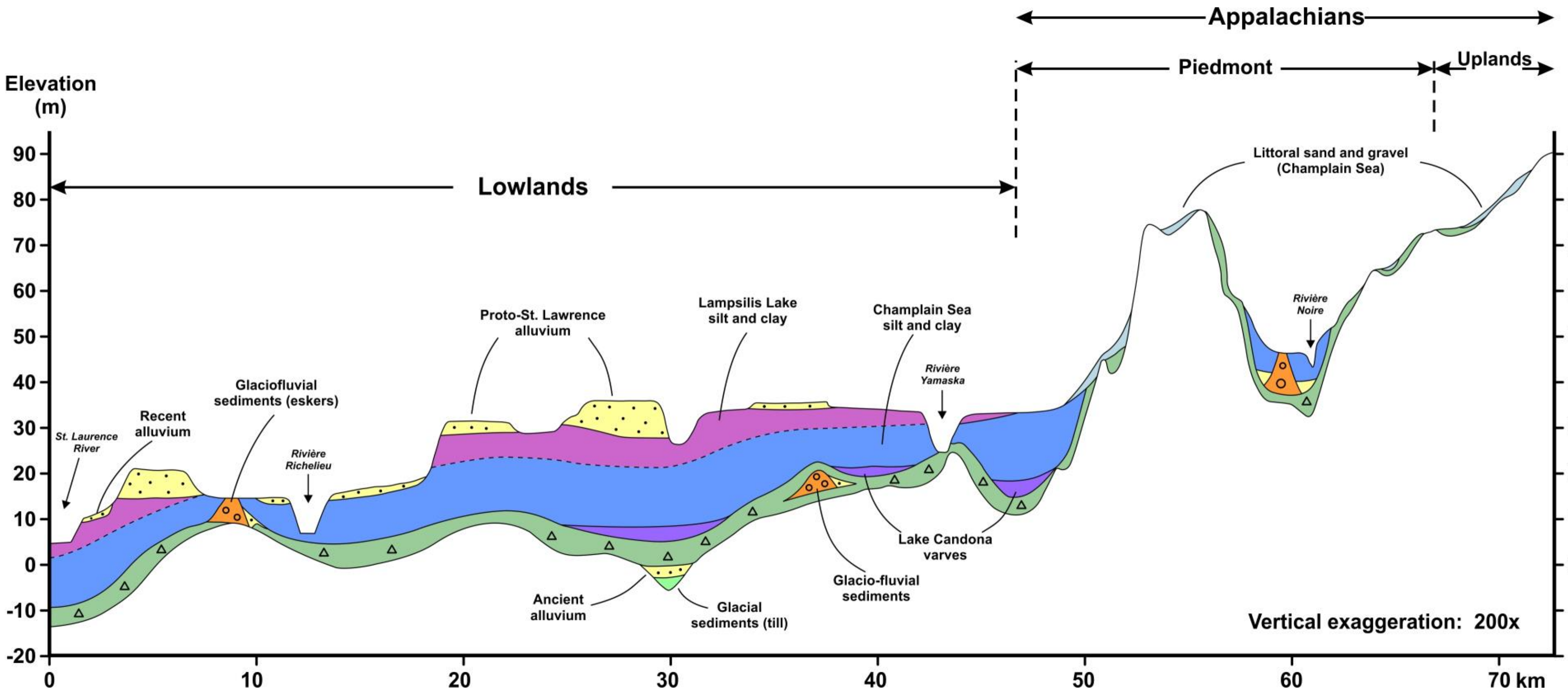


Figure 5: Schematic cross-section showing representative Quaternary units in the northern part of the study area.

3. Characteristics of the five hydrogeological contexts

Five hydrogeological contexts were defined for the Canadian part of the study area (Figure 6). The Appalachians were subdivided in two zones: the **External zone (Piedmont)** and the **Internal zone (Uplands)**, mainly on the basis of regional bedrock geology, but this limit also generally corresponds to the marine limit (highest shorelines of the Champlain Sea), which lies near the contact of the Piedmont and Uplands.

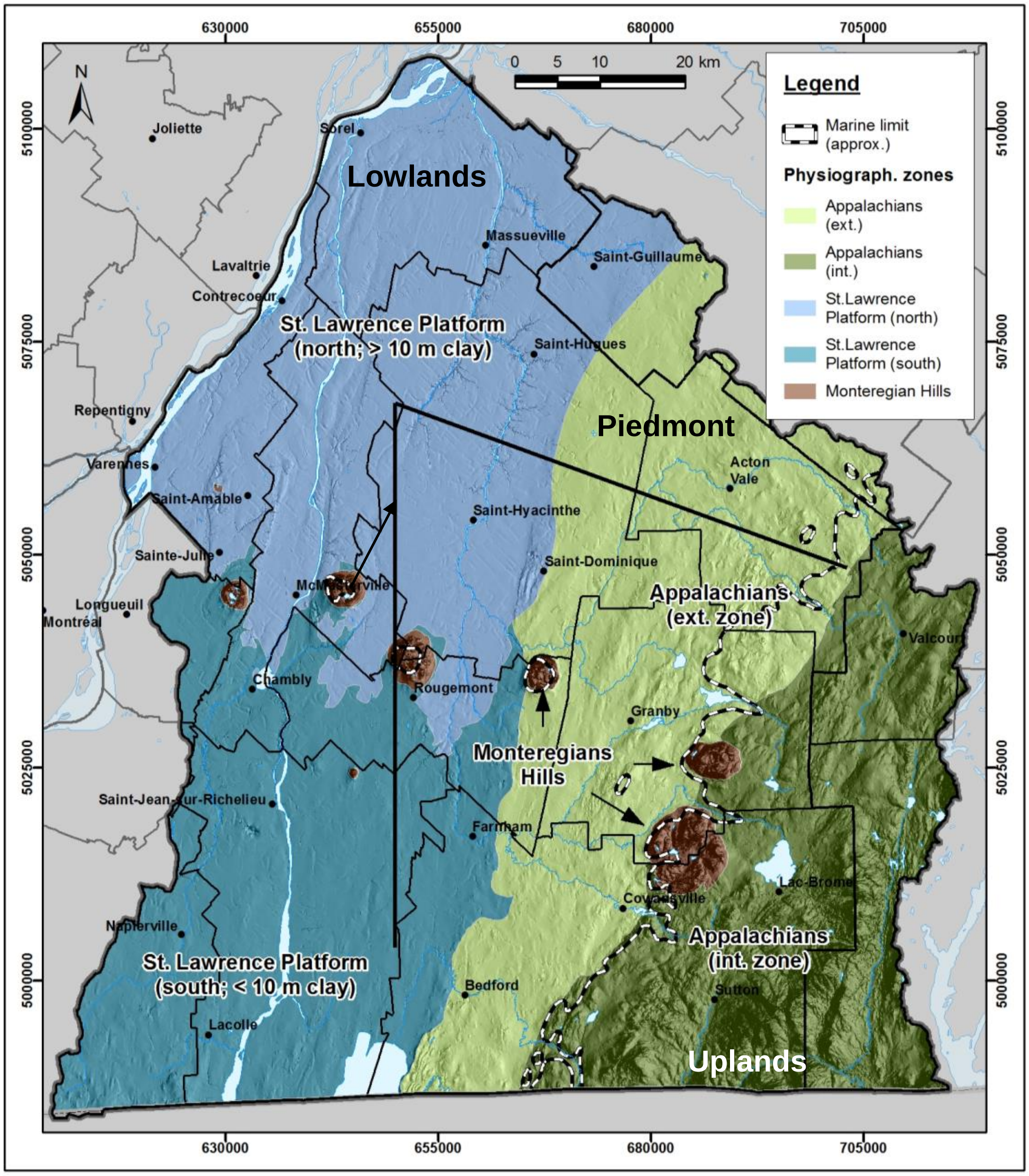


Figure 6: Hydrogeological contexts of the Montérégie Est area. Location of the two conceptual model cross-sections is also indicated (Figures 12-13-14 and 20-21-22). The marine limit is shown by the dashed line. Areas lying to left side of the limit were submerged by the Champlain Sea from about ~11 200 years BP until about 9 800 years BP.

The **St. Lawrence Platform** was subdivided in two hydrogeological contexts. The **Northern Platform** lies north of the Monteregian Hills and is characterised by a thick and continuous cover of low permeability marine clay that prevents recharge to the underlying aquifers. The **Southern Platform** lies south of the Monteregian Hills and is characterised by a relatively thin (<10 m) cover of relatively permeable Quaternary sediments consisting mainly of reworked till and littoral sand. The **Monteregian Hills** constitute the fifth hydrogeological context; these prominent intrusive bodies cut across the Platform and Appalachians.

In these five hydrogeological contexts, fractured rock is the main aquifer and, therefore, most of the water supply wells in the study area are completed in bedrock. Hydraulic conductivities (K) vary mostly between 10^{-7} and $5x10^{-5}$ m/s. It was found that K throughout the different hydrogeological contexts varies more with depth within bedrock than with lithology (Laurencelle et al., 2011). Indeed, spatial variations of hydraulic conductivities (K) of the various geological formations are not statistically significant. The interpretation of pumping tests also suggested equivalent porous media behaviour (Carrier et al., 2013a). Glaciofluvial sediments can also have good aquifer potential, but their areal extent is very limited; they are mainly located in Appalachian valleys and south of Monteregian Hills (see Figure 5). Several municipalities in Montérégie Est are concerned with their water supply and require increased capacity, but finding high-yield wells has proven difficult. Typical yields are < 1 L/s and wells with large pumping rates are seldom found. Municipal bedrock supply wells of this area have an average yield of 3.8 L/s, with a maximum of 12.7 L/s, whereas municipal wells completed within Quaternary sediments can reach a yield of 19.0 L/s (Carrier et al., 2013a).

Potentiometric contours are mainly controlled by topography: groundwater flows from the Uplands towards the Piedmont. However, our data show that the Yamaska River acts as a major discharge zone (see discussion in Stop #3). Both the geochemical study and modelling with HELP, a 1-D infiltration model, indicate that recharge occurs mainly around Monteregian Hills, as well as through part of the **External zone (Piedmont)** and in the southern part of the **Platform**. Groundwater depth in the region is usually close to the surface (on average from 2 to 4 m), except in the Monteregian Hills, where it is 30 m deep on average.

Groundwater samples from 242 wells, with 206 in bedrock, were analyzed for conventional parameters. Isotopic analyses were done on selected samples, including stable isotopes (δ^2H, $\delta^{18}O$, $\delta^{13}C$) and radioactive isotopes (^{14}C and ^3H) for groundwater dating purposes. For this project, groundwater types were geochemically classified in 8 groups defined by PCA (principal component analysis) using 16 parameters and more conventional graphical analysis (Beaudry, 2013). This analysis allowed us to improve the understanding of the groundwater evolution from recharge zones to discharge zones. From this work, three different zones of groundwater quality were also defined: "non-potable", "fair" and "acceptable" (see Figure 7). The "non-potable" area corresponds to the brackish groundwater zone, in the north-western part of the region. The "fair" water area is mostly located in the southern part of the St. Lawrence Platform and in the northern part of the External zone (Piedmont), within the limits of Champlain Sea submergence. This water quality is the result of various leaching mechanisms; it exceeds drinking water limits or recommendations for Ba, F and TDS, with pH being also often quite elevated. The "acceptable" zone is mainly located in the Internal zone (Appalachian Uplands), where almost none of the parameters exceed drinking water limits. Nonetheless, iron, manganese and hydrogen sulphides often exceed aesthetical criteria, as in many wells throughout the study area. Results from both the regional geochemical study and the local study on nitrogen cycling show that very little nitrate is found in groundwater within bedrock, despite the fact that this region is intensely farmed. No wells exceeded the drinking water quality standards for nitrate concentrations (10 mg/L of NO3-N) in the bedrock aquifer. This is likely attributable to two mechanisms: subsurface runoff due the presence of fine-grained soils and compact tills close to the surface and artificial drainage by widespread drain pipes towards streams. Significantly, groundwater in the study area is rarely “young” (less than 60 years old, i.e. the period of large-scale industrial fertilization) and therefore may not have been impacted yet.

Vulnerability to surface contamination was estimated with the commonly used DRASTIC index (Aller et al., 1987), which utilizes the sum of seven (quantitative or qualitative) parameters and associated weights that were defined according to their presumed importance in a contamination process from a surface source. The higher the estimate, the more vulnerable the aquifer is. A vulnerability estimate below 100 is generally considered low, while above 150, it is considered high. In Figure 8, the relative vulnerability is presented using relative classes adapted to the region. Vulnerability is, in this region, mainly controlled by the nature of the Quaternary sediment cover and, thus, by the nature of aquifer confinement. Therefore, aquifers are more vulnerable where the silt and clay layer is thin or absent, as in the Piedmont and southern lowlands. The mean vulnerability for the entire region is 124, which corresponds to a moderate vulnerability, and variability for a given hydrogeological context is not that large (from 94 in the northern platform, the lowest due to the confinement layer, to 141 in the External zone (Piedmont)). In the Internal zone (Appalachian Uplands), steep slopes and lower groundwater depth result in low to moderate vulnerability indices. One of the Ph.D. students is currently working on a methodology to define aquifer confinement, and thus hydrogeological contexts, around a well on the basis of well hydrograph responses.

Another Ph.D. student is currently working on historical modelling to simulate past and present hydrogeological conditions, taking into account the main historical events of the last glacial-deglacial cycle to better understand their impacts on groundwater flow (Laurencelle et al., 2013). A preliminary 2D groundwater flow and transport model of the regional bedrock aquifer of the Montérégie Est area was constructed using homogeneous horizontal and vertically anisotropic hydraulic property distribution and simplified boundary conditions. The objective of this modelling is to provide an understanding of current groundwater flow dynamics, and also its evolution during the last glacial-deglacial cycle. This includes during retreat and ablation of the last ice sheet, invasion of the aquifer by Champlain Sea water, and subsequent system adjustments to present-day conditions.

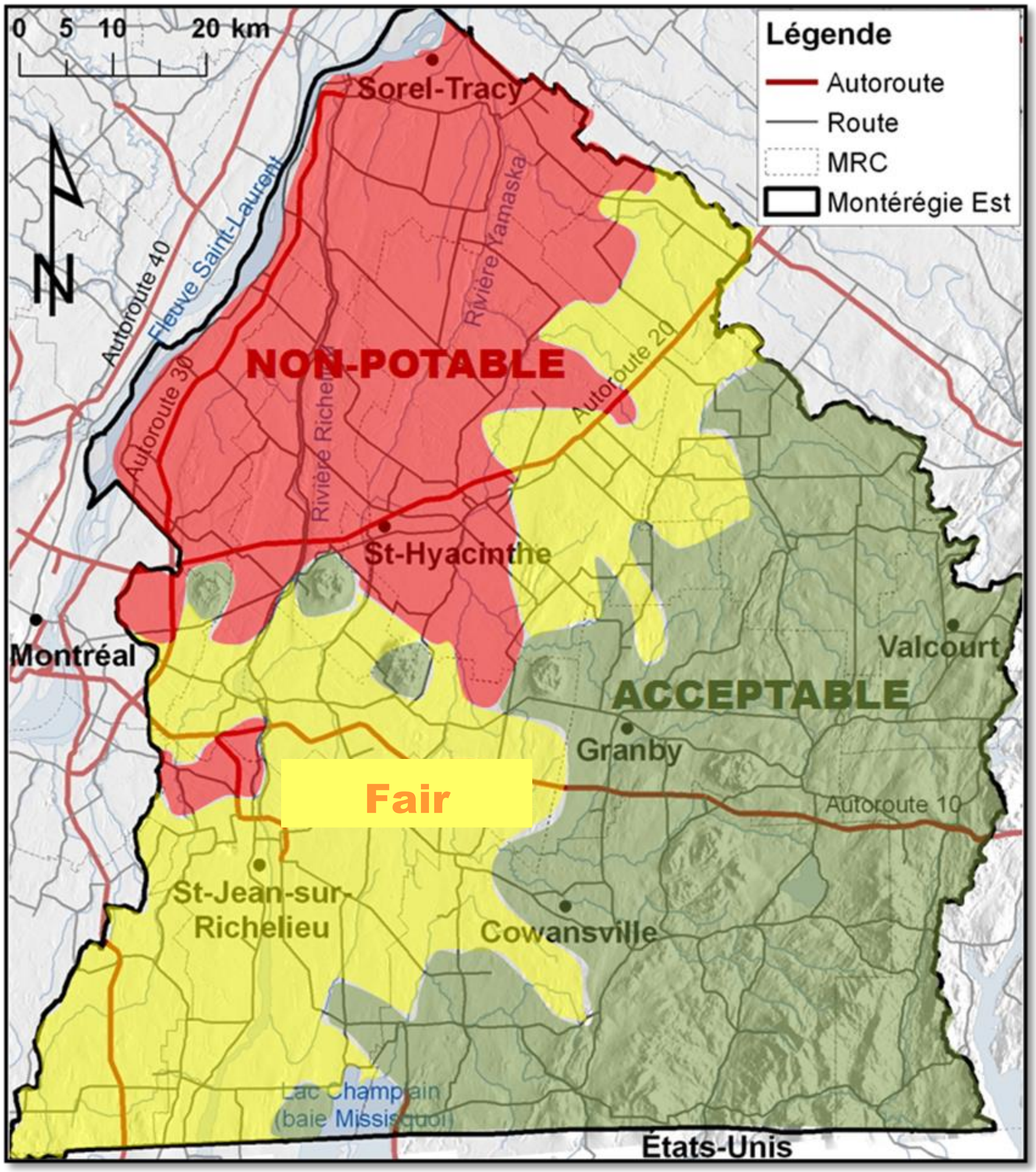


Figure 7: Geographical distribution of the three groundwater quality zones in Montérégie Est (Beaudry, 2013).

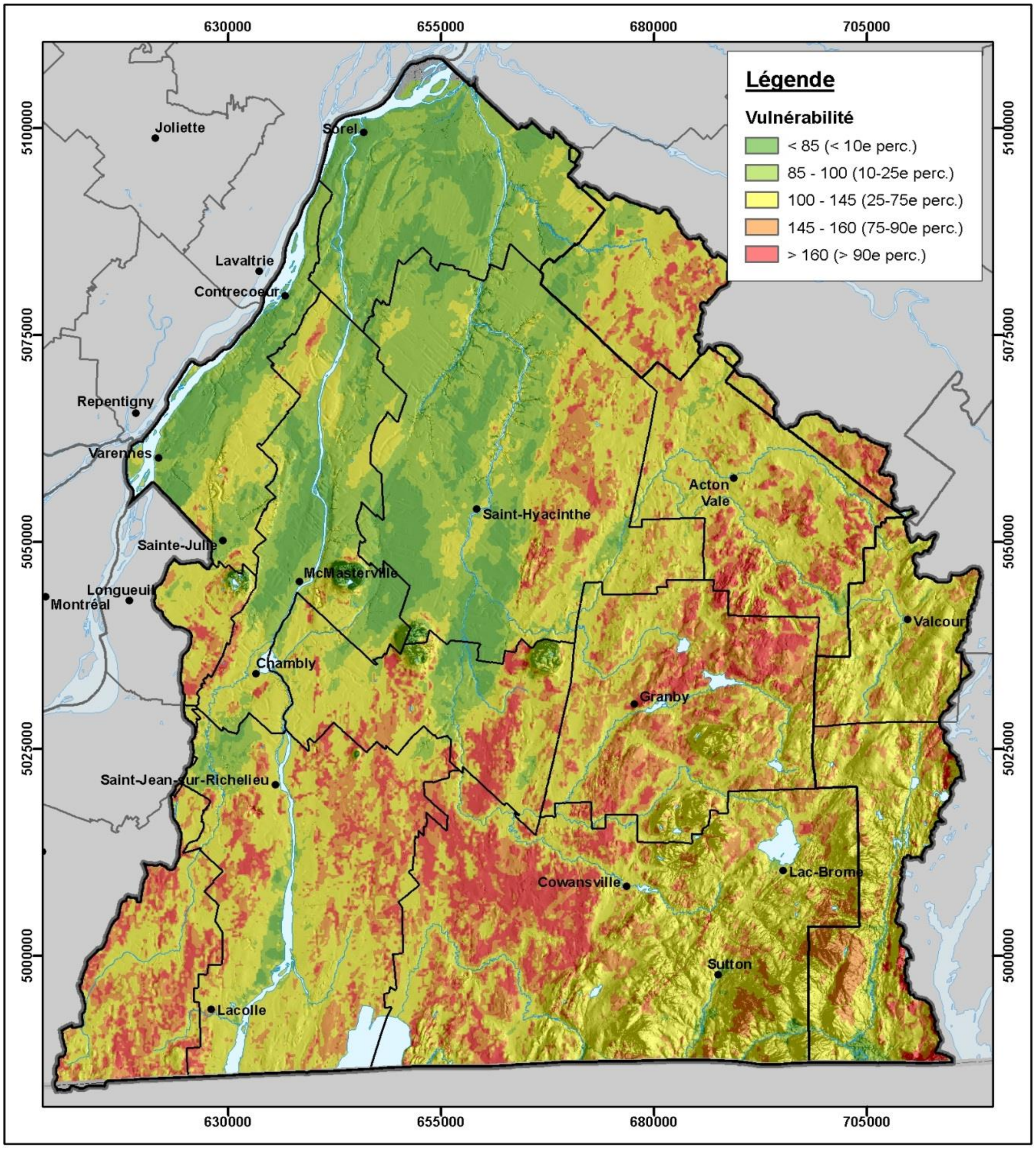


Figure 8: Relative vulnerability estimated using the DRASTIC index, using 5 classes based on percentiles of the distribution of DRASTIC values in the area, so as to best illustrate the relative importance of vulnerability in the study area (Carrier et al., 2013a)

4. Stop #1: Yamaska River near St-Hugues

Location: Map 31 H/15 UTM : 665 200 m East 5 072 350 m North (see Figure 9)

Stop #1 was located on a bridge crossing the Yamaska River near St-Hugues, about 17 km north of St-Hyacinthe.

Geology

Previous surveys (Clark, 1964a and 1964b) indicate that no outcrops have been observed along the Yamaska River downstream of the northwest-trending reach near St-Hugues (see Figure 9), several outcrops were mapped along the upstream reach between St-Hyacinthe and St-Hugues. This led us to infer that the continuity of the marine clay cover may have been breached by the Holocene entrenchment of the Yamaska River (see Figure 5) and to further assess the possible role of the valley in maintaining remnant marine waters below Champlain Sea muds in the northern lowlands. When the Yamaska River level is low, it is possible to see rock outcrops in the riverbed under the bridge at stop 1.

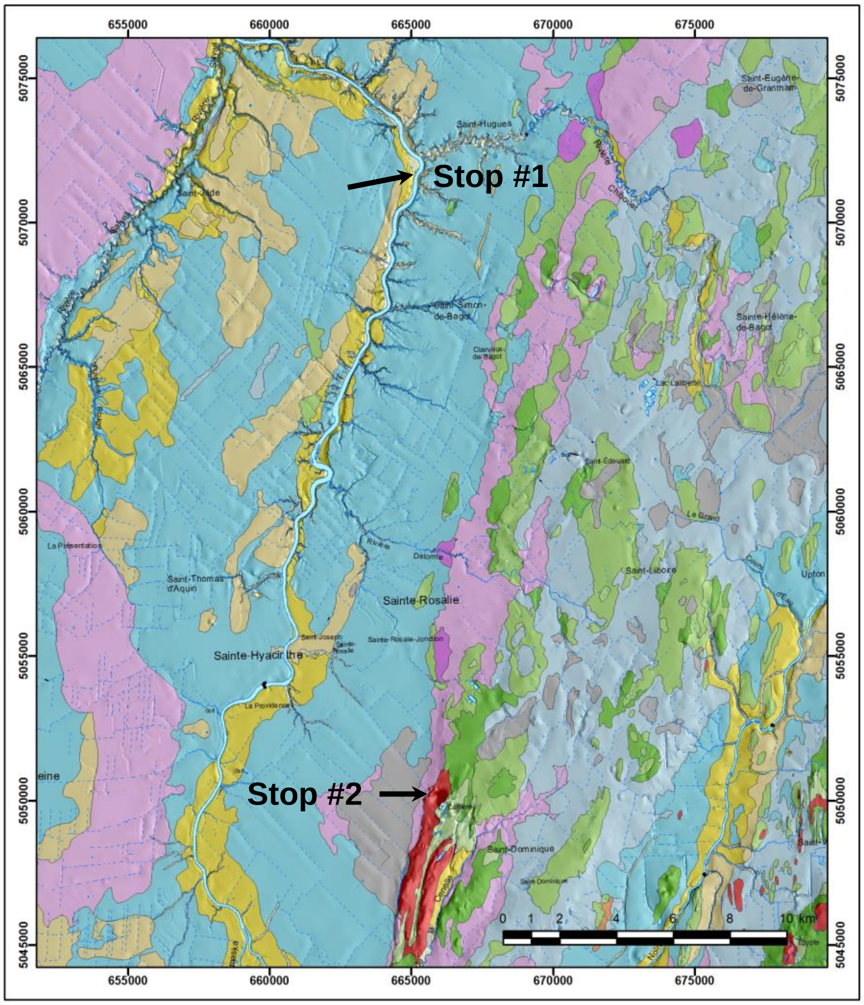


Figure 9: Quaternary map and location of the St-Hugues and St-Dominique stops

Four cores obtained by sonic drilling allowed us to obtain key lithostratigraphic and hydrostratigraphic records in this region, which lacked useful stratigraphic information. Of the 4 core logs (Figure 10), three (RS-01, RS-02 and RS-04) are from the northern lowlands, while the last one (RS-05) was obtained in the southern lowlands near Rougemont (i.e., south of the Rougemont Monteregian Hill).

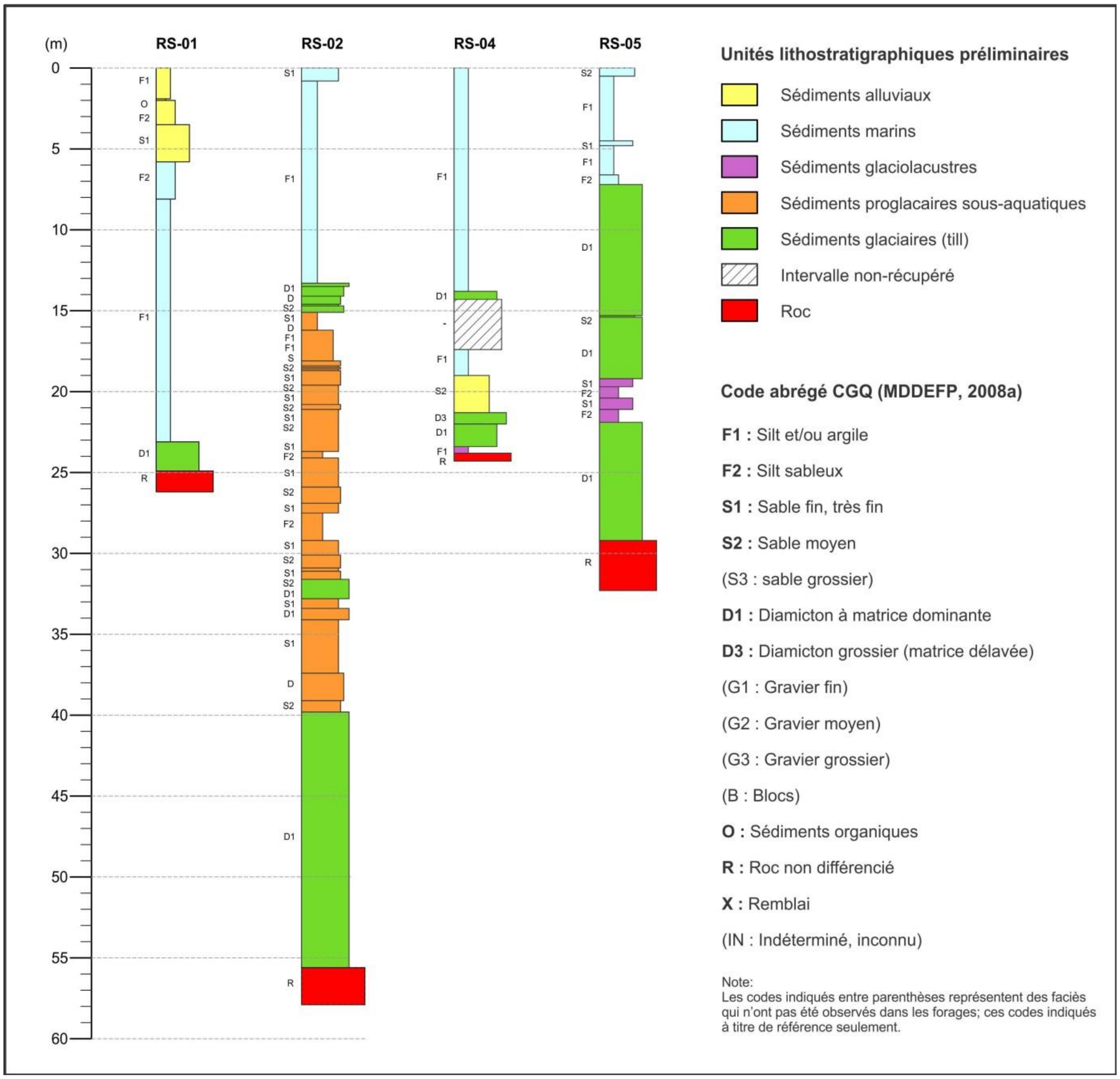


Figure 10: Summary stratigraphic logs of sonic cores obtained in Montérégie Est (Carrier et al., 2013a). The y axis shows borehole depth.

The core logs indicate a complex stratigraphic record of units concealed below Champlain Sea sediments (Figure 10, Sédiments marins). Core RS-04 was from a site about 5 km north of stop #1. Due to inadequate recovery at the time of the original drilling, a second hole was drilled to obtain new cores from the missing interval. Biostratigraphic investigations and ^{14}C dating of the missing core intervals are ongoing. Notwithstanding the outcome of the new work, core RS-04 shows that the till underlying Champlain Sea muds overlies an older marine unit which in turn overlies an organic-rich alluvial unit dated at 31 270 ± 200 years BP (Beta-343397). Underlying the alluvial sand is another till unit which overlies thin rhythmites resting on bedrock. This subtill stratigraphic record is new in southern Québec and we expect it will lead us to revisit the nature and timing of events that preceded the advance of the Laurentide Ice Sheet prior to the Last Glacial Maximun (LGM) in the St. Lawrence valley .

The stratigraphic record of RS-02 will be discussed at Stop #5 in St-Césaire. Core RS-01 was investigated for its biostratigraphic (foraminifers and ostracods) and paleosalinity record; this work indicates that RS-01 provides a particularly useful record of the second half of Champlain Sea history.

Hydrogeology

Groundwater flowing within bedrock underlying much of the northern St. Lawrence Platform is brackish. As a result, homes in the northwestern part of the study area are now all connected to a water supply system fed by a treatment plant in St-Denis-sur-Richelieu. Work conducted in the course of this project indicates that groundwater salinity is of marine origin, dating back to the Champlain Sea episode. Existing and newly collected geochemical data were used to delineate this brackish groundwater zone, including electrical conductivity, TDS, chlorides and bromides, as well as the absence or presence of water supply systems and the distribution and density of wells (Beaudry et al., 2011). This work showed that this brackish groundwater zone covers about 2200 km^2 (Figure 11). The main conclusion is that its presence is due to the thick silty-clay aquitard above that impedes direct recharge and the fact that groundwater from the Appalachians discharges in the Yamaska River. Logan's Line, a fault zone separating the St. Lawrence Platform and Appalachians geological provinces, likely plays a key role in this interception of water coming from the east. As can be seen in Figure 11, the contact zone between fresh and brackish water is particularly sharp along Yamaska River. Groundwater horizontal hydraulic gradients within bedrock are also very distinct east and west from this interface. Due to the flat topography, the horizontal hydraulic gradient to the west is very weak. These elements have combined to slow down the process whereby old marine water has been gradually flushed by recent freshwater in other parts of the study area. The piezometric low associated with the Yamaska River indicates that groundwater coming from the east does not cross this boundary, which is locally in direct contact with bedrock, as indicated by outcrops in the riverbed or stream banks.

Two-dimensional conceptual models were developed in order to integrate and summarize the understanding of the aquifer system acquired during the Montérégie Est project. Figure 12 shows a conceptual model of the typical geology along a SE-NW cross-section in the northern part of the study area (location of section is shown in Figure 6); the cross-section shows the transition from the Appalachian External zone (Piedmont) to the St. Lawrence Platform (Lowlands). Two other conceptual models were also developed for the hydrogeological contexts in terms of quantity and quality (Figures 13 and 14). The geological cross-sections are schematic representations of the topography, bedrock geology and surficial geology. Their purpose is also to facilitate the description of hydrogeological conditions in the study area. These sections are not meant to represent specific conditions; their intent is to represent typical characteristics of the main hydrogeological contexts in the region. For instance, the stratigraphic architecture of Quaternary units shown in these models is representative of a given context, but is not necessarily present at this precise location. Similarly, fracture patterns in bedrock are schematically depicted.

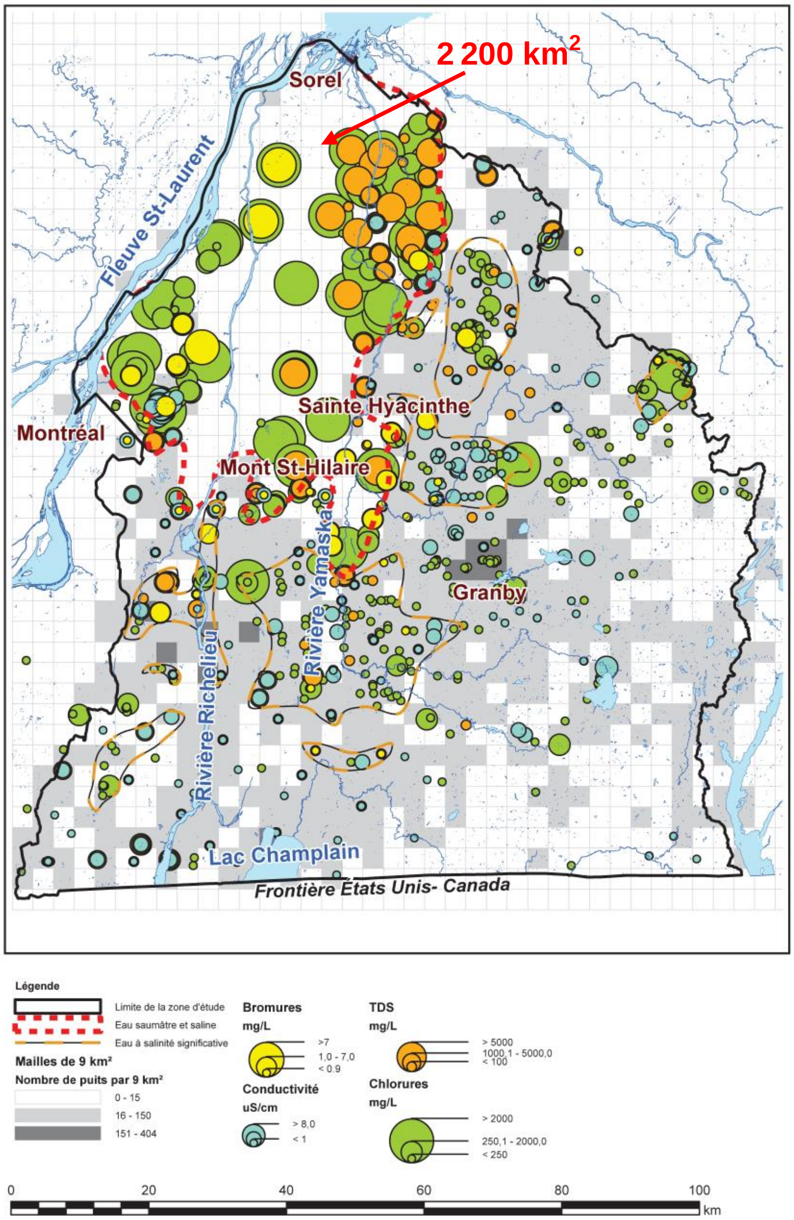


Figure11: Delineation of the 2200 km^2 brackish groundwater zone in the north-western part of the study area (Beaudry et al., 2011)

The cross-section of Figure 12 shows that the sediment cover tends to be thicker in valleys, but even thicker in the St. Lawrence Platform, where a large part of this cover consists of very fine-grained marine mud (silty clay). Low to moderately permeable sediments (till) are present on topographic highs. Finally, permeable sediments (outcropping or buried) occur mostly in valleys and as thin veneers along rivers. Figure 13 shows that the metasedimentary rocks of the External zone are characterised by low to moderate permeability. These rocks are commonly more fractured in the first few meters below the sediment/bedrock contact. Fracture density also tends to increase near fault zones. Sedimentary rocks of the St. Lawrence Platform are moderately permeable in the region. Topography and the nature of the sediment cover control, in part, recharge and groundwater flow conditions.

Figure 13 shows that this sector is characterised by limited groundwater flow to the west of the Yamaska River, as indicated by very low hydraulic gradients. As mentioned above, there is significant groundwater discharge into the river and at abrupt slope changes, such as at the outer edge of the Piedmont. Recharge zones are located on topographic highs which have more permeable sediments at the surface. Water table fluctuations are more important in these zones. Within the External zone (Piedmont), the use of groundwater is quite important, as residential and municipal wells draw water from the regional bedrock aquifer. No groundwater is pumped in the north-western part of the St. Lawrence Platform due to its fairly elevated salinity. Some municipalities have wells completed in surficial sediments in valleys (with variable confinement conditions).

Groundwater flow conditions and past geological events (Champlain Sea) in the region affects water quality (Figure 14). Better groundwater quality can be found in, or close to, recharge zones. However, these areas are also more vulnerable. Groundwater quality is rated “unacceptable” in the St. Lawrence Platform west of the Yamaska River, due to the presence of brackish water, but also because other elements exceed drinking water limits due to the composition of the bedrock itself. In the Appalachian External zone (Piedmont), groundwater could be a mixture of young recharge water with older, more mineralized water coming from the Uplands; here, the main quality issues are related to aesthetical criteria (e.g. Fe, Mn). In the Appalachian / St. Lawrence Platform contact zone, some of the drinking water standards are more frequently exceeded, such as baryum (Ba) and fluorides (F); aesthetical criteria for sodium (Na) and chlorides (Cl) are also often exceeded.

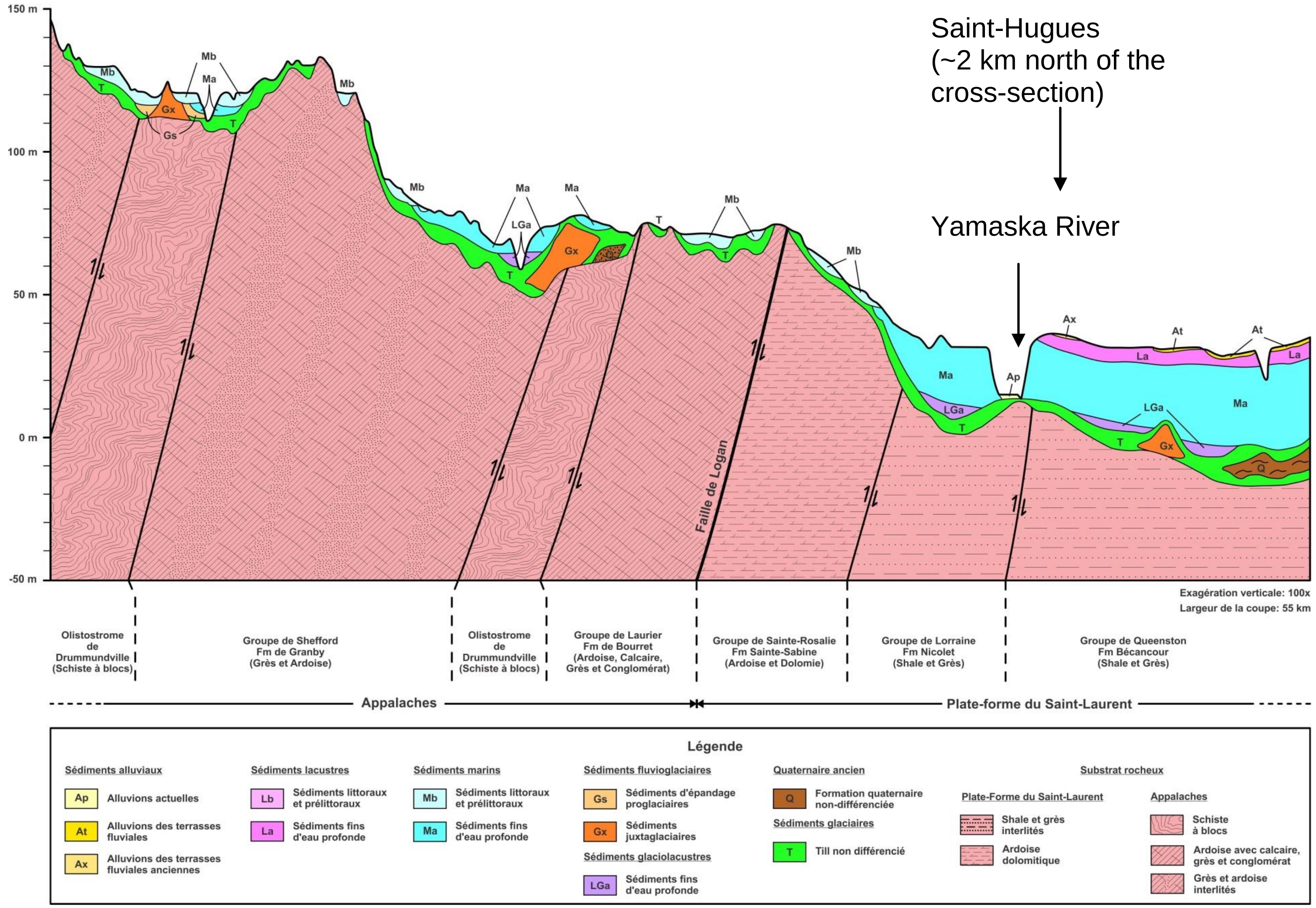


Figure 12: Conceptual geological model along a SE-NW cross-section (see Figure 6 for location) showing the St. Lawrence Lowlands and the Appalachian Piedmont (Carrier et al., 2013b).

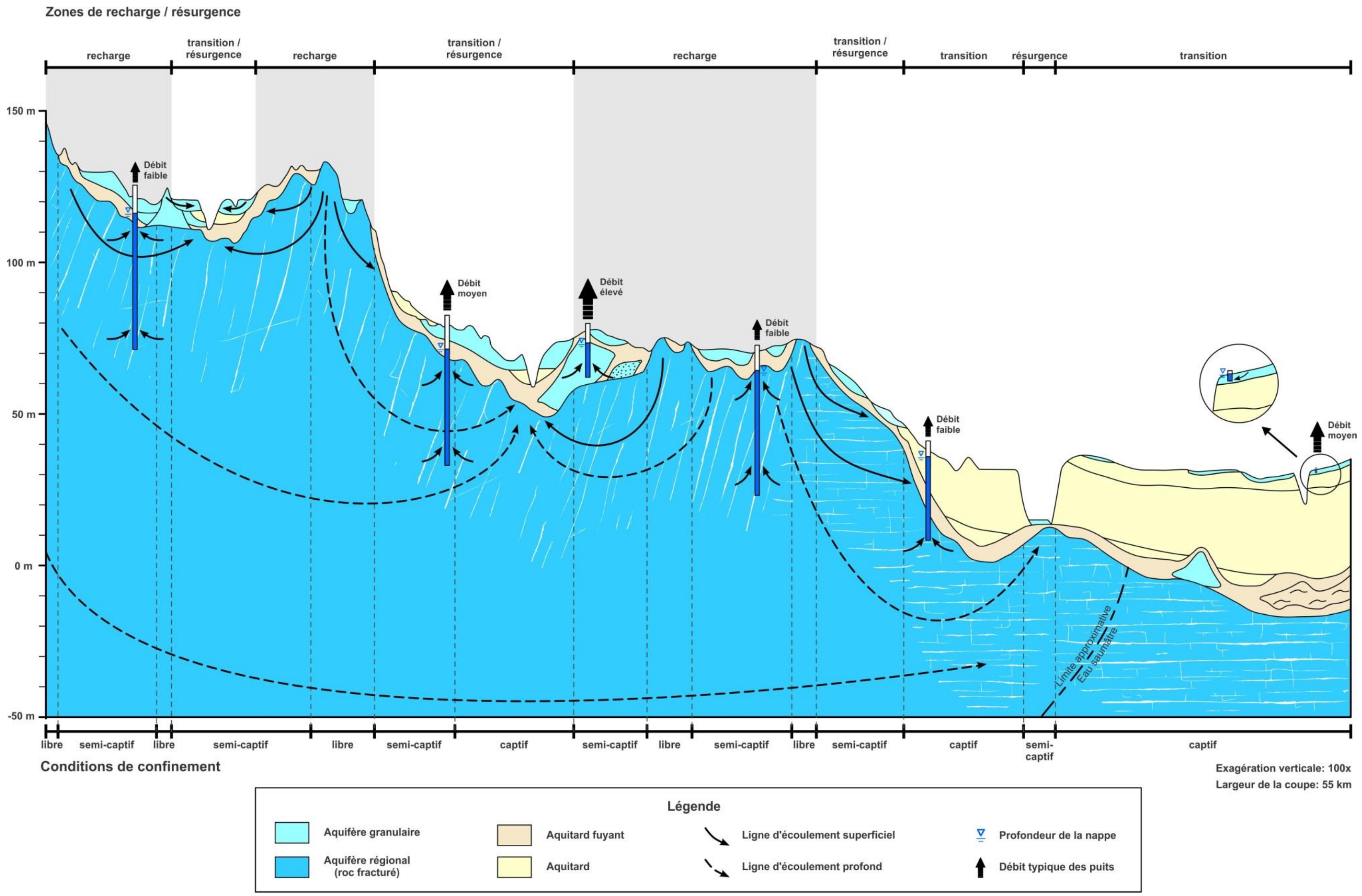
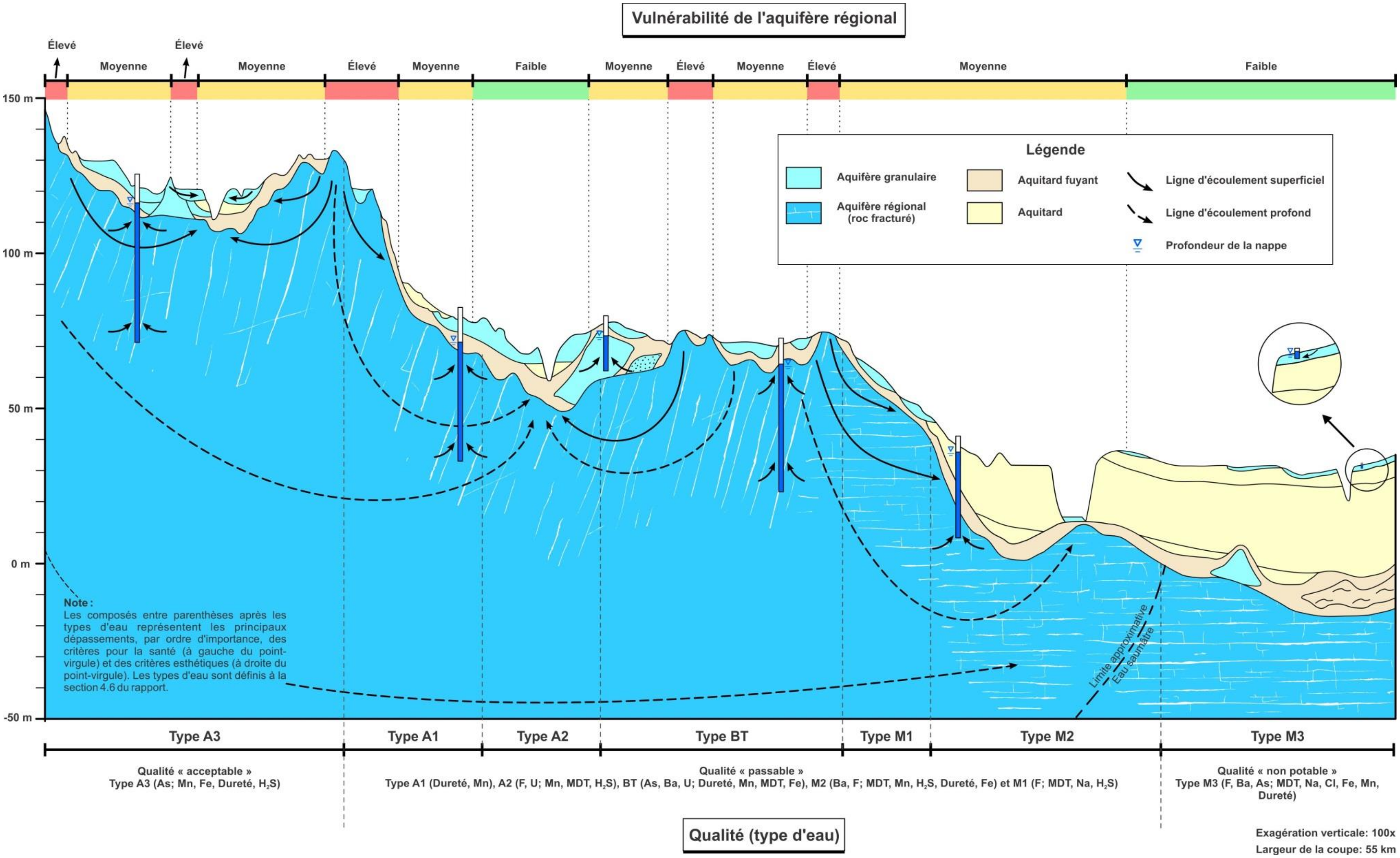


Figure 13: Conceptual hydrogeological model along a SE-NW cross-section (see Figure 6 for location) (Carrier et al., 2013b).



Note :
Les composés entre parenthèses après les types d'eau représentent les principaux dépassements, par ordre d'importance, des critères pour la santé (à gauche du point-virgule) et des critères esthétiques (à droite du point-virgule). Les types d'eau sont définis à la section 4.6 du rapport.

Figure 14: Conceptual model of groundwater quality and vulnerability along a SE-NW cross-section (see Figure 6 for location) (Carrier et al., 2013b).

5. Stop #2: St-Dominique thrust slice

Location: Map 31 H/15 UTM : 665 915 m East 5 049 491 m North (see Figure 9)

Stop #2 was located near St-Dominique, along Highway 235, to look at a limestone outcrop with the quarry in the background. The ridge is located just east of St-Hyacinthe (see Figure 9). Dr. Stephan Séjourné, a structural geologist who worked extensively on this crest during his Ph.D., was the lead for this stop.

Geology

The Saint-Dominique thrust slice is located south-east of Saint-Hyacinthe, just west of the Logan's Line (Figures 15 and 16). It is part of an imbrication of thrust sheets emplaced along the structural front of the Appalachians during the Late Ordovician Taconian Orogeny.

Although similar tectonic slices are documented at depth along the Logan's Line from Quebec City to the State of Vermont, the Saint-Dominique ridge is one of the very few places where sedimentary bedrock outcrops can be seen in the Appalachian External zone (Piedmont). This crest is, however, composed of coarse-grained dark grey limestone, shaly limestone and dolostone. It is thus not representative of the regional bedrock aquifer in the study area, which is mainly composed of shale and sandstone.

The deformation style is characterised by decollement planes and fault-bend folds in the less argillaceous lithologies, and fault-propagation folds in the shaly limestone. Most natural fractures are sealed by calcite. Post-Taconian, Mesozoic strike-slip faults and dykes are also documented in the Saint-Dominique quarry.

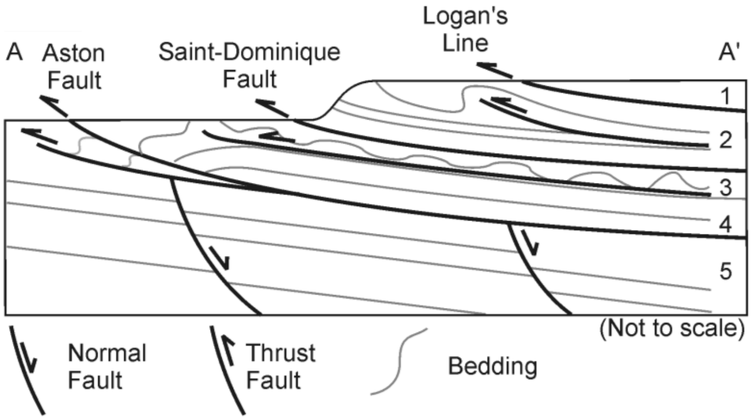


Figure 15: Simplified cross-section showing the different structural elements of the area (Séjourné and Malo, 2007)

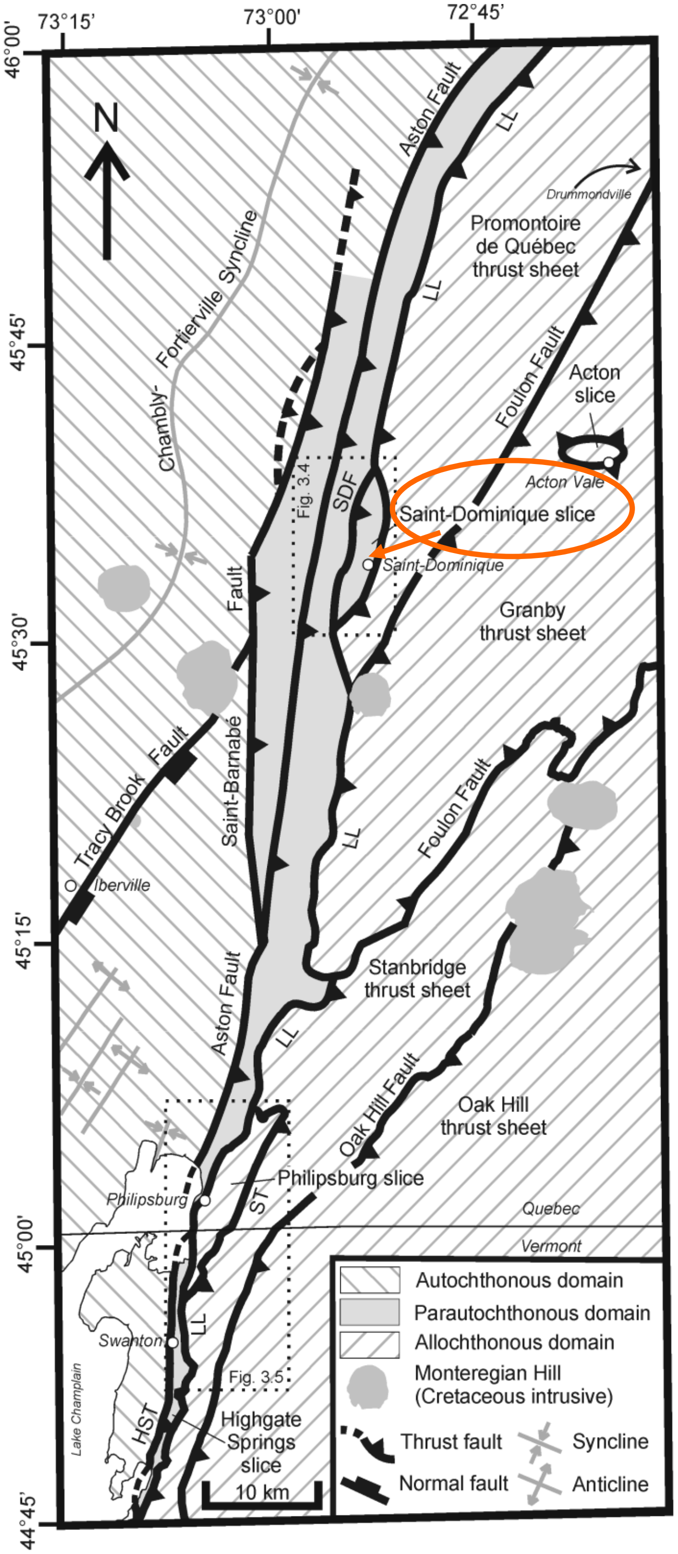


Figure 16: Map of main tectonostratigraphic units of southern Quebec and location of the carbonate slices (Séjourné and Malo, 2007). LL: Logan's Line; SDF: Saint-Dominique Fault.

This limestone was used for the construction of several buildings in the area, one of which is the St-Hyacinthe cathedral (Figure 17). The quarry opened in 1810, and had to adapt through the years to different situations. At first, only limestone blocks were extracted. Around 1930, the construction market went down with the financial crisis and the quarry started producing lime for farmers, and still does. In addition, the increasing use of concrete for building construction significantly decreased the demand for blocks, but developed a new market for crushed stone aggregates.

Figure 17: The St-Hyacinthe cathedral, completed in 1908

Hydrogeology

While fracturing in the Saint-Dominique crest is not representative of the regional fracture patterns seen elsewhere in the study area, this stop, where bedrock is well exposed, is useful to discuss fracturing in the study area. Borehole geophysical surveys, especially acoustic televiewer logs and flowmeter testing, were performed in 29 wells in the different contexts and 19 sites (outcrops and quarries) were visited and investigated. Geological structures and fracture networks are expected to greatly influence groundwater flow of the regional aquifer (Ladevèze et al. 2013).

Throughout the study area, the predominant structures are oriented in a N25° direction (varying from N340° to N50°). This NNE orientation is parallel to the direction of the main structural axes of the region (e.g. the Fortierville-Chambly syncline, the imbricated faulted zone near Logan’s Line, as well as folds and faults of the Appalachian region (Carrier et al., 2013a). For the St. Lawrence Platform, a single fracture set is dominant. It corresponds to shallow-dipping (0 to 22°) fractures striking N30°. The presence of sub-vertical fractures was observed in outcrops, notably near Saint-Hyacinthe. From this, the existence of an orthogonal fracture network may be assumed: sub-horizontal fractures, parallel to bedding planes, are intersected by sub-vertical fractures. However, the attitude (strike and dip) of these sub-vertical fractures are not well known for the study area, due to a lack of samples of these structures, both in boreholes and in outcrops/quarries. In the Appalachians, two fracture sets were identified. The first one, striking N33° and dipping 60°NW, is predominant in the dataset. The second set, under-represented in the available dataset, is oriented N23°; 42°SE. These two sets also seem to be orthogonal. The steeper dip for the Appalachians can be explained by the intense deformation (folds and thrust faults) these rocks have undergone. It was noted that the Internal zone is deformed more homogenously along a NNE axis, while the External zone shows more diverse fracture orientations.

These different fracture patterns likely have influenced anisotropy, and thus hydraulic properties and groundwater flow. A schematic view of the orientation of fracture sets is presented in Figure 18.

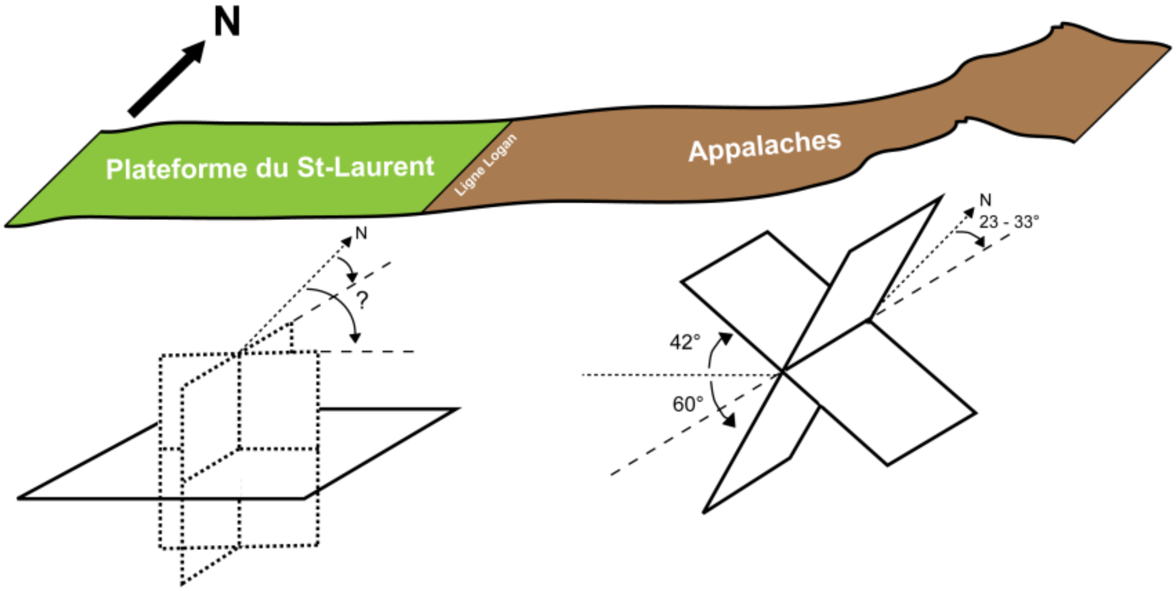


Figure 18: Schematics of the main orientation of the fracture set planes for both the St. Lawrence Platform and Appalachians in Montérégie Est (Carrier et al., 2013a).

6. Stop #3: Gault Nature Reserve (Mont St-Hilaire)

Location: Map 31 H/15 UTM : 644 177 m East 5 044 815 m North (see Figure 19)

Stop #3 was located within the Gault Nature Reserve, which belongs to McGill University, on Mont St-Hilaire. A lunch was provided in the beautiful Gault House on Lake Hertel. Some of the work of Dr. Pierre Richard, emeritus professor at the Université de Montréal, on the paleoecology and paleohydrology of Mont St-Hilaire was presented by Michel Parent.

Cores retrieved by Dr. Richard from the bottom of Lake Hertel were instrumental in demonstrating two key elements of the Late Quaternary history of southern Québec. The first one (Richard and Occhietti, 2005) is the large reservoir age (about 1800 ^{14}C years) affecting radiocarbon ages obtained from Champlain Sea shells. One of the most important results of this finding is the timing of the Champlain Sea incursion which is now thought to have occurred at about 11 100 ± 100 ^{14}C years BP. The other important result from the Lake Hertel cores (Muller et al., 2003) is that the natural level of the lake underwent a series of oscillations during the last 8000 years. The oscillations recorded in this headwater lake, with lowstands of 3 to 5 m below natural lake level, indicate three (3) protacted period of dry conditions during these 8 000 years. These lake-level fluctuations, although this was not specifically discussed in their work, suggest similar variations of groundwater levels.

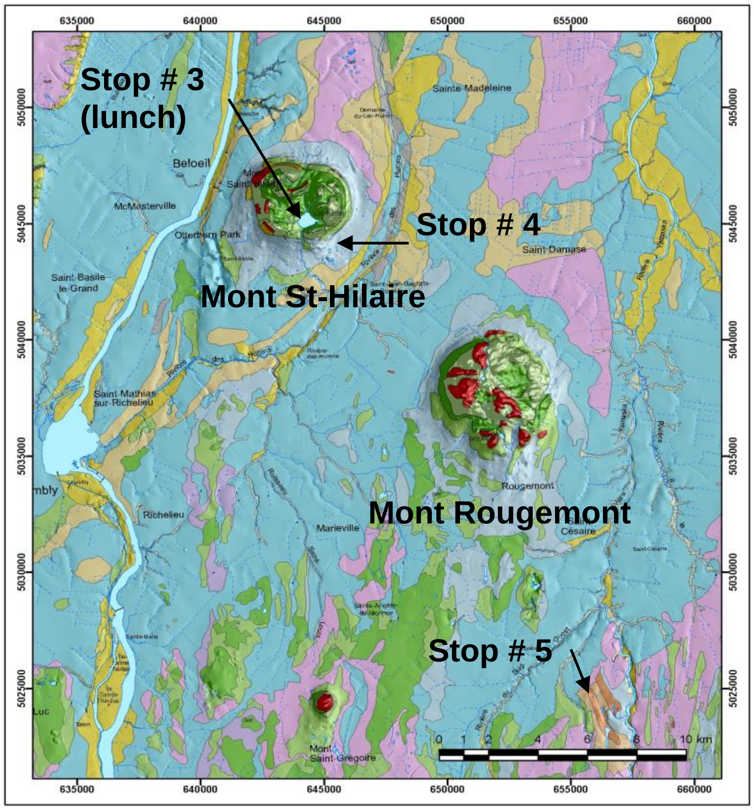


Figure 19: Quaternary geology of the Mont St-Hilaire, Mont Rougemont and St-Césaire area. This clip is extracted from the 1:50 000 maps (31 H/06 and 31 H/11) (Dubé-Loubert et al., 2014). The Monteregian Hills are surrounded by sedimentary rocks of the St. Lawrence Platform.

7. Stop #4: Rue Noiseux (Mont St-Hilaire)

Location: Map 31 H/15 UTM : 644 765 m East 5 043 902 m North (see Figure 19)

Stop #4 was located at the foot of the Mont St-Hilaire, one of the most prominent Monteregian Hill, along its southeastern slope (see Figure 19). The participants walked uphill to have a better view of the adjacent plain and of the other Monteregian Hills.

Geology

This stop is located in an almost abandoned gravel pit which exposes two of the most common Quaternary units in the region. The top unit consists of a variety of Champlain Sea littoral sediments. These sandy sediments overlie a compact till which can be observed in many of the small streams that run across the pit floor. This stratigraphic setting is schematically depicted on the margins of the Monteregian Hill shown in the conceptual geological model (Figure 20).

The littoral sediments range in elevation from about 50 m at the pit entrance to about 110 m, which is marked by a well-developed cobblestone ridge. This fairly large range in elevation allows us to observe several typical lithofacies of littoral sediments, mainly sand here, as well as characteristic marine fauna that thrived in shallow Champlain Sea environments. The fossil shells observed in the upper part (80 to 90 m ASL) of the pit consist essentially of *Hiatella arctica* and *Balanus crenatus*, two species that thrived on stony substrates throughout the Champlain Sea history. This is why most of the fossil shells lie close to the contact of the littoral sands with the underlying till. At lower elevations, a few additional species, namely *Macoma balthica* and *Mya arenaria*, both of which thrived on sandy substrates, may be observed. The presence of *Mya arenaria* indicates that the cold waters of the early marine phase had become more temperate as relative sea level had fallen during the second half of the Champlain Sea episode.

The till exposed along the banks of the small streams is quite characteristic of that observed in boreholes and surface exposures in the study area. It is a matrix-dominated, compact and fissile diamicton that contains abundant faceted and striated stones. At this locality, the till is lithologically diverse, with stones of distant as well as local provenance. Abundant seeps observed at the sand-till contact indicate that, where present, this till unit acts as a partial barrier to infiltration on the lower flanks of the Monteregian Hills.

Hydrogeology

Conceptual models for the hydrogeological contexts for both quantity and quality in the area surrounding one of the Monteregian Hills are presented in Figures 21 and 22. Figure 21 shows that bedrock is more permeable in the fractured zone near the sediment/bedrock interface and could also be more fractured close to the Monteregian intrusive bodies and associated dykes. Figure 22 also highlights that local and more regional groundwater flow occurs within the bedrock aquifer and that Monteregian Hills are preferential recharge zones. The bedrock aquifer typically provides limited yields that are adequate for residential needs. Although this is not the case near Mont St-Hilaire, moderate to high yields can be obtained in coarse surficial sediments that extend southeastward of some of the Monteregian Hills, notably Mont Rougemont. This will be discussed at stop #5. Dotted arrows below the Monteregian Hill (Figures 21 and 22) infer the possibly of mixing of “young” and “old” recharge water.

8. Stop #5: St-Césaire gravel pit

Location: Map 31 H/15 UTM : 656 250 m East 5 024 500 m North (see Figure 19)

Geology

Stop 5 is located in the St. Lawrence Lowlands, about 10 km southeast of Mont Rougemont (see Figures 19 and 20). It provides a key example of discontinuous aquifers consisting of ice-contact gravels and ice-proximal glaciolacustrine sands underlying the regional surface till. At this site, the surface till is overlain by a partial suite of fossiliferous fine- and coarse-grained Champlain Sea sediments. The subtill sand and gravel are interpreted to be a discontinuous esker system characterised by a particularly continuous series of subaqueous sandy fans. In fact, gravelly facies are seldom observed in the St-Césaire esker system, a feature that was confirmed by the current pit owner. The esker system can be observed in several pits aligned southeastward of Mont Rougemont, but its subsurface extent and continuity are not fully constrained by the available subsurface data.

The till unit stratigraphically overlying and at least partly covering the esker system is particularly well exposed in the pit. It is representative of relationships observed in many other esker systems in the southern St. Lawrence lowland. The till unit consists of very compact diamicton with a silty sand matrix and is relatively clast-free, due to its derivation from the underlying sands. The surrounding fields are strewn with cobbles and small boulders, however, that are likely derived from erosion and winnowing of the esker and overlying till. Along the pit walls, the till sheet can be observed to increase in thickness toward the margins of the esker system. The lower part of the exposed till sheet often consists of deformation till and brecciated rhythmites. The till has been partly winnowed and reworked by Champlain Sea waves and currents. Occasionally, the contact between the till and the overlying littoral sediments is marked by fossil shells or, more locally, by shell-rich horizons.

Hydrogeology

Closer to Mont Rougemont, buried segments of the esker system constitute aquifers that are extensively exploited by relatively small municipalities (e.g. Rougemont, St-Césaire) and by private wells. Groundwater drawn from this partly buried esker is of very good quality. The granular aquifer near Rougemont is inferred to be recharged vertically through the overlying reworked till and by Mont Rougemont.

The municipality of St-Césaire, located 50 km east from Montreal along the provincial highway 112, has two wells in this unit: one is located 2 km southwest from the town center and is the main supply well, the other one is located in a golf course and has not been in operation since 2004. These two wells appear to be “completed in the same sand and gravel unit of limited extent” (Laforêt Nova Aqua Inc., 2005) and are believed to exploit the same discontinuous esker system. The main supply well has a total depth of ~20 m and is composed of sand and gravel, with a thin layer of material described as ‘soil’ at the top. The backup well has a similar stratigraphy and ends at 17.4 m. Both wells were reported to end at the bedrock surface, although some observation wells indicate the local presence of a basal till layer. Our well logs indicate that a clay unit of variable thickness, presumably Champlain Sea clay, overlies the sand and gravel aquifer.

The transmissivity of the esker is estimated to be in the order of 2×10^{-2} to 4.2×10^{-2} m^2/s, based on a 72-h pumping test using a pumping rate of 40 L/s (La Compagnie Internationale des Eaux ltée, 1977). Although very permeable, this unit is very limited in extent. The storage coefficient was estimated to be $S=1.3 \times 10^{-2}$, indicating unconfined conditions. A negative limit was reached after 21 hours of pumping. The consultant also thought that the two small artificial lakes nearby also contributed significantly to the flow rate since their level decreased during the pumping test. The saturated thickness was around 16 m at the main municipal well in 1977 (La Compagnie Internationale des Eaux Ltée, 1977). The recommended yield in 1977 was 2730 m^3/d (31.6 l/s). Laforêt Nova Aqua Inc. (2005) provided data for flow rates of the main well from 2000 to 2004. The yield seems to have steadily increased, from around 1 500 m^3/d to 2 100 m^3/d. The current pumping rate from the two wells is around 2 235 m^3/d (25.9 l/s) (extracted from the MDDEFP database 'Registre pour la gestion des prélèvements d'eau' pour 2010).

The consultant noted that in 2005 the static level had decreased by 6 m in the main well and by 3 m in the backup well since their installation in 1971, suggesting an over-exploitation of the aquifer. The esker, as mentioned earlier, is limited in extent and is surrounded by low-permeability sediments (clay over till). It receives direct recharge mainly where the clay cover is absent, and likely also laterally from the basal till layer surrounding the esker. This till is compact, and was estimated to have a transmissivity of 5.7×10^{-6} m^2/s using pumping tests in 2005 (Laforêt Nova Aqua Inc., 2005).

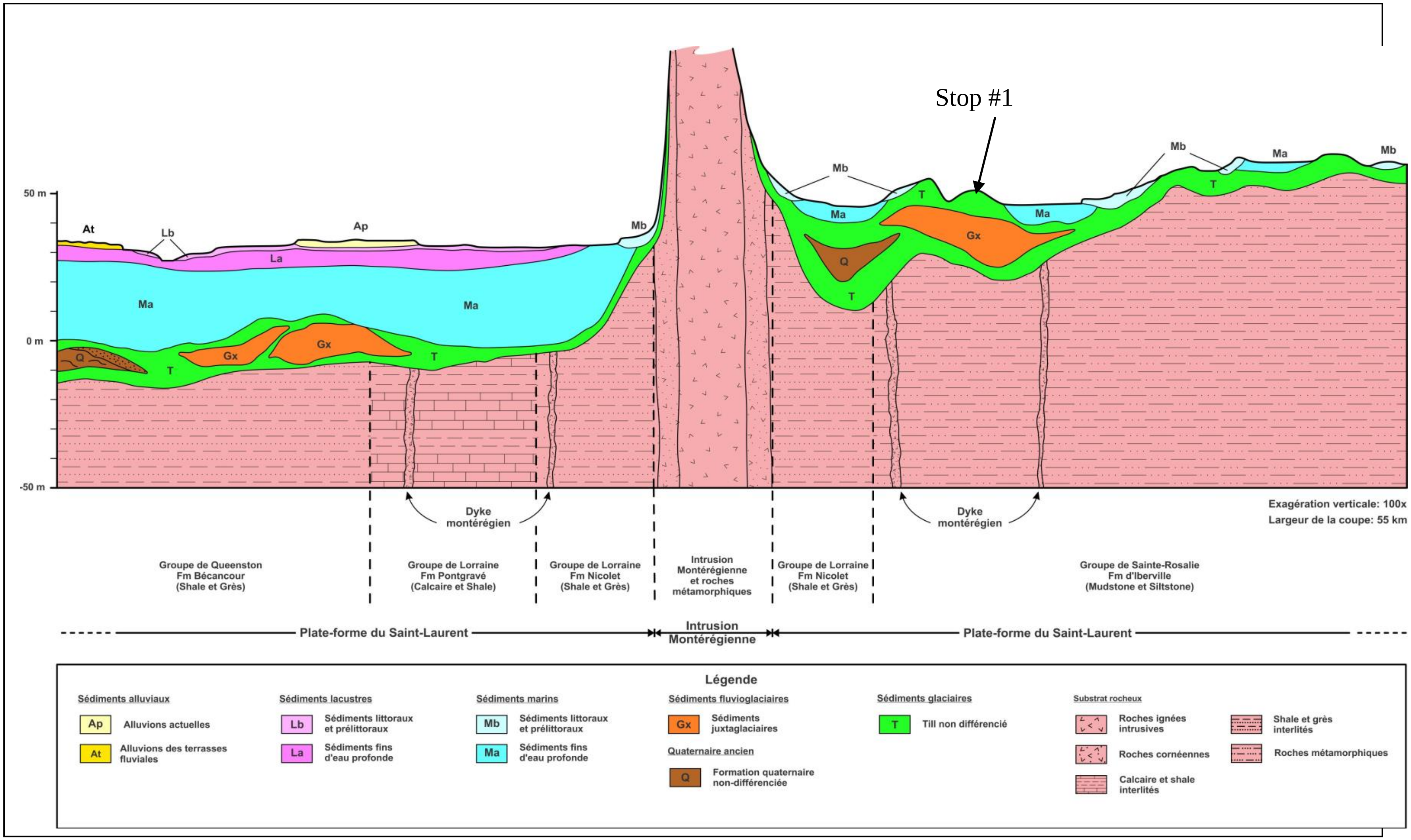


Figure 20: Conceptual geological model along a N-S cross-section (see Figure 6 for location) showing Mont Rougemont (Monteregian Hill) as well as the northern and southern parts of the St. Lawrence Platform (Carrier et al., 2013b).

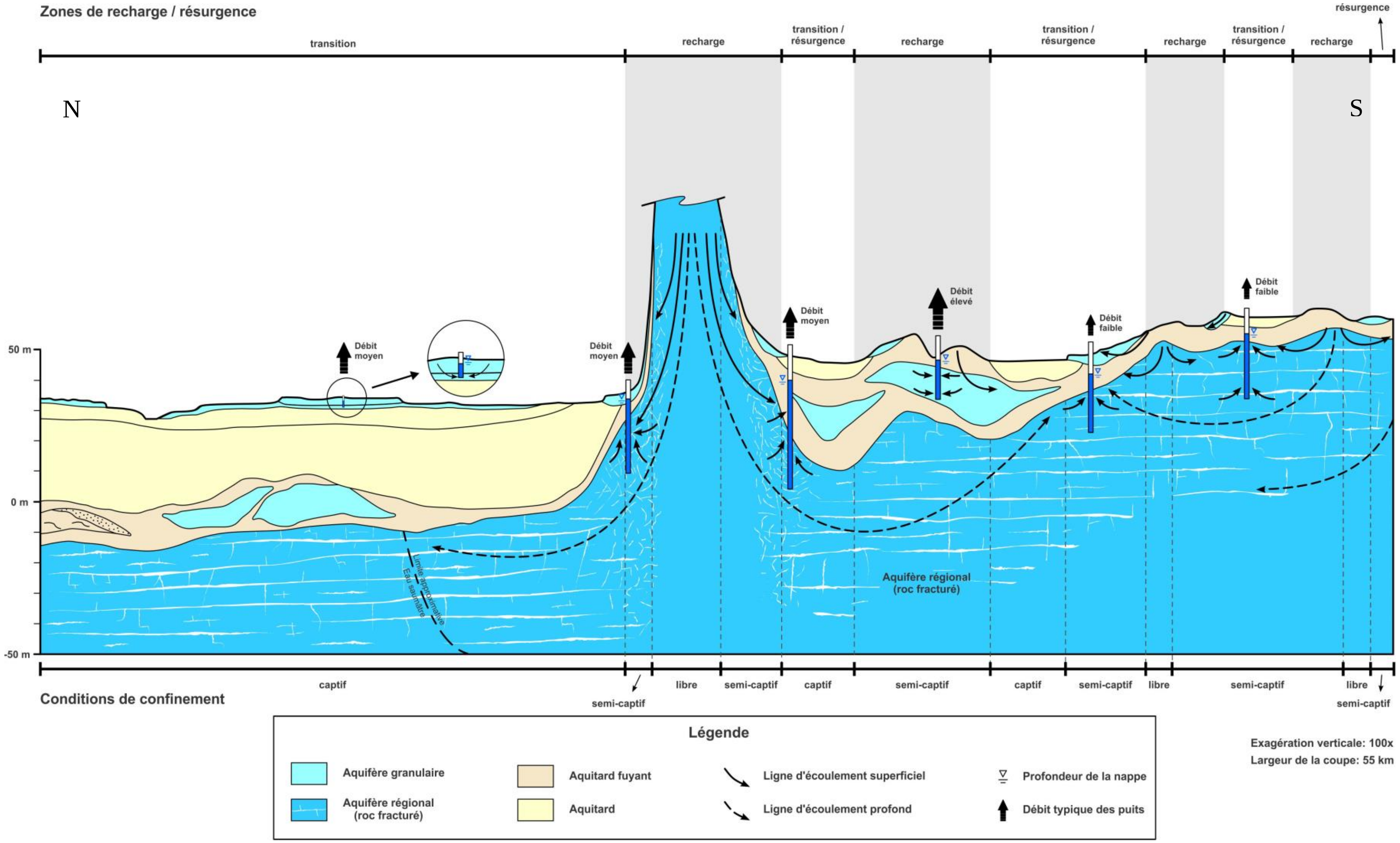
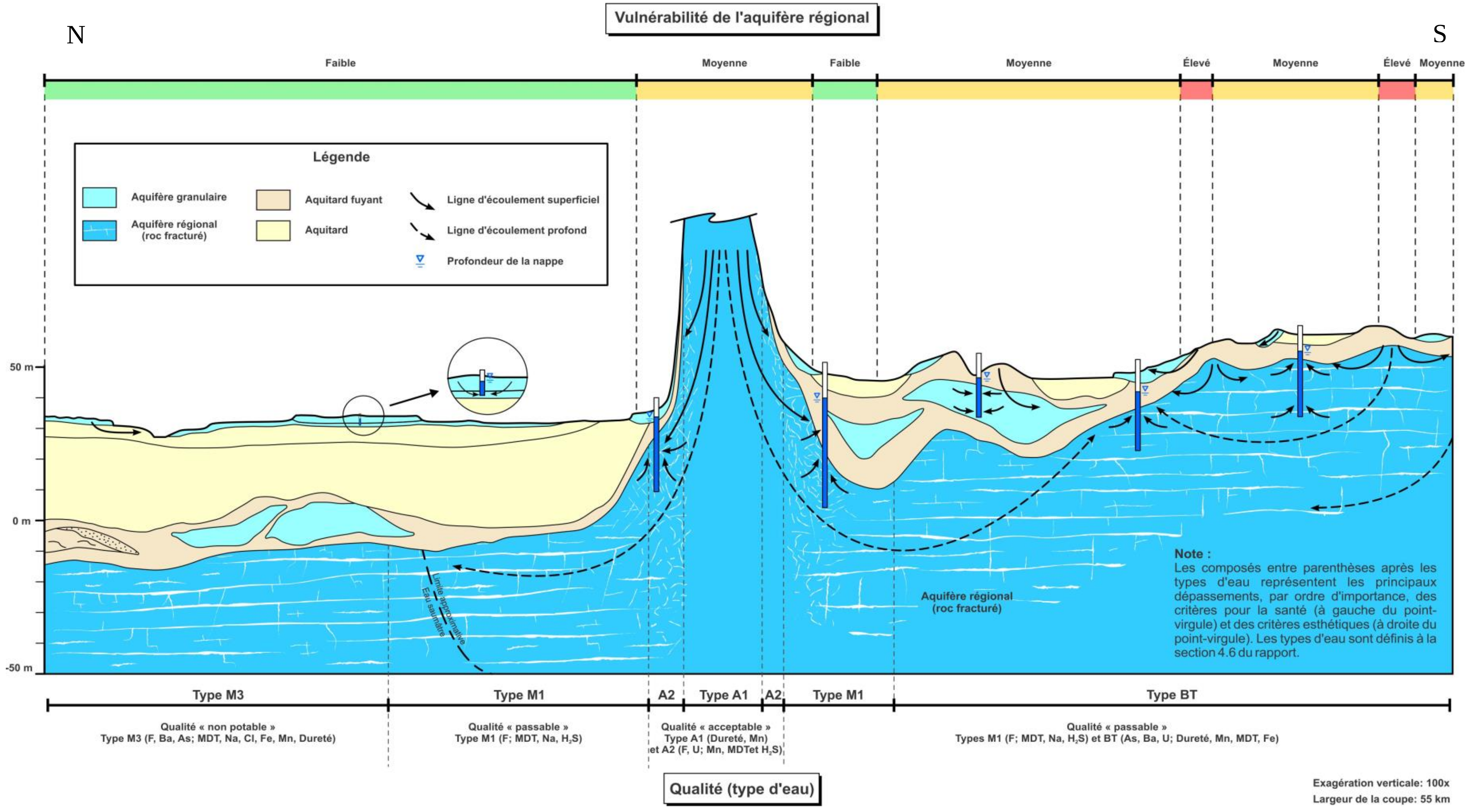


Figure 21: Conceptual hydrogeological model (quantity) along a N-S cross-section (see Figure 6 for location) (Carrier et al., 2013b).



Note : Les composés entre parenthèses après les types d'eau représentent les principaux dépassements, par ordre d'importance, des critères pour la santé (à gauche du point-virgule) et des critères esthétiques (à droite du point-virgule). Les types d'eau sont définis à la section 4.6 du rapport.

Figure 22: Conceptual hydrogeological model (quality and vulnerability) along a N-S cross-section (see Figure 6 for location) (Carrier et al., 2013b).

9. Summary

Distinct hydrogeological conditions characterise the five hydrogeological contexts defined in the Montérégie Est region and were presented during a 1-day post-conference fieldtrip on October 3, 2013. Five stops had been strategically selected to best describe them. In Montérégie Est, bedrock is the main regional aquifer, though yields are typically low to moderate. Good aquifer potential can be found in coarse-grained sediments in valleys and south of the Monteregian Hills, but these areas are very limited in extent. Groundwater quality within the regional bedrock aquifer varies from poor to acceptable regionally, but only from poor to fair below the upper limit of the Champlain Sea.

The northern part of the St. Lawrence Platform is characterised by flat lowlands and more importantly by a thick silty-clay cover (> 10 m). These conditions imply that recharge to the bedrock aquifer is practically null and that groundwater movement is very slow. Because of these conditions, brackish water remains trapped below the clay cover, as a result of the incomplete leaching of Champlain Sea water. Although the clay sediment cover protects groundwater from surface contamination, this region (~2 200 km^2) is solely supplied by surface water because of the presence of this non-potable brackish groundwater.

In the southern part of the St. Lawrence Platform, the sediment cover is typically thin (< 10 m). Bedrock is usually overlain by a till sheet which allows significant bedrock aquifer recharge (~106 mm/y on average). There are hydraulic connections between the regional bedrock aquifer and streams, especially along the Richelieu River, which is a discharge zone. Vulnerability is considered moderate.

In the External zone context (Piedmont), the till cover is thin and somewhat discontinuous, a situation that also allows for moderate recharge (~120 mm/y on average). In the southern portion, groundwater is discharged from the Appalachian Uplands. Groundwater is also discharged in valleys and in the contact zone between the Appalachians and the St. Lawrence Platform (see stop #3 for more details), which decreases the quantity of water that can circulate within the St. Lawrence Platform to mix with brackish water. The most important use of groundwater occurs in the piedmont. Water in the southern part of the St. Lawrence Platform and the External zone (Piedmont), an area which roughly coincides with the maximum extent of the Champlain Sea, is of fair quality; this is due to the fact that several parameters exceed aesthetical criteria and drinking water thresholds, and to the occasional presence of elevated TDS.

The highest recharge values (198 mm/y on average) occur in the Internal zone (Appalachian Uplands), due to the thin and discontinuous till cover on bedrock. Groundwater discharge occurs in river valleys where, in addition, the fine-sediment cover locally reduces aquifer vulnerability. The best groundwater quality in Montérégie Est area is found in this context, which has not been invaded by the Champlain Sea. Granular deposits are used as a municipal water supply in certain areas (e.g. Sutton).

The hydrogeological context corresponding to the Monteregian Hills represents a main recharge zone for the regional bedrock aquifer. There is a good aquifer potential within the fractured bedrock, but also on the southeastern side where some significant accumulations of permeable coarse sediments may be found (e.g. St-Césaire). However aquifers in both bedrock and granular material are relatively vulnerable. This context is likely characterised by a distinct type of water reflecting both local recharge and contribution from older water.

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APPENDIX: Summary of the fieldtrip in a few images

The bus left the Bonaventure Hotel, downtown Montreal, at around 8h45. Luckily, it was a beautiful, sunny and particularly warm day for this time of year (October 3).

Stop #1: The group is on a small bridge crossing the Yamaska River (near Saint-Hugues), in the northern part of the St. Lawrence Platform, where a thick layer of marine silty clay sediments is present, impeding recharge of the bedrock aquifer. Christine Rivard and René Lefebvre are using maps from the project atlas to discuss hydrogeology of the area.

Stop #2: Stephan Séjourné, presenting the geology of the St-Dominique thrust slice, just across from a large limestone quarry.

Stop #2: The fieldtrip participants, sitting on a large limestone outcrop, St-Dominique thrust slice.

Stop #3: Michel Parent, discussing geological and paleoecological work carried out by Dr. Pierre Richard and co-workers on cores pulled from Lake Hertel, at the McGill Natural Gault Reserve.

Stop #4: Michel Parent, showing several fossil shell assemblages in littoral sediments associated to the former Champlain Sea on Mont St-Hilaire (Monteregian Hill).

Stop #4: Just before taking the bus to return to Montreal. We had chosen this stop to benefit from an excellent point of view, overlooking the St. Lawrence valley, to discuss general results from the project.