ANNEXE C

Rapport préliminaire de paléosismologie

Preliminary Report

PALEOSEISMIC INVESTIGATION OF LONG-TERM RATES OF LARGE EARTHQUAKES IN THE CHARLEVOIX AND PROPOSED RABASKA SITE AREAS

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PALEOSEISMIC INVESTIGATION OF LONG-TERM RATES OF LARGE EARTHQUAKES IN THE CHARLEVOIX AND PROPOSED RABASKA SITE AREAS

Executive Summary

Earthquake-induced paleoliquefaction features found along the Gouffre River in the Charlevoix area formed between A.D. 780 and 7590 B.C. (or 1170 and 9540 years B.P.). They indicate that at least one large Holocene paleoearthquake was centered in the Charlevoix area. The event was probably larger than the 1988 **M** 5.9 Saguenay earthquake and possibly larger than the 1925 **M** 6.2 Charlevoix earthquake. No Holocene paleoliquefaction features have been found along the Etchemin or Jacques-Cartier Rivers in the region of the proposed site for the Rabaska LNG terminal. Sediments that are susceptible to liquefaction do occur in the Rabaska site region and are likely to contain a record of large local Holocene earthquakes, if they occurred. Unfortunately, cutbank exposures were relatively poor at the time of reconnaissance. Given the current lack of paleoseismic data for the Rabaska site area, it would be premature to draw comparisons with the paleoseismic record for the Charlevoix area. This investigation has been limited by the small number of rivers surveyed in both areas and by the poor exposure along rivers in the site area. To realize the full potential of this paleoseismic investigation, an additional effort is needed to locate areas where liquefiable sediments and good exposures of Holocene deposits occur and to search those exposures for earthquake-induced liquefaction features. A better understanding of the distribution of paleoliquefaction features will help to assess whether or not the Charlevoix seismic zone extends into the Rabaska site area.

1. INTRODUCTION

This report presents a reconnaissance-level paleoseismic investigation to help define seismic source zones relevant to the design of the proposed Rabaska LNG terminal near Levis, Quebec. This investigation begins to address the question of long-term rates of large earthquakes in the Charlevoix seismic zone and Rabaska site area located about 70 km to the southwest. During this study, rivers are evaluated for presence and exposure of potentially liquefiable Quaternary sediments, searches for earthquake-induced liquefaction features are conducted along selected portions of rivers, sites where liquefaction features do and do not occur are documented, samples of organic material from these sites are dated to provide age control of sediments and liquefaction features, and observations are interpreted in terms of timing, magnitude, and source areas of paleoearthquakes and their implications for seismic source zones.

1.1 Purpose

The purpose of this paleoseismic study is to provide information about the approximate timing, magnitude, and source area of large Holocene earthquakes in the Charlevoix and Rabaska site areas in order to reduce uncertainties in seismic source models used in a site-specific earthquake hazard assessment of the proposed Rabaska LNG terminal site near Levis. As noted in the earthquake hazard assessment of the proposed Rabaska site, the seismicity rate is lower in the site area than the Charlevoix area but higher than in other areas of the St. Lawrence and Ottawa valleys (Atkinson, 2006). In addition, the study points out that the relationship of seismicity to major faults in the Charlevoix region is unclear and the geographical extent of faults responsible for Charlevoix seismicity uncertain. To represent the geological uncertainty of the seismic source zones, several models are considered in the hazard assessment, including one that limits the extent of the Charlevoix source zone to the area of historically high levels of seismicity and another that broadens the Charlevoix source zone to include the area of higher than average levels of seismicity near Levis. The report recommends that a paleoseismic investigation be conducted in the Charlevoix and Rabaska site areas to determine if the recurrence rate of large earthquakes is lower in the site area than in the Charlevoix area. If there were evidence in the Holocene (past 10,000 yr) geologic record for repeated large earthquakes in the Charlevoix area but not in the Rabaska site area, the seismic source model that extends the Charlevoix zone into the site area would receive less weight in the hazard assessment.

1.2 Scope of Work

The primary goals of this study are to evaluate whether or not sites conditions are suitable for paleoliquefaction investigation in the Charlevoix-Rabaska site region and to compare geologic records of strong ground shaking in the Charlevoix and Rabaska site areas during the Holocene. The scope of work includes the following tasks:

- gather background geological and geotechnical information relevant to the project:
- review the background information and develop a plan for field work;
- conduct field work in the Charlevoix-Rabaska site region to select sections of three rivers for reconnaissance and to document the presence and/or absence of liquefiable sediments and earthquake-induced liquefaction features;
- perform radiocarbon dating of organic samples for the purpose of estimating the ages of sediments, liquefaction features, and paleoearthquakes;
- analyze results of field work and radiocarbon dating in terms of timing, magnitude, and source areas of paleoearthquakes and their implications for seismic source zones; and
- prepare this report summarizing results of the paleoseismic study and making recommendations regarding further study.

2. REGIONAL SEISMOTECTONIC SETTING

The proposed site of the Rabaska LNG terminal in Levis, Quebec is located along the Appalachian Front, coincident with the St. Lawrence River in the site area (Figure 1; Douglas, 1969, 1972, 1973). This region has a long and complicated tectonic history punctuated by four major tectonic events. These events include the Grenvillian collision (1100 to 900 Ma), rifting related to opening of the Iapetus Ocean (700 Ma), Taconic orogeny related to closing of the Iapetus Ocean (450 Ma), and a Devonian meteor impact (350 MA) (Kumarapeli and Saull, 1966; Rondot, 1979; Lamontagne et al., 2000). Northwest of the Appalachian Front, faults resulting from these tectonic events can be observed in Precambrian granitic gneisses, granulite, and charnockite (Figure 2). Faults related to Iapetan rifting are parallel to the St. Lawrence River. Under the St. Lawrence River and to the southeast of the front, the Iapetan faults are overlain by several kilometers of folded Cambrian and Ordovician sedimentary strata.

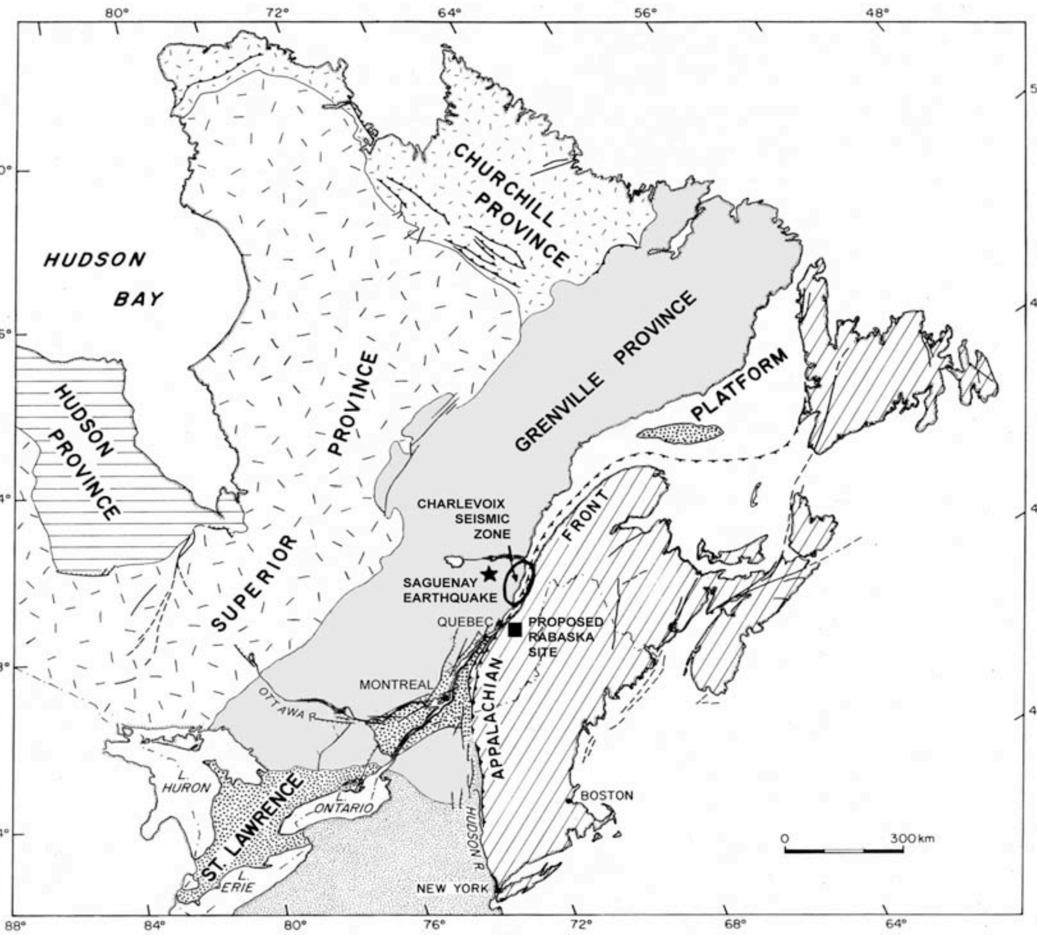


Figure 1. Geological provinces of eastern Canada and northeastern United States, showing locations of Charlevoix seismic zone, 1988 Saguenay earthquake, and proposed Rabaska site in Quebec (from Tuttle et al., 1992; after Douglas, 1973).

The Charlevoix seismic zone is one of the most seismically active areas in eastern North America (e.g., Adams and Basham, 1989; Figure 1). The seismic zone has generated five earthquakes greater than moment magnitude (**M**) 6 since 1663 and thousands of small earthquakes since 1977 (Lamontagne et al., 2000). The Quebec City area, including the Rabaska site, is not as seismically active as the Charlevoix area but is more active than other portions of the St. Lawrence and Ottawa valleys (Atkinson, 2006). Throughout the region it is difficult to correlate earthquakes with specific faults (Figure 2). In the Charlevoix seismic zone, earthquakes occur from the surface to 30 km depth, with most between 7 and 15 km (Lamontagne et al., 2000). In the Appalachian province, earthquakes occur below the Paleozoic strata at depths of 5 to 20 km in Precambrian rock.

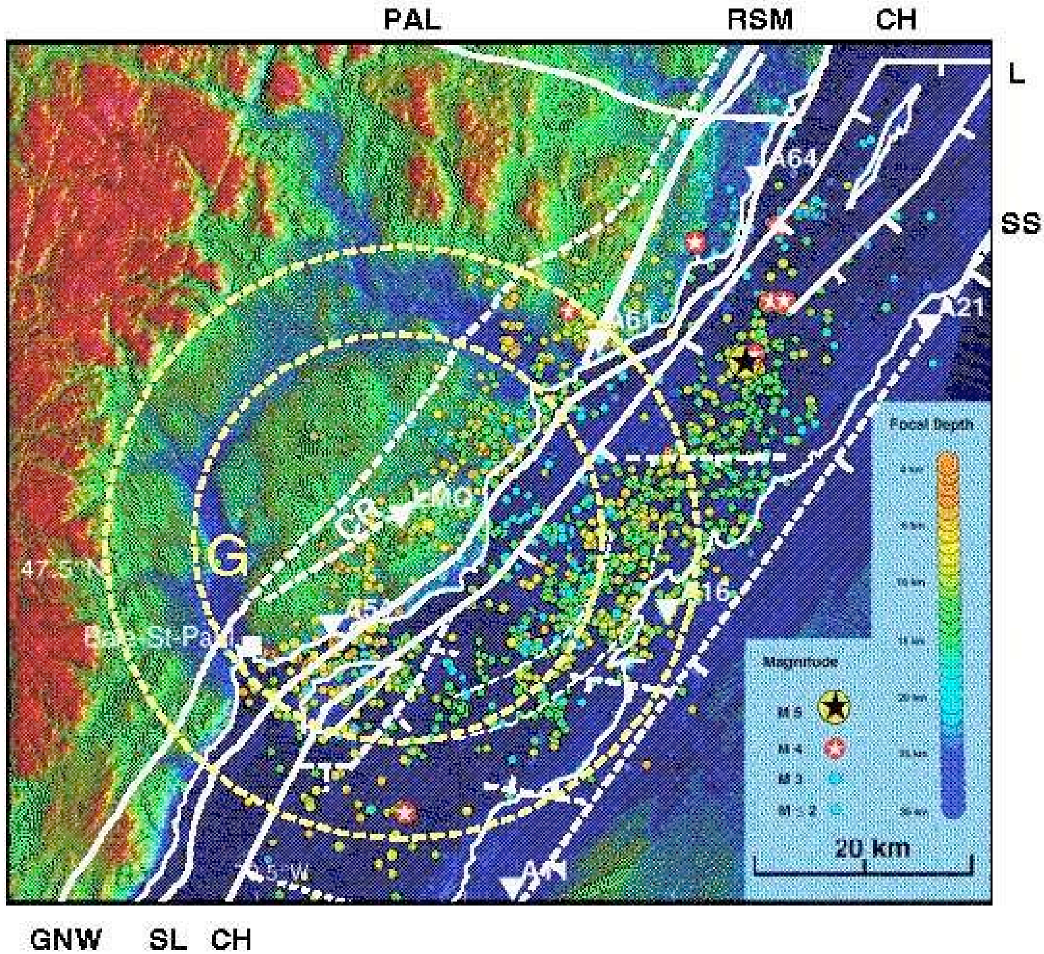


Figure 2. Combined RADARSAT-SAR ortho-image and terrain elevation, showing interpreted structures of Charlevoix seismic zone: RSM - Rang Sainte-Mathilde fault; SL - Saint-Laurent fault; CH - Charlevoix fault; L - Lièvres fault; SS - South Shore fault; G - peripheral graben of the impact structure; CR - crater fault; GNW - Gouffre NW fault; PAL - Palissades fault. Earthquake hypocenters (circles) are from January 1978 to September 1999, with colors reflecting focal depth. White triangles are station locations of the local and national seismograph network (from Lamontagne et al., 2000).

The reason for the high seismicity rate in the Charlevoix area is a topic of much debate. Some investigators think that the earthquakes are caused by reactivation of regional Iapetan faults in a uniform continent-wide stress field (e.g., Adams and Basham, 1989), while others think that the impact crater contributes to the high seismicity rate (e.g., Anglin, 1984; Lamontagne et al., 2000). The two models have significantly different implications for seismic hazards along the St. Lawrence valley. Little is known about the long-term behavior of the faults in the Charlevoix and

Rabaska site areas. Paleoseismology, which attempts to extend earthquake history back in time, has the potential to address this question.

3. PREVIOUS PALEOSEISMIC STUDIES IN THE REGION

Only a few paleoseismic studies, all of limited geographical scope, have been conducted in the Charlevoix-Rabaska site region. Nevertheless, the studies found a geologic record of prehistoric earthquakes that could help to characterize Holocene seismicity and earthquake potential. Studies of sediment cores from a few lakes in the Laurentide Mountains correlated anomalous silt layers with modern and historic earthquakes and attributed other silt layers deeper in the sections to prehistoric earthquakes (Doig, 1990 and 1998). The lake core studies suggested that there had been more frequent earthquakes in the Charlevoix area than in the Saguenay area during the Late Holocene. In addition, studies of landslides in the Saint-Maurice River valley near Shawinigan and in the Gouffre River valley near Baie St. Paul attributed mass movements to the 1663 Charlevoix earthquake and possibly to other events during the Holocene (Figure 2; Desjardins, 1980; Filion et al., 1990).

Accounts of the 1870 and 1925 Charlevoix earthquakes describe ground failure indicative of liquefaction in the Gouffre River valley (Smith, 1966), probably in sandy portions of Holocene fluvial and Late Wisconsin glaciomarine deposits (Rondot, 1972). Investigators excavated a large (2 m high and 10 m in diameter) mound in the Gouffre River valley and interpreted it to be a sand volcano resulting from seismic activity (Chagnon and Locat, 1988). Subsequent excavation of a nearby mound revealed blocks of tilted and folded stratified deposits (Tuttle, 1994). The mound was interpreted as an erosional remnant of a landslide block derived from the nearby hillslope. Radiocarbon dating of organic material buried beneath the block yielded a calibrated date of A.D. 1210-1400, indicating that the landslide occurred after A.D. 1210, possibly during the 1663 Charlevoix earthquake thought to be centered near La Malbaie about 30 km northeast of Baie-Saint Paul (Figure 2).

The 1988 **M** 5.9 Saguenay earthquake, centered about 50 km northwest of the Charlevoix seismic zone in the Laurentide Mountains, induced liquefaction up to 30 km from its epicenter.

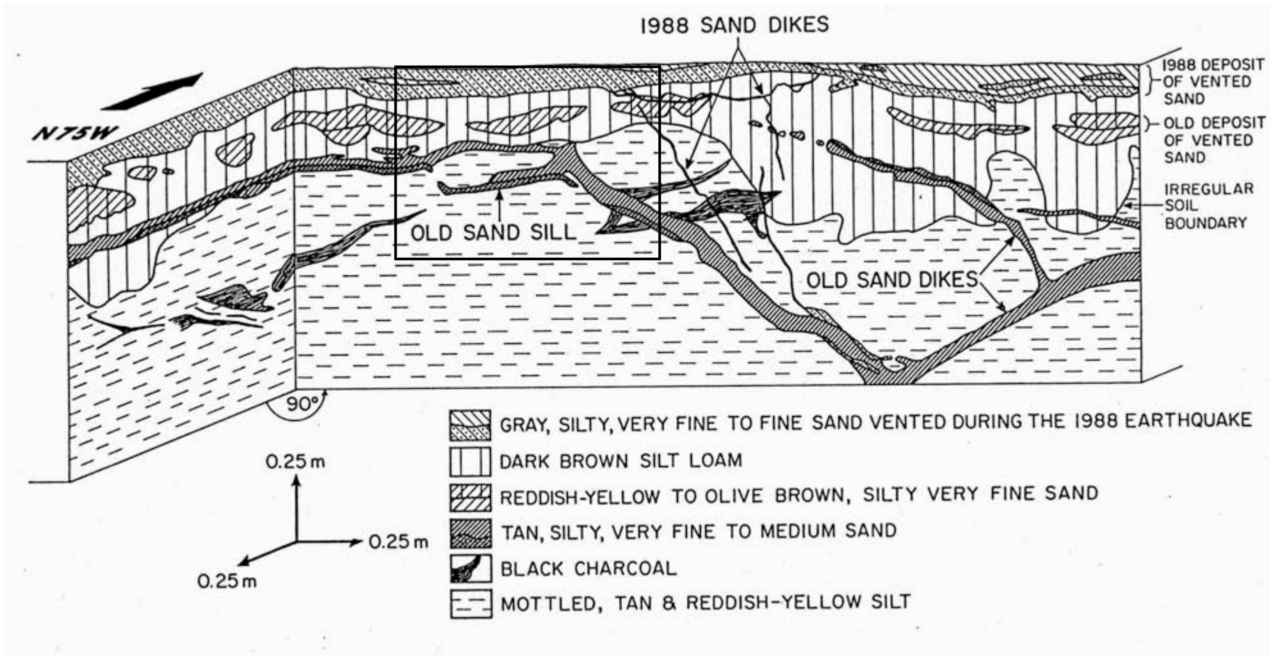
Liquefaction occurred in Holocene fluvial and Late Wisconsin glaciofluvial and glaciolacustrine deposits in the Ferland-Boilleau valley (Figure 1; Tuttle et al., 1990). During excavation and documentation of the liquefaction features, investigators found liquefaction evidence for a prior earthquake (Figure 3; Tuttle et al., 1992; Tuttle, 1994). Radiocarbon dating of the paleoliquefaction features indicated that a large earthquake occurred in the region in A.D. 1420 ± 200 yr. Given the relative size of the two generations of features, the previous event may have been larger or located closer to the Ferland-Boilleau valley than the 1988 Saguenay earthquake.

4. METHODOLOGY

Paleoseismology, or the study of past earthquakes as preserved in the geologic record, extends our knowledge of seismic activity into the prehistoric period, and thereby improves our understanding of the long-term behavior of fault zones or earthquake sources. Paleoseismology has proven especially useful in regions where the historical record of earthquakes is short and where strain rates are relatively low and recurrence intervals of large earthquakes relatively long.

In eastern North America, where surface traces of seismogenic faults are uncommon or difficult to identify, many paleoseismic studies have employed earthquake-induced liquefaction features. Other studies have used landslides, subaqueous slumps, and siltation layers in lacustrine deposits to infer paleoearthquakes, but there is greater uncertainties regarding the triggering mechanism of these features. Notable paleoliquefaction studies include those in the New Madrid seismic zone, source of the 1811-1812 **M** 7.5-8 earthquakes, in the central United States (e.g., Tuttle et al., 1996, 2002, 2005), the Charleston seismic zone, source of the 1886 **M** 7.3 earthquake in South Carolina (e.g., Amick et al., 1990; Talwani and Schaeffer, 2001), and the Wabash Valley seismic zone in southern Indiana and Illinois (e.g., Munson et al., 1997; Obermeier et al., 1993). Established methods for dating liquefaction features and estimating the timing, magnitude, and source areas of paleoearthquakes will be used in this paleoseismic investigation in southeastern Quebec. For more complete reviews of methods used in paleoliquefaction studies, the reader is referred to Obermeier (1996) and Tuttle (2001).

A



B

Figure 3. Two generations of earthquake-induced liquefaction features in Ferland, Quebec (Tuttle, 1994). Older features are more weathered and cut by younger sand dikes. A) Log of liquefaction features including sand blows and sand dikes exposed in excavation. B) Photograph of portion of trench wall outlined by box in A).

During a regional paleoliquefaction study, it is critical to narrowly constrain ages of liquefaction features so that they can be correlated over large distances and used to estimate the source areas and magnitudes of paleoearthquakes. Also, the better the age control on individual liquefaction features, the smaller the uncertainties associated with the timing, and thus recurrence times, of earthquakes. This is especially important where large earthquakes occur fairly frequently or there are multiple earthquake sources. Radiocarbon analysis is the most common dating technique used in paleoliquefaction studies. Analysis of artifacts found in soil horizons bounding liquefaction features can be employed in regions where ceramic and projectile point chronologies are well established. In addition, soil development within liquefaction features and bounding horizons can help to estimate the age of liquefaction features.

Of the various types of liquefaction features, sand blows provide the best opportunity for dating paleoearthquakes. Organic material and cultural artifacts in soil horizons developed in or above sand blows provide minimum age estimates of the features, and thus the event(s). Organic material and cultural artifacts within soil horizons buried by sand blows provide approximate, or at least maximum, age estimates of the event(s). In the case of sand dikes, their maximum ages can be determined by dating the uppermost stratigraphic unit that they crosscut or otherwise deform. Their minimum ages can be determined by dating material that clearly post-dates the liquefaction features, such as intruding roots and cultural pits. Deposits that overlie deformation related to liquefaction or an unconformity that truncates liquefaction features can provide minimum age estimates. Unfortunately, the method of bracketing the age of liquefaction features adds to uncertainties in age estimates. It is not uncommon for age estimates to have uncertainties of a couple of hundred years (using 2-sigma calibrated dates), even in the best of circumstances. Therefore, it is important to examine each site carefully for organic samples that will provide close minimum and maximum dates.

Case studies of many earthquakes around the world have shown that for an event of a given magnitude, liquefaction-related ground failures occur within certain epicentral and fault distances (Ambraseys, 1988). Also, the severity of liquefaction has been found to decrease with distance (Youd and Perkins, 1987). Therefore, the size distribution of liquefaction features can be used to estimate the location and magnitude of earthquakes, so long as variables such as liquefaction susceptibility of sediments, topography, and mechanism of ground failure are taken into account (Tuttle, 2001). Also, local earthquakes that induced liquefaction in the region, such as the **M** 6.2 1925 Charlevoix and **M** 5.9 1988 Saguenay event for Quebec, can serve as calibration events and help to interpret paleoliquefaction features.

Evaluation of scenario earthquakes using liquefaction potential analysis can help to place constraints on locations and magnitudes of paleoearthquakes. This is usually done using either the cyclic-stress method or the energy-stress method. We prefer the cyclic-stress method, also known as the simplified procedure (e.g., Seed and Idriss, 1982; Youd et al., 2001) because it is relatively easy to apply and is suitable for many field and tectonic settings. Using appropriate ground motion relations, peak ground accelerations are estimated for earthquakes of various magnitudes (e.g., **M** 5.5, 6, 6.5, 7.0, and 7.5) at distances of interest from known or suspected sources. Having derived peak ground accelerations, cyclic stress ratios generated by the various scenario earthquakes are calculated. Using empirical relations between cyclic stress ratio and corrected blow counts, it is determined whether or not representative layers at a site would be likely, or not likely, to liquefy. By comparing results of this analysis with field observations, one or more scenario earthquake can be selected that may reflect the locations and magnitudes of paleoearthquakes. During this analysis, minimum values of acceleration (liquefaction threshold) are estimated that may have been experienced during the earthquakes. For distal sites of liquefaction, the values may be close to the actual accelerations. Uncertainties in this method are related to identifying the layer that liquefied and estimating the susceptibility of the sediments at the time of the event.

Given the history of earthquake-induce liquefaction and the presence of sandy Holocene and Late Wisconsin deposits along tributaries to the St. Lawrence (e.g., Bolduc, 2003; Bolduc et al., 2003; and Cloutier et al., 1997), a record of large post-glacial earthquakes is likely to exist in the Charlevoix-Rabaska site region. If so, this paleoseismic investigation has the potential to extend the history of large earthquakes in the region by thousands of years. Possible limitations to this investigation include the distribution of liquefiable sediments, adequate exposure of Holocene and Late Wisconsin deposits, and preservation of features in narrow stream valleys and on floodplains disturbed by farming practices.

5. PROJECT RESULTS

The aim of this reconnaissance-level paleoseismic investigation is to provide information to determine if large Holocene earthquakes have occurred in the Charlevoix and Rabaska site areas in order to reduce uncertainties in seismic source models used in a site-specific earthquake hazard assessment of the proposed Rabaska LNG terminal site near Levis. During this investigation conducted in August and September 2006, we reviewed background information on the surficial geology of the Charlevoix-Rabaska site region, evaluated rivers in the region for presence and exposure of potentially liquefiable Quaternary sediments, searched selected portions of three river for earthquake-induced liquefaction features, documented sites where liquefaction features do and do not occur, dated organic-material from these sites to provide age control of sediments and liquefaction features, and interpreted observations in terms of timing, magnitude, and source areas of paleoearthquakes and their implications for seismic source zones (Figure 4).

5.1 Review of Background Information

Rabaska made available to this project reports by SNC-Lavalin (2006), Technisol (2005a, 2005b), and Terratech (2006) that contain relevant geological and geotechnical information for the Levis area. In addition, we gathered surficial geology maps and scientific articles on Quaternary geology and stratigraphy of the Charlevoix and Rabaska site areas (see References) and downloaded and printed digital topographic maps (1:50,000) produced by Energy, Mines, and Resources Canada. Also, we requested a search of the Quebec Ministry of Transport and Quebec Ministry of Natural Resources databases for previously collected borehole data describing sediment type and standard penetration test blow counts or N, a measure of relative density, for the following rivers: Beaurivage, Du Sud, Etchemin, Gouffre, Jacques-Cartier, Malbaie, Sainte-Anne, and Ouelle (Figure 4). This information would help to characterize the liquefaction susceptibility of sediments along the rivers. In addition, the information could be used to evaluate scenario earthquakes in a later phase of this investigation, if warranted. So far, one geotechnical report has been found for a study of the foundation of retaining walls along Route 138 in Riviere Malbaie (D'Astous, 1996).

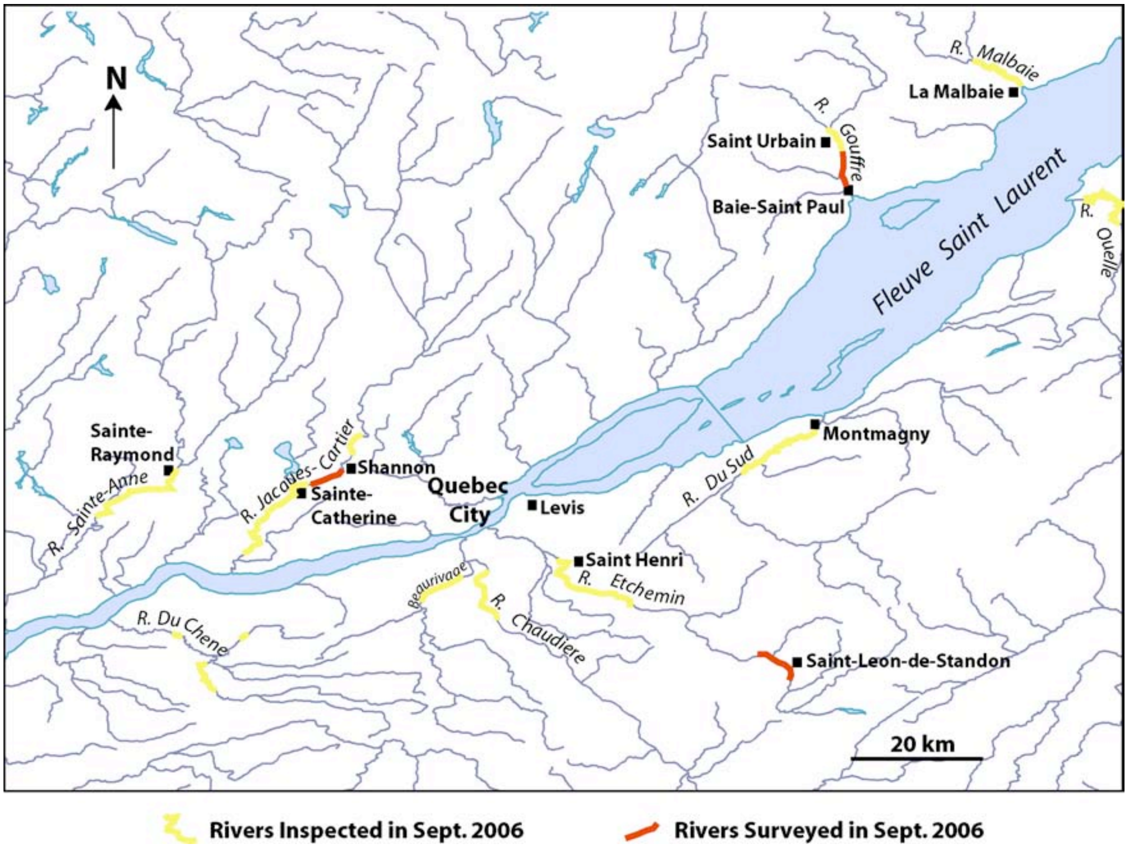


Figure 4. Map of surface hydrology in the Quebec City region (from Quebec Resources Naturelles et Faune; scale1:1,000,000), showing portions of rivers inspected to assess suitability for reconnaissance (yellow) and surveyed to search for earthquake-induced liquefaction features (red).

According to the report by SNC-Lavalin (2006), Quaternary deposits in the Levis area include till, fluvio-glacial sediments, clayey marine sediments, sandy marine sediments, organic sediments, and recent fluvial sediments. Quaternary stratigraphy varies laterally and vertically across the area. The most common stratigraphic sequence is peat over sandy marine sediments over clayey marine sediments. This sequence is observed in the drainage basins of the Etchemin and Chaudiere Rivers. Where bedrock is close to the surface, sandy marine sediments overlie till or rest directly on rock. This is the case in the northern part of the area and along the Chaudiere River. Of the various sediment types, sandy marine sediments and clayey marine sediments cover most of the surface area.

Consistent with the reports mentioned above, a recent surficial geology map of the Levis area shows that Holocene fluvial and Wisconsin marine littoral deposits occur along the Beaurivage and Chaudiere Rivers (Bolduc, 2003; Table 1). Similar deposits and Wisconsin marine deep-water deposits are mapped along the Etchemin River. Surficial geology maps of the Quebec and Saint-Marc-des Carrieres areas depict Holocene fluvial and organic deposits and Wisconsin marine deltaic deposits along the Jacques-Cartier and Sainte Anne Rivers (Bolduc et al., 2003; Cloutier et al., 1997; Table 1). Similar deposits and Wisconsin marine littoral deposits are mapped along the Montmorency River. To the northeast in the Charlevoix area, Quaternary glacial, fluvial, and marine deposits are fairly widespread and have been mapped along both the Gouffre and Malbaie Rivers (Rondot, 1969 and 1972; Table 2). Unfortunately, the different types of Quaternary deposits are not differentiated on these maps of the Charlevoix area. Surficial geology maps have not been identified or reviewed for the southern shore of the Saint Lawrence River southwest or northeast of Levis where the Du Chene, Du Sud and Ouelle Rivers are located (Figure 4). The Quaternary geology is likely to be quite similar to the Levis area where Holocene fluvial and Wisconsin marine deposits are mapped along river courses.

As reported in a geotechnical report for the proposed west option site LNG receiving terminal (Terratech, 2006), granular soils in the upper 16 m are generally compact to dense with standard penetration test blow counts (N) that range from 20 to 50, and with a few values less than 10. N values from 0 to 4 indicate very loose relative density, from 4 to 10 reflect loose density, and from 10 to 30 point to moderate density (Terzaghi and Peck, 1967). Liquefaction susceptibility decreases with increasing relative density or N (Youd and Perkins, 1987). If saturated, sediments with low blow counts (0 to 10) are thought to be susceptible to liquefaction during strong earthquakes. As demonstrated in the liquefaction potential analysis performed by Terratech (2006), the sandy portions of the soil profile with low blow counts at the west option site are susceptible to localized liquefaction at depth, not viewed as a risk for lightly loaded shallow foundations. Geotechnical investigations were conducted also for proposed pipeline crossings of the Beaurivage, Etchemin and Chaudiere Rivers (Technisol, 2005a and 2005b). Near the pipeline crossing on the south side of the Beaurivage River, borehole log F-BE-02 indicates sand with a trace of silt and N values of 3 to 13 from 0 to 2.5 m below the surface, silty sand, sand, and silt, with a trace of clay and N values of 11 to 12 from 2.5 to 5 m depth, similar sediment with an N value of 28 from 5 to 7.25 m, and interbedded silty clay and silty sand with N values of 1 to 5 from 9.1 to 15.5 m depth. A liquefaction potential analysis has not been performed with these data, but low N values for a few of the sandy layers suggest that they are likely to be susceptible to liquefaction. Sediments encountered in boreholes at the pipeline crossings of the Etchemin and Chaudiere Rivers, on the other hand, did not appear to be susceptible to liquefaction. The geotechnical investigations indicate that liquefiable sediments do occur in the Rabaska site area and suggest that a record of large local Holocene earthquakes could exist in the form of liquefaction features, if such events occurred.

According to the geotechnical study for the retaining walls along Route 138 in Riviere Malbaie (D'Astous, 1996), silty sand with traces of gravel and clay and N values ranging from 2 to 9 occurs from 0.3 to 3.8 m below the surface, and silt and sand with traces of clay and N values of 12 to 28 occur from 3.8 to 7.6 m below the surface. Both the upper and lower sedimentary units are within the range of blow counts for which liquefaction is possible if they are saturated and subjected to strong ground shaking. Liquefaction potential analysis would have to be conducted to determine whether or not these sediments are likely to liquefy at various levels of ground shaking.

5.2 Selection of River Sections for Field Inspection

According to compilation of worldwide data on earthquakes that induced liquefaction, saturated Holocene sandy deposits of fluvial, deltaic, and lacustrine origins are highly to moderately susceptible to liquefaction (Youd and Perkins, 1978). Locally, the 1988 Saguenay, Quebec earthquake induced liquefaction in Holocene sandy fluvial and Late Wisconsin sandy glaciofluvial and glaciolacustrine deposits up to 30 km from its epicenter (Tuttle et al., 1990). Therefore, in the study region, Holocene and Late Wisconsin sandy fluvial, deltaic, and lacustrine deposits are likely to be susceptible to liquefaction. In addition, the formation of liquefaction features is likely to be enhanced where the sandy deposits are interbedded with fine-grained deposits, such as silty or clayey fluvial or marine deposits, that would promote the buildup of pore-water pressure during ground shaking.

Meandering rivers often provide exposures of Quaternary deposits. Therefore, we viewed rivers in the region using Google Earth to identify meandering sections. After reviewing maps, papers, and reports mentioned above, we selected meandering river sections for field inspection where Holocene fluvial and Late Wisconsin marine deltaic and littoral deposits had been mapped. These included sections along the following rivers: Beaurivage, Chaudiere, Du Chene, Du Sud, Etchemin, Gouffre, Jacques-Cartier, Malbaie, Montmorency, Ouelle, and Sainte Anne. See Figure 4 and Tables 1, 2 and 3 for a summary of the locations, mapped surficial deposits, and other characteristics of the selected river sections.

5.3 Field Inspection of Rivers

In early September 2006, we inspected selected meandering sections of rivers in the Charlevoix-Rabaska site region where Holocene fluvial and Late Wisconsin marine deltaic and littoral deposits had been mapped (Figures 4 and 5). We inspected the rivers at bridge crossings and along roads that come close to the rivers for cutbank exposure of sediments, canoeing conditions and access points. Unfortunately, cutbank exposure was poor along many of the rivers due to vegetative cover (Figures 6 and 7). Our observations are summarized in Tables 1, 2, and 3.

Figure 5. Photograph of meandering Etchemin River near Saint-Leon-de-Standon.

Figure 6. Photograph of Beaurivage River showing poor cutbank exposure in September 2006. Borehole data indicates that sediments likely to be susceptible to liquefaction occur along river.

Figure 7. Photograph showing cutbank exposure of sandy and silty sediments along Etchemin River in September 2006. Even in meander bends, cutbanks are partially vegetated.

Table 1. Rivers in Rabaska Site Area.

River	Location	Mapped Surficial Deposits	Canoeing Conditions	Exposure
Beaurivage	Near Saint-Etienne-de-Lauzon	Holocene fluvial; Wisconsin marine littoral	Good	Steep banks suggest erosion in bends; vegetated
Chaudiere	Rue des Lilas to Rt. 73 bridge	Mostly Wisconsin marine littoral; some Holocene fluvial	Good to R1 rapids	Low vegetated banks; rock outcrops
Du Chene and tributaries	Near Val-Alain West of Laurier-Station Near Saint Edouard	Unknown; probably similar to Chaudiere and Etchemin	Small creeks; little water Good Rapids	Vegetated banks Grassy, slumpy banks; may have potential Boulders
Etchemin	Near Saint-Jean Chrysostome Saint-Anselme to Saint-Henri Near Saint-Leon-de-Standon	Holocene fluvial Holocene fluvial; Wisconsin marine littoral and deep water Unknown	Easy to R1 rapids Good to R1 rapids Good	Poor exposure; vegetated banks; rocky and boulders Observed in few places; vegetated and rocky banks Vegetated banks; little exposure in bends; sandy
Jacques-Cartier	Upstream from Saint-Gabriel-de-Valcartier Near Shannon and St. Catherine	Modern and Holocene fluvial; Wisconsin marine deltaic Holocene fluvial; Wisconsin marine deltaic	Good to R1 rapids Good to R1 rapids	Vegetated cobbley banks; high banks-sand above cobbles inset in silt Vegetated banks; sandy exposure near Shannon
Sainte-Anne	Near Saint-Raymond Near Sainte-Christine	Holocene fluvial; Wisconsin marine deltaic Holocene fluvial; Wisconsin marine deltaic	Good Good	Vegetated; retaining wall; little exposure; cobbley Some exposure of sandy sediment

Table 2. Rivers in Charlevoix Area.

River	Location	Mapped Surficial Deposits	Canoeing Conditions	Exposure
Gouffre	Bridge crossings St. Urbain, Rt. 138, and Rt. 362 in Baie-Saint Paul	Quaternary glacial, fluvial, or marine	Good to R1 rapids	Few exposures; sand, pebbles, cobbles, and boulders
Malbaie	Clermont bridge to La Malbaie bridge crossing	Quaternary glacial, fluvial, or marine	Good	Low banks - many cobbles; high banks - fine layered sediment
Ouelle	Saint-Pacome to Riviere Ouelle	Unknown; probably Holocene fluvial	Good	Vegetated and rip rap; few sandy exposures downstream from Rt. 20

Table 3. Rivers between Charlevoix and Rabaska Site Areas.

River	Location	Mapped Surficial Deposits	Canoeing Conditions	Exposure
Du Sud	Saint-Francois to Montmagny	Unknown; probably Quaternary glacial, fluvial, or marine	Good	Mostly vegetated; little exposure in bends
Montmorency	Barriere du Seminaire to Ile Enchanteresse	Modern and Holocene fluvial; Wisconsin marine littoral	Rapids; R2 and higher	Rocky

On the basis of mapped surficial deposits and field observations including exposure, we selected the following river segments for an initial phase of reconnaissance: 16 km of the Gouffre River between Rt. 138 and Rt. 362 near Baie-Saint Paul, 12 km of the Etchemin River near Saint-Leon-de-Standon, and 6 km of the Jacques-Cartier River downriver from Shannon.

5.4 River Reconnaissance and Radiocarbon Dating

We conducted reconnaissance of sections of the Gouffre, Etchemin, and Jacques-Cartier Rivers, examining cutbank exposures of Holocene and Wisconsin sediments for earthquake-induced liquefaction features and other co-seismic deformation. For each river, we described exposure and sedimentary conditions for several representative sites. In addition, we described all sites where liquefaction features or soft-sediment deformation structures occur. We measured the size and orientations and described grain-size, degree of weathering or soil development, and stratigraphic context of liquefaction features. We photographed significant features and collected wood and other organic materials for radiocarbon dating. The location of each site was marked on a 1:50,000 scale topographic map and a hand-help global positioning system device was used to measure its position. The information was recorded on site description forms and is summarized in Tables 4, 6, and 7. Beta Analytic, Inc., conducted radiocarbon dating of organic samples for this study. They used the accelerator mass spectrometry (AMS) technique recommended when high precision is desired. The results of the radiocarbon dating are summarized in Tables 5 and 8 and discussed below.

5.4.1 Observations for the Gouffre Rivers

We conducted river reconnaissance along 16 km of the Gouffre River between Rt. 138 and Rt. 362 near Baie-Saint Paul (Figure 8). Exposure along the Gouffre River is good to excellent in river bends, most cutbanks are 6 to 13 m high, and slumping is common. In most exposures, a coarse-grained deposit of sand, pebbles, and cobbles is underlain by a fine-grained deposit of clay, silty clay, or silt with interbeds of sand (Table 4). In several locations, the fine-grained silty clay deposit is underlain by loose fine to medium sand exposed at the base of the cutbank or encountered below the river level with a soil probe. The sedimentary conditions appear to be good for the formation of earthquake-induced liquefaction features. Radiocarbon dating of organic material collected near the base of the cutbank at site GR6 from the silty clay deposit indicates that it was deposited 9410-9540 years B.P. (Table 5). Therefore, sediments exposed along the Gouffre River are old enough to record Holocene earthquakes.

At sites GR1 and GR2, the coarse-grained deposit is overlain by a clayey silt deposit with tilted bedding, interpreted as a landslide deposit. A buried soil/organic-rich layer occurs at the upper contact of the coarse-grained deposit and represents the land surface at the time of mass movement. Radiocarbon dating of samples (GR1-W1, GR2-C1) collected from the buried soil/organic-rich layer at the two sites indicates that the landslide occurred after A.D. 1440 and possible after A.D. 1640 (Table 5). Like others in the Charlevoix region, the landslide could have been triggered by the 1663 Charlevoix earthquake.

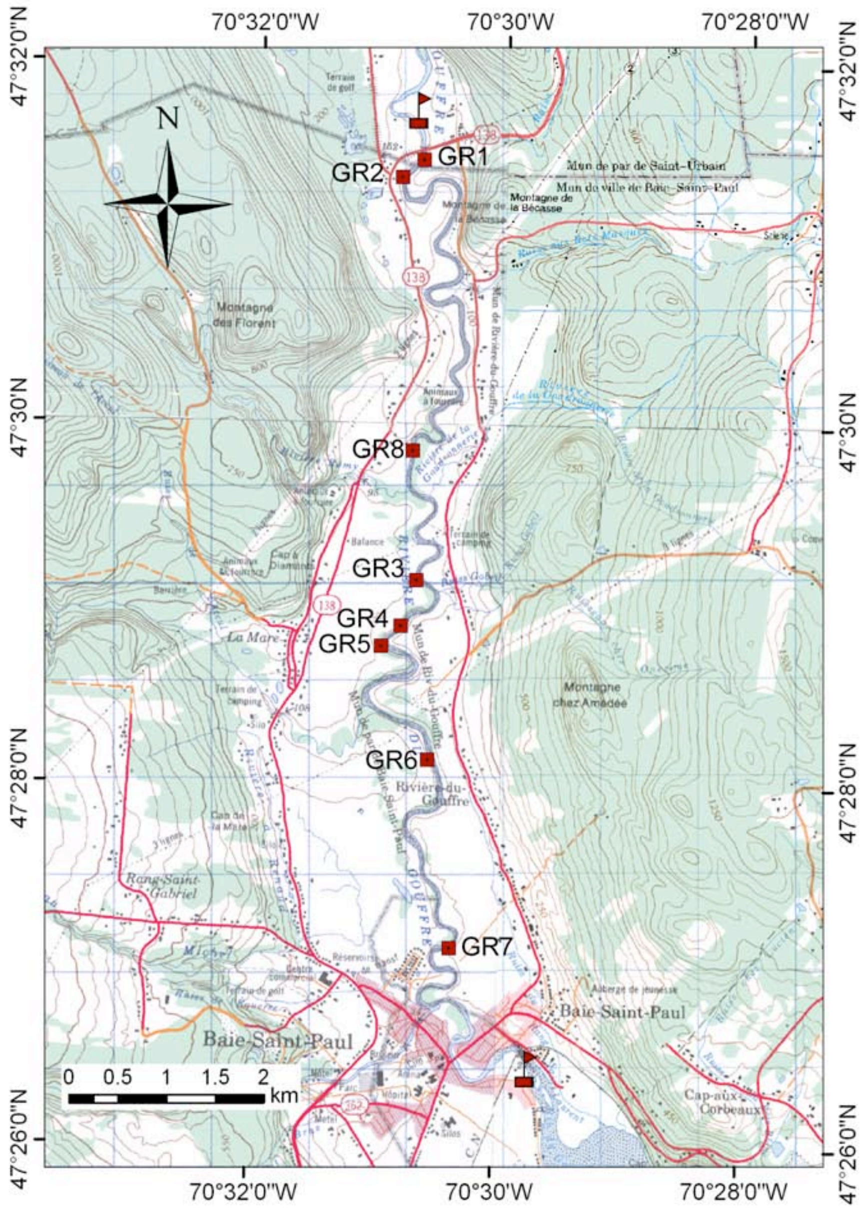


Figure 8. Topographic map of Gouffre River near Baie-Saint Paul showing locations of study sites described in Table 4. Red flags mark beginning and end points of river reconnaissance.

We found eight sand dikes interpreted as earthquake-induced liquefaction features at sites GR3 and GR4, another possible sand dike at site GR8, and a loose sand layer that may be an intruded sill at GR2 (Tables 4 and 6). The three sand dikes at GR3 range from 9 to 15 cm in width. The two larger dikes extend upward through 3 m of a silty clay deposit and terminate in the base of an overlying sandy deposit (Figure 9). The dikes fine upward from coarse sand to silty, very fine sand and contain clasts of silty clay. Small subhorizontal dikes extend from and between the two large dikes about 15 cm below the contact between the silty clay and overlying sand deposit. There is little to no weathering in all three dikes. Many small pieces of organic material occur in root casts or animal burrows in the tips of the two larger dikes. The biological casts post-date the formation of the sand dikes. Radiocarbon dating of a sample of the organic material from one of the casts (GR3-C1) yielded a calibrated date of A.D. 650-780 and provides a minimum age estimate for the sand dikes (Table 5). The date indicates that the sand dikes are prehistoric in age and formed before A.D. 780. A very small sample of organic sediment (GR3-C2) was collected between the two larger sand dikes from the silty clay deposit 17 cm below the contact with the overlying sand deposit. Radiocarbon dating of the sample gave a result of 16,130-15,400 B.C. This date is much older than those from other samples collected along the Gouffre River. The sample was small, mineral in nature, and could have been reworked. The date of 7460-7590 B.C. (or 9410-9540 years B.P.) from GR6-W1, a sample of leaves and other plant material collected only 80 cm above the water level, may more closely reflect the age of the clayey silt deposit. If so, the sand dikes formed between A.D. 780 and 7590 B.C. (or 1170 and 9540 years B.P.). Even so, the age of the sand dikes is not well-constrained.

The five sand dikes at GR4 range from 1 to 3 cm in width (Tables 4 and 6). All of the sand dikes terminate within a silty clay deposit exposed along the base of the cutbank. The small dikes extend no more than 1.1 m above the river level at the time of reconnaissance. All the dikes are composed of very fine sand and exhibit little to no weathering. No organic material for dating was found at this site. Given that they terminate within the silty clay deposit, the sand dikes likely formed since 7590 B.C.

At site GR7, we found only one possible sand dike (Tables 4 and 6). It is 1 cm wide and only 1.25 m in length, pinching out in both directions within a silt deposit at the base of the cutbank. The dike is composed of very fine sand and could be a sand lense within a tilted slump block.

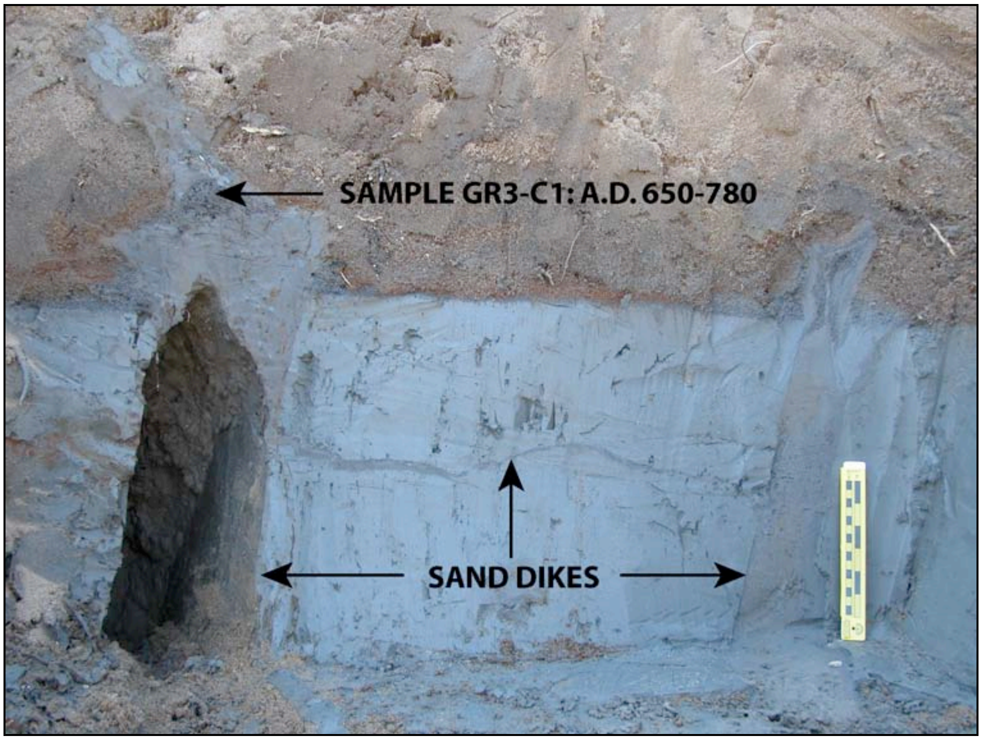


Figure 9. Photograph of sand dikes (left one partially washed out) at site GR3 intruding silty clay deposit and terminating in base of overlying sand deposit. Note small subhorizontal dike extending between larger subvertical dikes. Plant material from root cast or animal burrow in top of sand dike provides minimum age constraint of A.D. 650-780 and indicates that it is prehistoric.

A possible sill at GR2 is 5 cm thick, composed of loose, fine to medium sand, and occurs within a sand layer that fines upward from fine sand to silt (Tables 4 and 6). There is no feeder dike associated with the sill, but there are discontinuous domains of similar sand at one end of the sill. In addition, there is a possible source layer of very loose medium to fine sand at the base of the cutbank below an intervening clay deposit. The possible sill occurs near the top of a coarse-grained deposit and below a landslide deposit described above. A radiocarbon date from charcoal (sample GR2-C1) in the buried soil does not help to estimate the age of the possible sill.

Table 4. Description of Study Sites along the Gouffre River.

Site Number	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)	Liquefaction Features Observed	Exposure	Sediments Observed in Cutbank
GR1	47.5245	70.5112	None	Excellent in scarp of slump failure	Cross-bedded sand ovelies tilted massive to layered clayey silt; underlain by interbedded sand, pebbles, and cobbles with organic layer at upper contact
GR2	47.5228	70.5142	Possible sill	Fair; bank mostly vegetated	Brownish clayey silt overlies generally fining upward sequence of cobbles, pebbles, and sand with organic layer at upper contact; underlain by blue-gray clay and very loose, medium to fine sand
GR3	47.4856	70.5114	Sand dikes	Excellent	Interbedded cross-bedded sand and cobble layers overlies silty clay with interbeds of silty sand and silt
GR4	47.4814	70.5134	Sand dikes	Lower 1.2 m of bank very good; otherwise vegetated	Gray, silty clay
GR5	47.4795	70.5159	None	Very good but slumpy	Slump blocks of sandy, cobbley, and silty deposits; upside down tree in sandy deposit
GR6	47.4691	70.5094	None	Good; bank partly vegetated	Interbedded coarse to silty very fine sand overlies clayey silt with interbeds of sand; organic material in silt deposit low in cutbank
GR7	47.4517	70.5060	None	Excellent	Interbedded silt and sand overlies silt with interbeds of sand becomes massive below
GR8	46.4976	70.5122	Possible sand dike	Excellent	Cross-bedded sand overlies layered silt; some portions appear tilted

Table 5. Radiocarbon Dating of Samples from Study Sites along the Gouffre River.

Sample Number Lab Number	$^{13}C/^{12}C$ Ratio	Radiocarbon Age Yr B.P.[1]	Calibrated Radiocarbon Age Yr B.P.[2]	Calibrated Calendar Date A.D./B.C.[2]	Sample Description
GR1-W1 Beta-221043	-26.4	370 ± 40	310-510	A.D. 1440-1640	Plant material collected 4.5 m below surface from organic layer below tilted silt deposit and at top of interbedded sand, pebbles, and cobbles
GR2-C1 Beta-221504	-26.4	460 ± 40	470-540	A.D. 1410-1480	Charcoal collected 2 m below surface from buried soil below silty clay and above fining upward unit of cobbles and sand
GR3-C1 Beta-221044	-26.0	1320 ± 40	1170-1300	A.D. 650-780	Plant material collected 10 m below surface from top of sand dike
GR3-C2 Beta-221505	-26.6	14790 ± 50	17340-18080	16130-15400 B.C.	Organic sediment collected 10 m below surface or 2.9 m above water level from silty clay; 17 cm below contact with overlying sandy deposit
GR6-W1 Beta-221045	-24.4	8460 ± 60	9410-9540	7460-7590 B.C.	Plant material collected 7.2 m below surface or 80 cm above water level from organic layer within interbedded clayey silt and sand

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1 Conventional radiocarbon ages in years B.P. or before present (1950) determined by Beta Analytic, Inc. Errors represent 1 standard deviation statistics or 68% probability.

2 Calibrated age ranges as determined by Beta Analytic, Inc., using the Pretoria procedure (Talma and Vogel, 1993; Vogel et al., 1993). Ranges represent 2 standard deviation statistics or 95% probability.

Table 6. Earthquake-Induced Liquefaction Features along Riviere Gouffre.

Site number	Sand Dike or Sill Width (cm)	Strike and Dip of Sand Dikes	Weathering Characteristics	C14 Age Constraint	Age Estimate (A.D.) of Features
GR2	5	Sill; not measured	Some iron-staining but loose	After 7590 B.C.	Holocene
GR3	15 12 9	N24°E, 73°SE N59°E, 78°SE N19°E, 86°NW	Little to none	Before A.D. 780 After 7590 B.C.	Holocene
GR4	3 2 1	N84°W, 88°NE N34°W, 86°NE N33°W, 85°NE	Little to none	After 7590 B.C.	Holocene
GR8	1	Not measured	Little to none	After 7590 B.C.	Holocene

The sand dikes found on the Gouffre River are classic earthquake-induced liquefaction features. The source beds that liquefied must occur below the silty clay deposits intruded by the sand dikes and at least 9 m below the floodplain. None of the observed sand dikes reached the surface. This is not surprising given the thick section of coarse-grained deposit they would have to cross. This leads one to wonder about the liquefaction-related ground failure described during the 1870 and 1925 earthquakes. Why did we not find historic liquefaction features? Do they occur in areas that are currently poorly exposure or upstream from the section searched? Could the paleoearthquake have been stronger than the 1925 earthquake and produced more obvious liquefaction features? Additional study is needed along the Gouffre to answer these questions that may have implications regarding the use of the 1925 earthquake as a calibration event.

5.4.2 Observations for the Etchemin River

We conducted reconnaissance along 12 km of the Etchemin River near Saint-Leon-de-Standon (Figure 10). Exposure along this section of the river is fair in river bends with 50 percent or more of the 2 to 3 m high cutbanks covered by vegetation (Table 7; Figure 7). In most exposures, an interbedded silt and very fine sandy silt deposit containing buried soils overlies a medium to coarse sand or pebbly sand deposit. Radiocarbon dating of plant material from organic layers near the base of the cutbank at three sites (EC2, EC3, and EC6) provides excellent age control for sediments along the river and indicate they were deposited since 7310 B.C. (or 9260 years B.P) (Table 8). Wood collected 1.6 m below the surface from a soil developed in the top of a silt deposit yielded a calibrated date of 2920-3120 B.C. and 3220-3320 B.C. (or 4860-5070 and 5170-5270 years B.P.). The sandy sediments above the soil were deposited since 3320 B.C. (or 5270 years B.P.). The 3-m section of sediments exposed along the Etchemin River in September 2006 are old enough to record earthquakes during the past 9200 years.

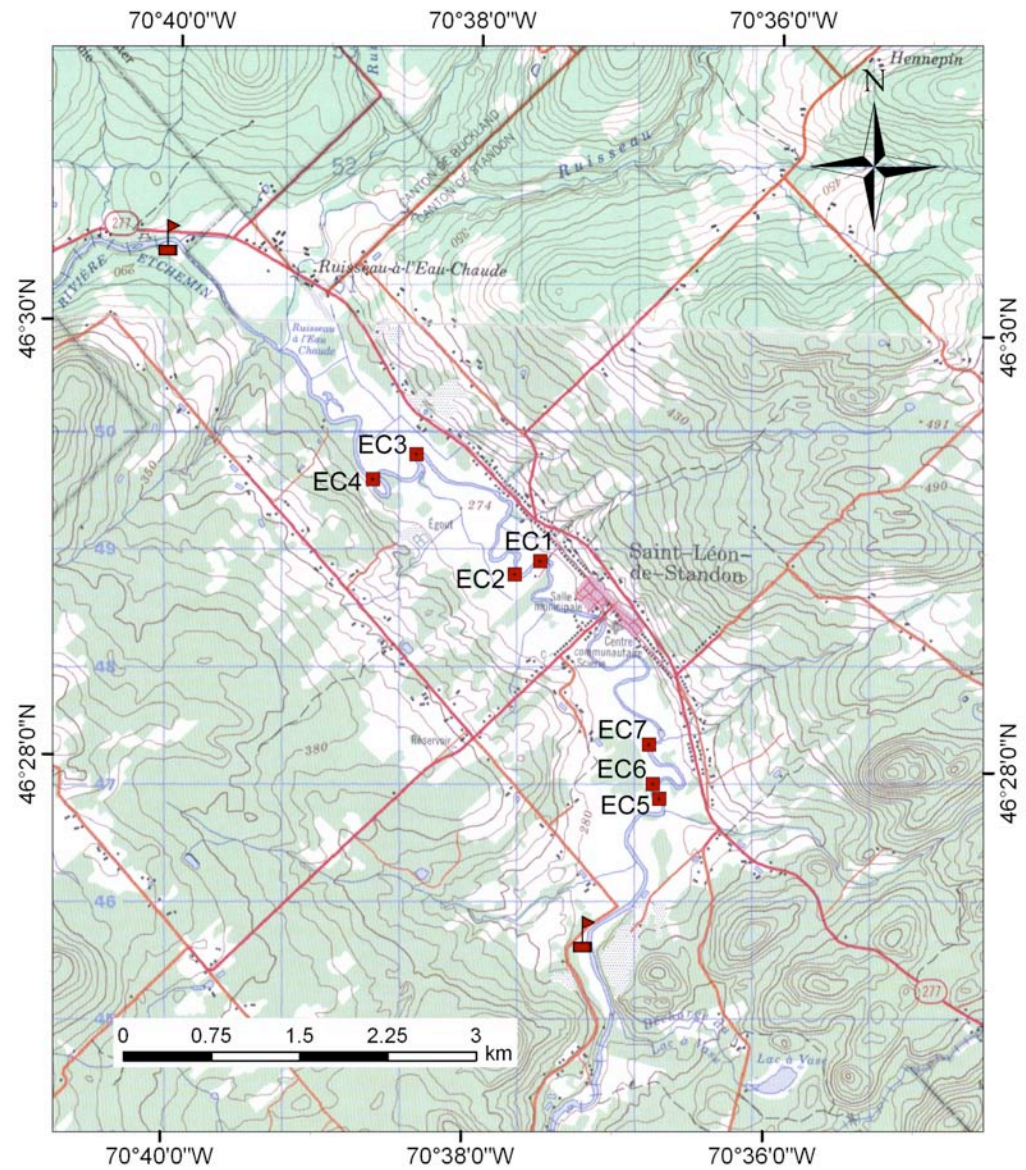

Figure 10. Topographic map of Etchemin River near Saint-Leon-de-Standon showing locations of study sites described in Table 7. Red flags mark beginning and end points of river reconnaissance.

Sedimentary conditions appear to be suitable for the formation and preservation of liquefaction features; yet, we found no sand dike or other unequivocal earthquake-induced liquefaction feature (Figure 11). If exposure had been better, we could be more confident that liquefaction features do not occur in the Holocene sediments near Saint-Leon-de-Standon. We did observed soft-sediment deformation structures at sites EC2 and EC7 (Table 7; Figure 12). Given the age of the sediments along the river, these deformation structures must have formed in the past 9200 years. Certain types of deformation structures such as load casts and heave structures are sometimes attributed to ground shaking (Sims, 1973). Features such as these could help to constrain ground-shaking but would require additional study.

Figure 11. Photograph of weathered silty very fine sand over cross-bedded medium to coarse sand at site EC4. Sedimentary conditions appear suitable for formation of earthquake-induced liquefaction features. So far, no uneqivocal liquefaction feature has been found along Etchemin River.

Table 7. Description of Study Sites along the Etchemin River.

Site Number	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)	Liquefaction Features Observed	Exposure	Sediments Observed in Cutbank
EC1	46.4822	70.6258	None	Fair; banks slumpy and partly vegetated	Interbedded pebbley sand and very fine sandy silt with buried soil horizon overlies pebbley sand
EC2	46.4812	70.6286	Soft-sediment deformation	Fair	Interbedded very fine sandy silt and silt; buried soil
EC3	46.4902	70.6398	None	Good	Interbedded very fine sandy silt and silt with organic and pebbley sand layers
EC4	46.4882	70.6445	None	Excellent	Interbedded very fine sand and silty very fine sand with manganese nodules overlies crossbedded medium to coarse sand
EC5	46.4642	70.6121	None	Fair; banks slumpy and 65% vegetated	Silty very fine sand overlies pebbley sand
EC6	46.4653	70.6128	None	Fair; banks 50% vegetated	Very fine sandy silt overlies silt with buried soils; sand 1 m below water level
EC7	46.4683	70.6134	Soft-sediment deformation	Good	Interbedded very fine sandy silt and silty very fine sand

5.4.3 Observations for the Jacques-Cartier River

We conducted reconnaissance along 6 km of the Jacques-Cartier River downriver from Shannon. (Figure 13; Table 9). Except for the upstream 2 km, the exposure along this section of the river is poor. The banks are heavily vegetated and in places protected from erosion with large boulders or riprap. At sites JC1a and JC1b, cutbank exposures reveal interbedded silty fine sand, sand, and silt. At site JC2, medium sand overlies rhymites of clayey silt and very fine sand. We found organic material for radiocarbon dating only at site JC1b. The sample came from an organic layer within a deposit of interbedded silt and silty very fine sand that appears to be a channel fill of a nearby creek. The sample yielded a calibrated date of A.D. 650-770 (or 1180-1300 B.P.) (Table 8) which represents the age of the channel fill and post-dates the sandy deposit in which it is incised. Further reconnaissance of the river was abandoned due to poor exposure at the time.

Figure 12. Photograph of soft-sediment deformation structure at site EC7 on Etchemin River. Sand diapir suggests upward remobilization of sand and deformation of overlying silt lamination. Alternatively, this may be a flame structure related to depositional processes.

Table 8. Radiocarbon Dates of Samples from Study Sites along the Etchemin and Jacques-Cartier Rivers.

Sample Number Lab Number	$^{13}C/^{12}C$ Ratio	Radiocarbon Age Yr B.P.[1]	Calibrated Radiocarbon Age Yr B.P.[2]	Calibrated Calendar Date A.D./B.C.[2]	Sample Description
EC2-W1 Beta-221041	-26.8	8130 ± 60	8990-9260	7040-7310 B.C.	Plant material collected 2.5 m below surface from organic layer within interbedded silt and very fine sandy silt
EC3-W1 Beta-221503	-28.1	7550 ± 40	8330-8400	6380-6450 B.C.	Leaf fragments collected 2.4 m below surface from organic layer within interbedded silt and very fine sandy silt
EC6-W1 Beta-221042	-24.0	6860 ± 50	7600-7780	5660-5830 B.C.	Wood collected 2.8 m below surface from outer 1 cm of tree trunk bedded in silt
EC6-W2 Beta-221502	-28.0	4420 ± 40	4860-5070 5170-5270	2920-3120 B.C. 3220-3320 B.C.	Wood collected 1.6 m below surface from paleosol developed in silt
JC1b-W1 Beta-221506	-27.10	1330 ± 40	1180-1300	A.D. 650-770	Plant material including leaf and needles collected 2.8 m below surface from organic layer within interbedded silt and silty very fine sand

[1] Conventional radiocarbon ages in years B.P. or before present (1950) determined by Beta Analytic, Inc. Errors represent 1 standard deviation statistics or 68% probability.

[2] Calibrated age ranges as determined by Beta Analytic, Inc., using the Pretoria procedure (Talma and Vogel, 1993; Vogel *et al*., 1993). Ranges represent 2 standard deviation statistics or 95% probability.

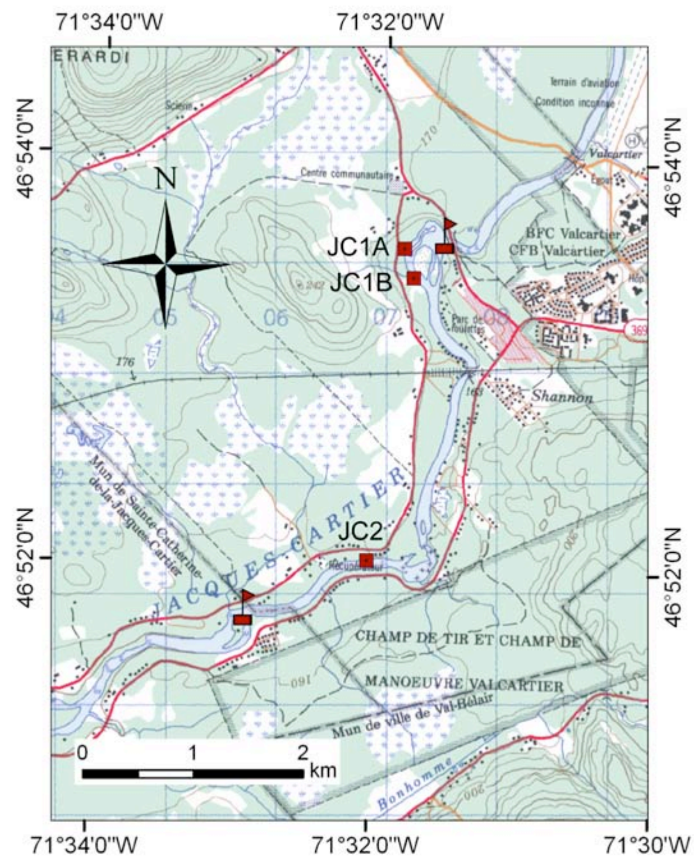

Figure 13. Topographic map of Jacques-Cartier River near Shannon showing locations of study sites described in Table 9. Red flags mark beginning and end points of river reconnaissance.

Table 9. Description of Study Sites along the Jacques-Cartier River.

Site Number	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)	Liquefaction Features Observed	Exposure	Sediments Observed in Cutbank
JC1a	46.8927	71.5308	None	Excellent	Interbedded silty fine sand and medium to fine sand
JC1b	46.8904	71.5296	None	Excellent	Interbedded silty fine sand and medium to fine sand overlies interbedded silt and silty very fine sand; organic layer at base
JC2	46.8673	71.5342	None	Very good; but only 5 m in length	Medium sand overlies rhymites of clayey silt and very fine sand

5.5 Interpretation of Results

Interpretations of field observations and radiocarbon dating are given below. This investigation has been limited by the small number and poor exposure of river sections searched for liquefaction features in the Charlevoix-Rabaska site region.

5.5.1 Charlevoix Area

In the Charlevoix area, sand dikes resulting from earthquake-induced liquefaction occur along the Gouffre River. There is no evidence to suggest that they formed during more than one event, although this possibility cannot be ruled out with the current data. The sand dikes are prehistoric in age and formed between A.D. 780 and 7590 B.C. or 1170 and 9540 years B.P. Additional dating of sediments cut by the prehistoric sand dikes along the Gouffre River could help to further constrain the age of the paleoearthquake.

The geographical distribution of paleoliquefaction features in the Charlevoix area is not known because no other rivers in the area have been searched so far. Therefore, it is not yet possible to determine the location of the paleoearthquake responsible for the liquefaction features, although it was probably centered somewhere in the Charlevoix area. Inspections of rivers suggested that cutbank exposures of Holocene and Late Wisconsin deposits are available along sections of the Malbaie and Ouelle Rivers. Reconnaissance along these rivers may or may not lead to the discovery of additional liquefaction features, but could help to define the distribution of paleoliquefaction features and thus the location of the paleoearthquake.

The Gouffre River sand dikes range up to 15 cm in width. The sand dikes that formed during the 1988 **M** 5.9 Saguenay earthquake are only 1 to 5 cm in width. Assuming liquefaction susceptibility of sediments is similar in the two areas, the larger size of prehistoric sand dikes along the Gouffre River suggests that the responsible earthquake may have been located less than 30 km away or been greater than **M** 5.9. Geotechnical data for the Gouffre River sediments would help to assess their liquefaction susceptibility and to evaluate scenario earthquakes that could explain the occurrence of liquefaction features.

5.5.2 Rabaska Site Area

Exposure of Holocene and Late Wisconsin deposits is poor along the Chaudiere, Etchemin, and Jacques-Cartier Rivers in the Rabaska site area because river banks are heavily vegetated and places protected in places from erosion by boulders. Dams have been built along the rivers to control flood water and they have also reduced the amount of cutbank erosion. Smaller rivers in more rural settings and with fewer flood control measures, such as the Beaurivage, Du Chene, and Du Sud Rivers, might provide better exposures, especially after spring floods and before vegetation has grown on cutbanks.

The meandering section of the Etchemin River near Saint-Leon-de-Standon provided fair exposure of sediments in river bends. Radiocarbon dating indicates that there is a 9200-year sedimentary record along the river. In addition, conditions seem to be favorable for the formation and preservation of liquefaction features. Yet, we found no liquefaction features along the river, suggesting that this area has not been subjected to strong ground shaking for 9000 years. We did find a few soft-sediment deformation structures that might indicate low levels of ground shaking during this time period.

If we could be more confident that earthquake-induced liquefaction features do not occur in the Holocene age sediments near Saint-Leon-de-Standon and if we had geotechnical data confirming that the Etchemin sediments are highly susceptible to liquefaction, it might be possible to discount large paleoearthquakes in the Rabaska site area during the Holocene. If so, this would suggest that the Charlevoix seismic zone does not extend into the site area. For example, the Etchemin River near Saint-Leon-de-Standon is about 50-60 km from the Rabaska site area and 100-140 km from the Charlevoix area. According to Ambraseys' (1988) relation between earthquake magnitude and distance to liquefaction developed from a worldwide database of shallow earthquakes, **M** 6.7 earthquakes can induce liquefaction up to 70 km from their epicenters. Therefore, an earthquake of this magnitude centered in Charlevoix would not be expected to induce liquefaction in highly susceptible sediments near Saint-Leon-de-Standon; whereas, such an event centered near the Rabaska site would. It should be taken into consideration, however, that the 1988 **M** 5.9 Saguenay earthquake induced liquefaction up to 30 km from its epicenter, about 1.5 times farther than would be expected based on Ambraseys' relation. This may be due to higher than average frequency content or stress drop for the Saguenay earthquake compared to the earthquakes used to develop the magnitude-distance relation. If the Saguenay earthquake is typical of Quebec earthquakes, **M** 6.7 earthquakes might induce liquefaction up to 105 km from their epicenters in this region. If this were the case, a Charlevoix earthquake of this magnitude might have a minimal effect on the sediments (perhaps soft-sediment deformation structures) near Saint-Leon-de-Standon; whereas such an event centered near the Rabaska site would have an even greater impact than expected using the standard Ambraseys relation. If geotechnical data were available for the sediments along the Etchemin River near Saint-Leon-de-Standon, liquefaction potential analysis also could be used to evaluate various scenario earthquakes and to place limits on the magnitude of Holocene paleoearthquakes that might have been centered in the Rabaska site area.

5.5.3 Implications for Seismic Source Models

Findings of this study suggest that there was at least one large Holocene paleoearthquake in the Charlevoix area. Unfortunately, poor exposure along the Etchemin, Jacques-Cartier, and other rivers limited our ability to observe the Holocene record in the Rabaska site area. The Etchemin River near Saint-Leon-de-Standon, about 55 km southeast of the Rabaska site, provided a somewhat better glimpse at the Holocene record, where we found no unequivocal liquefaction features. If we could be more confident that earthquake-induced liquefaction features do not occur in the Holocene age sediments near Saint-Leon-de-Standon and along other rivers in the region, and if geotechnical data were available that indicated that the sediments are highly susceptible to liquefaction, we could better ascertain whether or not large Holocene paleoearthquakes have occurred in the Rabaska site area.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Review of surficial geology maps of the region, one geotechnical report for a retaining wall along the Malbaie River, and geological and geotechnical investigations conducted for the environmental impact assessment of the proposed Rabaska terminal and pipeline found that

Holocene and Late Wisconsin deposits that are likely to be susceptible to earthquake-induced liquefaction occur along rivers in both the Charlevoix and Rabaska site areas. We inspected meandering sections of rivers in the region, including the Beaurivage, Chaudiere, Du Chene, Du Sud, Etchemin, Gouffre, Jacques-Cartier, Malbaie, Ouelle, and Saint-Anne Rivers, and selected sections of one river, the Gouffre, in the Chalevoix area and of two rivers, the Etchemin and Jacques-Cartier, in the region of the Rabaska site for an initial phase of reconnaissance.

During survey of the Gouffre River, we found sand dikes resulting from earthquake-induced liquefaction. Dating of organic samples associated with sediments and liquefaction features indicates that they formed during a paleoearthquake between A.D. 780 and 7590 B.C. or from 1170 to 9540 years B.P. The event was likely centered in the Charlevoix area and at least as large as the **M** 5.9 1988 Saguenay earthquake and possibly larger than the 1925 **M** 6.2 Charlevoix earthquake. These findings suggest that at least one large Holocene paleoearthquake occurred in the Charlevoix area.

We found no similar earthquake-induced liquefaction features during surveys of the Etchemin and Jacques-Cartier Rivers in the Rabaska site region; but cutbank exposure was not very good along the Etchemin and was poor along the Jacques Cartier. Additional reconnaissance of well-exposed river cutbanks, either along the same river sections at a time when they are better exposed or along different river sections, is needed to determine whether or not large Holocene paleoearthquakes, similar to the one that affected the Gouffre River, have occurred in the Rabaska site area.

This reconnaissance-level investigation did not uncover enough new information about paleoearthquakes in the Charlevoix-Rabaska region to more clearly define the southwestern limit of the Charlevoix seismic zone. However, the investigation did make some progress towards this goal and the overall approach seems promising. Further progress is contingent on better exposure of Holocene deposits preferably in, but not limited to, the proposed Rabaska site area. Recommendations for additional study follows:

- Repeat surveys of the Etchemin and Gouffre Rivers at a time when cutbank exposure is better than it was in September 2006 to improve confidence in assessment of presence and absence of liquefaction features. Any additional liquefaction features found would be documented and samples collected for radiocarbon dating. Improved dating of paleoearthquakes in the Charlevoix area would help to estimate the rate of recurrence of large earthquakes. It probably would be best to resurvey rivers in early summer of 2007 after spring floods have cleaned banks, river levels have fallen, and before vegetation grows on the cutbanks. Depending on river and weather condition, an attempt could be made in late autumn of 2006.

- Survey portions of the Malbaie and Ouelle Rivers in Charlevoix area and the Beaurivage, Du Chene, and Du Sud Rivers in the Rabaska site area that appear to have reasonably good exposure of suitable Holocene deposits. As above, it probably would be best to wait until summer of 2007 to perform this task, but an attempt could be made in late autumn 2006.
- Extend search for liquefaction features to other rivers with better exposure farther afield but along the St. Lawrence in order to test the hypothesis that the Charlevoix seismic zone has a higher rate of seismicity than the regional Iapetan faults in the Rabaska site area. The search for paleoliquefaction features to the southwest of the Charlevoix seismic zone does not have to be limited to the site area. It is important to find good exposure of Holocene deposits that are themselves, or are underlain by, sediments that are susceptible to liquefaction. The Trois Riviere area, where Holocene fluvial and lacustrine and Wisconsin marine littoral deposits are widespread (Bolduc, 1999), may be an alternative location to search for liquefaction features resulting from large Holocene earthquakes centered near the Rabaska site area.
- Compile and tabulate borehole data of bridge crossings and from other geotechnical studies, including sediment description, depth ranges, and blow counts (N), and water-table depth, along surveyed rivers where earthquake-induced liquefaction features have and have not been found. If geotechnical data cannot be found for areas of interest, such as the Etchemin River near Saint-Leon-de-Standon, consider conducting in situ investigations (standard or cone penetration tests).
- Evaluate scenario earthquakes (~**M** 5, 5.5, 6, 6.5, and 7) in Charlevoix-Rabaska site region using liquefaction potential analysis and comparing results with field observations. This will make it possible to estimate with more confidence the location and magnitude of

paleoearthquakes that may have affected the two areas.

7.0 REFERENCES

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