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Abstract

This Open File documents known earthquakes with magnitude ≥ 4.0 (estimated or calculated) that have occurred near or in the estuary of the St. Lawrence River (i.e. between Quebec City and Baie-Comeau, Quebec) since 1600. The topography of the area reveals numerous scars left from past mass movements on land (sub-aerial) and at the bottom of the River (submarine). This Open File documents the earthquakes that had the potential (location and magnitude) to trigger some of these landslides. In addition, it lists eyewitness accounts of potential mass movements ("boiling" of the river and a possible tsunami wave). The Open File also documents the uncertainties of the current earthquake catalogue that must be considered in any study of mass movements along the St. Lawrence River. This catalogue of earthquakes can be used to correlate seismic events with dated landslide activity of the region. The catalogue is also a good basis to update the eastern Canadian component of the current Geological Survey of Canada earthquake database.

Résumé

Ce dossier public décrit les séismes connus de magnitude ≥ 4.0 (estimée ou calculée) qui se sont produits dans l'estuaire du fleuve Saint-Laurent ou à proximité (c'est-à-dire entre Québec et Baie-Comeau, Qc) depuis 1600. La topographie de la région recèle plusieurs cicatrices laissées par des mouvements de masse sur terre (subaériens) ainsi qu'au fond du fleuve (sous-marins). Ce dossier public documente les séismes qui avaient le potentiel (position et magnitude) pour déclencher quelques-uns de ces glissements de terrain. De plus, le dossier inclut des témoignages de mouvements de masse potentiels (« bouillonnement » du fleuve et une vague de tsunami possible). Ce dossier public décrit aussi les incertitudes qui doivent être considérées dans toute étude de mouvement de masse le long du fleuve Saint-Laurent. Ce catalogue de séismes peut être utilisé pour corréler les événements sismiques

avec les glissements de terrain datés de cette région. Ce catalogue est aussi une bonne base pour mettre à jour la partie de l'Est du Canada de la base de données des tremblements de terre canadiens.

1- Introduction

In this report, we document earthquakes that could have triggered submarine mass movements, such as landslides, beneath the estuary of the St. Lawrence River. We define the estuary of the St. Lawrence River as the section of the River located between Quebec City and the Gulf of St. Lawrence (Figure 1). One aspect of the Program Geosciences for Oceans Management is to document the natural hazards of this region, with a special emphasis on the sea floor of the estuary. Recent marine surveys have revealed numerous scars left by submarine landslides and slumps (Bolduc, 2007). These mass movements were possibly triggered by seismic shaking, but very few of them are dated. Before attempting to correlate these landslides with past earthquakes, it was decided to document the earthquakes that were capable of triggering these movements.

Along the Estuary, most earthquakes, historical or instrumentally-recorded, concentrate in two seismically active zones (Charlevoix and the Lower St. Lawrence). Historically, the largest known historical earthquake of the area is earthquake of 1663, estimated at magnitude[1] ~ 7. Due to its large magnitude (for an intraplate earthquake), this event is often used as the most probable seismic trigger of submarine mass movements of the area. There are, however, numerous smaller, but still significant, earthquakes (**M** 5-6½) that had the potential to trigger some of these slumps. There were also many smaller earthquakes that were sufficiently strong to be felt by people, but were probably too small to induce mass movements.

The primary goal of this report is to tabulate and document all known earthquakes that were large enough to potentially trigger these mass movements. For this purpose, the list

[1] Magnitude: See the Magnitude Section below for a description of the various magnitude scales.

of earthquake includes the most recent information on the earthquakes of the area. The uncertainties in the epicentre locations, magnitudes and completeness are examined and recommendations on the use of the information are proposed. This report is one step towards documenting the timing of the mass movements at the bottom of the St. Lawrence River estuary.

2- Seismically Triggered Landslides

It is generally proposed that submarine landslides depend on the presence of two main factors, either high pore pressures (leading to decreased frictional resistance to sliding) or the presence of weak layers within stratified sequences (Table 1; Masson et al., 1999). Elevated pore pressures can result from normal depositional processes or from transient processes such as earthquake shaking. According to Masson et al. (1999), historical evidence suggests that the majority of large submarine landslides are triggered by earthquakes.

The magnitude of an earthquake is one factor that describes the amount of energy released during an event. Converting magnitude to ground motion has some intrinsic uncertainty. A number of ground motion attenuation relations exist, for different frequencies, on the expected acceleration or velocity level as a function of distance. One must note, however, that these relationships have associated uncertainty. In the near field, it is particularly difficult to predict the level of ground motions due to factors such as rupture focusing, basin focusing and trapping effect, topography, and soil amplifications.

At the surface, numerous cases of rock slides and landslides are documented in epicentral regions, even for relatively weak main shocks. In the Charlevoix Seismic Zone, for example, the 1952 m_N 5.3 earthquake caused a rock fall (Lamontagne et al., 2007). In New York State, the **M** 5.0 Au Sable Forks earthquake (focal depth 11 km) caused a large rock slide (Pierre and Lamontagne, 2004). Another example, Bar Harbor earthquake of October 3, 2006 (focal depth 2 km with magnitude m_b(Lg) of only 4.2), caused a number of rock slides along jointed rock cliffs (Ebel et al., 2008). One might be tempted to correlate any given submarine landslide with the five known larger earthquakes of the Charlevoix zone. It is the author's opinion that correlating these earthquakes and mass movements may be uncertain for three main reasons.

First, the completeness of the catalogue, i.e. our capacity to completely describe the earthquake history, varies across the study area. Prior to the introduction of seismographs in the late 19th century, earthquake occurrences were only known through historical written accounts (felt information). In the estuary of the St. Lawrence region, the written earthquake history starts with the arrival of the first Europeans in the area . For earthquakes of magnitude 4.0, it is only since about 1963 (well after the introduction of the first seismographs) that events could be detected and located with a precision of about 10 km (see section below).

Second, there is a tendency to use the M 6+ Charlevoix earthquakes as triggers to any submarine landslide without consideration for the magnitude of them main shock and the distance from the epicentre. It is the author's opinion that more attention should be given to the ground motion levels that these earthquake can realistically produce at a given distance.

Third, there is a tendency to dismiss earthquakes smaller than magnitude 6. As seen above, there are cases of these smaller earthquakes (M 4 to M 6) triggering sub-aerial landslides very close to the epicentre. If they occur at a shallow focal depth, these earthquakes can possibly trigger submarine mass movements at short distances.

3- Location of the estuary in respect to the seismic zones

The estuary of the St. Lawrence River straddles a number of seismically active regions, including the most seismically active area of eastern Canada, the Charlevoix Seismic Zone.

a) The Charlevoix Seismic Zone (CSZ)

Historically, the zone has been subjected to five earthquakes of magnitude 6 or larger. Four of these events are known from written descriptions of their effect: 1663 (M ~ 7); 1791 (M ~ 6); 1860 (M ~ 6); 1870 (M ~ 6 ½). These events have approximate magnitudes evaluated using felt areas and descriptions of damage. The 1925 event (magnitude M_S 6.2 ± 0.3) is the only one recorded by seismographs and its epicentre is fairly well located. Since 1977, a seven-station local seismograph network, centred on the active zone, has monitored the earthquake activity (Lamontagne, 1999). Between 1985 and 2007 inclusively, the network detected more than 3000 local earthquakes, of which 54 exceeded magnitude 3.0, with 10 of magnitude 4.0 or larger. The current CSZ network detects more than 200 earthquakes per year. With the current network, all earthquakes larger than about magnitude m_N 1 on the Richter scale can be located. Hence, all earthquakes that could be felt (i.e. larger than magnitude 2.5) can be detected by the network and located. Overall, instrumentally-recorded events concentrate in a 30 by 85 km rectangle, elongated along the St. Lawrence River, and enclosing the towns of Baie-St-Paul, La Malbaie, La Pocatière and Rivière-du-Loup. Based on historical and current earthquake rates, the CSZ has the highest seismic hazard in continental eastern Canada. Due to its dense seismograph network, the CSZ is the only eastern Canadian region where earthquake focal depths are computed on a routine basis. The hypocentres located over the years have provided an insight into the CSZ seismotectonics. Most earthquakes cluster along or between the mapped Iapetan faults (also called St. Lawrence paleo-rift faults). CSZ earthquakes occur in the Canadian Shield, between the surface and 30 km depth, beneath Logan's line and the Appalachians. On average, an earthquake occurs in the Charlevoix region every day and a half. Larger events, on the other hand can occur decades apart.

b) The Lower St. Lawrence Seismic Zone (LSZ)

Located some 400 km downstream from Quebec City at the transition area between the estuary and the Gulf of the St. Lawrence River, the Lower St. Lawrence Seismic Zone

(LSZ) is also seismically active. As most earthquakes occur under the St. Lawrence River, between the regions of the Quebec North Shore and the Lower St. Lawrence, this zone is sometimes referred to as the "Lower-St. Lawrence-Quebec North Shore" Seismic Zone. Unlike the Charlevoix Seismic Zone, no large ($M \geq 6$) earthquake has ever been reported or recorded in the LSZ. Only two events are known to have exceeded magnitude 5.0. On June 23, 1944, an earthquake of magnitude 5.1 on the Richter scale occurred near Godbout, east of Baie-Comeau. More recently, on March 16, 1999, an earthquake of magnitude 5.1 occurred in this region, at about 60 km south of Sept-Iles (Lamontagne et al., 2004). Another earthquake, possibly slightly larger than those of 1944 and 1999, occurred on November 29, 1880, and damaged some chimneys.

Over the years, numerous lower magnitude events have been recorded there. Between 1985 and 2008, the Lower St. Lawrence Zone has had seven earthquakes of magnitude 4.0 or larger, whereas Charlevoix has had ten during the same time period. The region is closely monitored by a network of five local stations of the Canadian National Seismograph Network. With the current network, all earthquakes larger than about magnitude 2 on the Richter scale can be located. Hence, all earthquakes that could be felt (i.e. larger than magnitude 2.5) can be detected by the network and located. One Lower St. Lawrence earthquake is detected every five days on average giving a total of about 60 events annually. Most earthquakes occur under the St. Lawrence River, within a triangular zone with corners at Baie-Comeau, Sept-Iles, and Matane on the south shore. Although the network is not everywhere sufficiently dense to accurately determine earthquake focal depths, earthquakes in a sub-zone near Baie-Comeau were found to occur in the mid- to upper crust, between 7 and 25 km depth, similar to the CSZ (Lamontagne et al., 2004). From focal mechanism determinations and by analogy with the CSZ, most earthquakes probably cluster along or between the mapped Iapetan faults (also called St. Lawrence paleo-rift faults), beneath the Logan's line and the Appalachians.

c) Other areas of the St. Lawrence estuary

Other areas of the St. Lawrence estuary are weakly active with very few events recorded on a yearly basis. No damaging earthquake is known between Charlevoix and the Lower St. Lawrence Zone. A notable exception is the 25 November 1988 Saguenay earthquake which occurred in a region hitherto inactive, but outside the estuary of the St. Lawrence. This earthquake, referred to as the Saguenay earthquake, was located in a relatively aseismic region, had a calculated magnitude of 5.9 m_b, 6.5 M_N, and a depth of 29 km (Du Berger et al. (1991). It was characterized by a single foreshock, relatively minor aftershock activity, and a large amount of high frequency energy. The Saguenay earthquake is a reminder that not all moderate to large earthquakes occur in seismically active areas. In fact, about two thirds of larger earthquakes occur in areas identified by small earthquakes (Kafka and Walcott, 1998). The rest occurred in areas where there have been no previous small earthquakes.

d) Seismic zoning

The most recent seismic zoning exercise conducted to define the seismic provisions for the 2005 National Building Code of Canada used two seismic zone models. The first one is the “H” model, which defines the zones according to the historical level of seismicity. The other one is the “R” model which is based on the association between the earthquakes and the St. Lawrence paleorift system of faults. In the “H” model, earthquakes fall within a number of seismic zones: GNS, BSL, TAD, CHV, SAG, TRR and SEB. In the “R” model, most of the estuary falls under the IRM, LAB and IRN zones (see Table 2 for meanings of name abbreviations).

4- Selection of events for this study

Submarine landslides can be triggered by ground vibrations caused by earthquakes. The level of ground vibrations necessary to trigger a submarine landslide depends on the properties of the sedimentary succession and environment prior to the passage of the ground vibrations. Consequently, one cannot be definite about the level of ground motion necessary to induce a submarine mass movement.

As a first approximation, the level of ground motion sustained at a given site depends on the earthquake magnitude and the hypocentral distance to the site. At a more advanced level of complexity, rupture directivity and ground motion amplification due to changes in elastic properties of the materials can also modify the level of ground motion at a site.

We have selected earthquakes with estimated or calculated magnitude $m_b(Lg)$ larger or equal to 4, either based on evaluation from felt reports or on seismograph records. This M 4 level may appear somewhat low, however, we have selected this level to take into account the magnitude uncertainty of historical events.

Completeness and Precision of Source Information

For the reasons below, the list of earthquakes is not, and will never be, complete for M ≥ 4 earthquakes between 1600 and 2007 for the whole of the estuary. The attached list is as complete as possible at the time of writing. It is possible that future studies will reveal hitherto unknown events or will modify our knowledge of some of these events and their impact. Due to the nature of documenting earthquakes, such modifications to the list are more probable for pre-instrumental data.

Prior to the introduction of seismographs in the late 19th century, earthquake occurrences were only known through historical accounts (felt information). If an earthquake was sufficiently large or sufficiently close to inhabited regions, it could be reported in personal accounts, diaries or newspapers. This implies that pre-instrumental earthquakes are only known if they had been felt by people who reported what they felt in documents that were preserved and indexed. Consequently, our knowledge of pre-instrumental earthquakes depends entirely on the distribution of population with written history (as opposed to the oral tradition).   These information sources were used to create series of earthquake catalogues which we used to define our list.

Towards the end of the 19th century, seismographs were progressively installed in Canada. These early instruments were not very well adapted to recording local events and could only detect large, distant earthquakes (teleseisms). They were insensitive to earthquakes of magnitude less than about 5. More sensitive, short-period seismographs only began regular operations at the beginning of 1928 (Smith, 1962). Slowly, the number of stations increased and the ability to record local earthquakes increased (Basham et al., 1982).

Source parameters

Similarly to the completeness of earthquake reporting, the precision of the calculated earthquake source parameters has improved over the years. The sections below examine in more detail the uncertainty of the source parameters; origin time; location (latitude and longitude, depth) and magnitude.

1. **Origin Time**

The list provides both the origin time of earthquakes in local and in Coordinated Universal Time (UTC).

Historical earthquakes of the 17th, 18th and 19th centuries are reported with their approximate local time. In some cases, the best estimate of the origin time is the part of the day (day, morning, afternoon, evening, night). Burke (2007) discusses a method to calculate approximate Universal Time for earthquakes of the Pre-standard time era. Telegraphs associated with railroads were to improve the situation.

Events after the early 20th century were recorded by one or more seismographs and are reported according to UTC. Most dates (year/month/day) and times (hour:minute:second) are listed in UTC. This is the modern equivalent of Greenwich Mean Time (GMT) and is 5 hours later than Eastern Standard Time (EST), 8 hours later than Pacific Standard Time (PST). The difference is 4 and 7 hours respectively when compared with Daylight Saving times, a concept that started during the First World War without being consistently applied since then and across Canada. To help readers, the local time is also provided for events that were largely felt. This leaves out numerous offshore events that were too small or too distant to be felt by human beings. Please note that it is possible that the date of origin of an event is different in local time and universal time (for example the 1925 Charlevoix earthquake occurred on February 28 at 21:19 local time and is listed as March 1st at 02:19 U.T.).

For a lack of clarity in the written documents, it is difficult for some pre-instrumental earthquakes to assign a definite local time (and as a consequence UTC). For these, no local or UTC is given and the field is left blank.

2. Location (Region, Area, Latitude, Longitude, Depth)

The location of an earthquake refers to the position of its *epicentre* (latitude and longitude). Epicentres are given in terms of geographic latitude (decimal degrees North) and longitude (decimal degrees West). The epicentres of pre-20th century earthquakes are generally not as well defined as the more recent or instrumentally-recorded earthquakes. For pre-instrumental earthquakes, locations are approximated from felt information (where the epicentre is the centre of the felt area) or reports of damage (where the epicentre is generally the region of most significant damage). When there is only one felt report, the epicentre is sometimes co-located with the locality where the earthquake was felt.

Instrumentally-recorded earthquakes are located based on the arrival times of seismic waves at the stations. As the precision of these locations depend on the density, distribution and characteristics of the seismograph stations, more recent earthquakes are generally better located than older ones.

The epicentres listed are chiefly those found in the Canadian Earthquake Database. Focal depth can only be estimated from instrumental data and for this reason, only earthquakes recorded after the early 20th century have this information. Depth of the focus (hypocentre) is given in kilometers below sea level. All eastern Canadian earthquakes occur in the upper 30 kilometers of the Earth's crust. If the exact focal depth cannot be determined, it is fixed to a value representative of events in the area and given with (F). An 'x' means that the exact value is unknown.

3. Magnitude (Preferred Magnitude, Magnitude Type, Other magnitudes)

The magnitude of an earthquake is a convenient way of representing the size of an earthquake. First formulated in 1935, the local magnitude (M_L) scale was defined for moderate-size ($3 < M_L < 7$) earthquakes in southern California that occurred within 600 km of a Wood-Anderson seismograph. The M_L scale corresponds to the "Richter scale". All of the currently used scales for rating earthquake magnitudes (duration (m_D); surface-wave (M_S), body-wave (m_b), moment (M_w or $\mathbf{M}$), etc.) yield results that are only consistent with M_L over a limited range of magnitude. The most consistent estimate of earthquake size across a wide range of magnitudes is the moment magnitude (M_w or $\mathbf{M}$). This magnitude is based on the seismic moment which, unlike most scales that are derived from seismic phase amplitudes, does not saturate with earthquake size. For this reason, the moment magnitude best defines an earthquake size. In eastern North America, a specific magnitude, $m_b(Lg)$ was defined by Otto Nuttli based on the largest body wave amplitude (Lg) seen on vertical seismograms for continental paths. In eastern Canada, the GSC uses a variation of the $m_b(Lg)$ scale, called the Nuttli magnitude (m_N). Historical earthquakes, not recorded on seismographs, are sometimes scaled on the felt area magnitude (m_{FA}) or given a corresponding m_N value estimated from empirical felt area- m_N relationship.

In this list, several magnitude types are used:

- M_L - Local, or Richter magnitude.
- m_N - Nuttli, or body wave magnitude ($m_b(Lg)$). Used for earthquakes in eastern Canada.

- M_w or **M** - Moment magnitude.
- m_B and M_S - Compressional body wave by Gutenberg and surface wave magnitudes.
- m_{FA} and M_f (IV) - felt area magnitude and magnitude based on the Modified Mercalli Intensity IV area.

There are many magnitude scales and for this reason, it is difficult to give the best magnitude rating for an event. The author has chosen to use the Moment Magnitude rating as the primary magnitude when available. Some larger events have been rated on the Moment Magnitude scale based on their felt area or on their peak amplitudes (EPRI, 1994; Schulte and Mooney, 2008). Some additional information on the magnitudes of eastern Canadian earthquakes can be found in Bent (2009).

When the moment magnitude is unknown, for pre-instrumental events for example, the magnitude chosen was the best estimate from the information available. For earthquakes recorded prior to about 1955, earthquake magnitudes were not calculated on a routine basis and only a few were studied in detail to determine their magnitude ratings. For most, the magnitude rating is approximate and is identified as other (OT). This includes some events for which the magnitude is estimated by comparing felt effects with more recent earthquakes in the same region.

The magnitude values assigned to historical events are very approximate and should be used with caution. The values are based on felt reports, which are often limited in number, clarity and geographical distribution. For some historical events, the author chose not to use decimal units but rounded off the magnitude to the nearest ½ magnitude unit to reflect the very approximate magnitude value. Most pre-1925 earthquakes are assigned pre-defined magnitude values such as 3.7. This rating should not be taken at face value.

4. Maximum Intensity on the Mercalli Scale

Although many intensity scales exist, the Modified Mercalli Intensity (MMI) Scale is the most commonly used for North American earthquakes (Appendix 1). The MMI scale is designated by Roman numerals that range from no perceptible shaking (I) to catastrophic destruction (XII). Please note that "not felt" can also be rated as (0). Although intensity values are related to ground shaking levels, the MMI scale does not have a mathematical basis; instead it is an arbitrary ranking based on observed effects. Intensity scales differ from the magnitude scales in that the effects of an earthquake of a given magnitude vary greatly from place to place, so there may be many intensity values (e.g.: IV, VII) determined from one earthquake. Plotting the intensity values and contouring results in maps are referred to as isoseismal maps.

The MMI scale and isoseismal maps are not ideal to describe all possible consequences of an earthquake. First, rating intensity can be subjective since any level covers a range of effects on humans, structures and the natural environment. Some analysts look for many effects before assigning the level, whereas others consider the maximum level witnessed in a given area. Second, intensity reports only come from inhabited areas, which leave out many sparsely populated areas. In the 20th century, questionnaires were mailed to town postmasters who could only describe what they knew of the local impact. Nowadays, anyone who feels an earthquake can fill out internet-based questionnaires, providing a better sampling of the maximum local impact. The maximum intensity provided herein is that which was experienced on Canadian territory.

5- Sources of information

The author has used two primary sources of information. The first one is the Canadian National Earthquake Database which is partly on line (for post-1985 earthquakes) and partly available in ascii format from the GSC. The database is continuously updated with newly occurring events. Historical events are based mainly on Smith's catalogues of earthquakes (Smith, 1962 and 1966) for eastern Canada. The other source is the earthquake catalogue for pre-1925 earthquakes felt in Quebec (Gouin, 2001). This comprehensive survey of original sources includes a number of revisions that have not yet been included in the Canadian National Earthquake Database.

Fig. 2 shows the database entries that are currently in the GSC database for the period 1600-1925. Fig 3 shows all earthquakes in the current GSC catalogue that have a magnitude $\geq$ 4.0 (all magnitude types; 1600-2007). Finally, Fig. 4 shows all M $\geq$ 2.0 for the period 1980-2007. The seismically quiescent zone between Charlevoix and the Lower St. Lawrence Seismic Zone is evident. Of all these earthquakes, only a few have been recognized as significant for the Atlas of Canada (Lamontagne et al., 2008; Fig. 5).

6- Completeness and uncertainty

The completeness defines the year after which any earthquake occurrence would be referenced either from felt reports or seismograph records. In clear, above a certain magnitude, no earthquake would have been missed. This exercise has been done on an approximate basis for seismic hazard calculations for National Building Code applications. Table 2 refers to the work of Basham et al. (1982) and Adams and Halchuk (2003). The latter zoning exercise defined two sets of seismic zones: one based on historical data ("H" model; figure 6) and one on the geological basis ("R" model; Figure 7). The changes in the completeness during the 20th century are directly related to the operation of seismographs capable of recording short period ground motions. These are reviewed by Stevens (1980). Of these dates, 1928 refers to the start of operation at Shawinigan Falls and Seven Falls (near Quebec City) in September 1927. The other date, 1938, refers to the start of operation of a high-gain very short period seismograph at Kirkland Lake, Ontario, in December 1939. By 1950, there were still only five operating seismographs in eastern Canada. It is only since the mid-60's that earthquakes larger than magnitude 3.5 can be located over the entire Canadian territory. This explains the date 1963 found in Table 2.

Based on Table 2, we can define completeness as a function of areas. One must keep in mind that completeness does not mean accurate epicentre locations. The conclusions are as follows:

1) For the whole of the estuary, the occurrences of large events ($M \geq 6.3$) are known since about 1850 (Figure 8). We estimate that the upper estuary (between Tadoussac and Quebec City) has been complete since 1660 (possibly since 1608) thanks to the permanent settlement in Quebec City.
2) For the whole of the estuary, the occurrences of moderate events ($M \geq 4.8$) are known since about 1928 only (Fig. 9). For the on shore area, the completeness period is much shorter for the Quebec North Shore area (1953). Due to the population established on the south shore of the River, we believe that the completeness is probably much better there (possibly since 1880).
3) Earthquakes of magnitude between 4.0 and 5.0 are complete for the most recent part of the 20th century only (Fig. 10). Depending on its distance to the inhabited areas, an earthquake in this magnitude range can occur without being noticed by the population and can go unreported. It is the density of the seismograph network that insures completeness of these earthquakes. On the other hand, these earthquakes are marginally capable of triggering a submarine landslide even at short epicentral distances. Consequently, we can assume that the database of magnitude 4.0 to 5.0 earthquakes is complete for the lower estuary since 1963 and since 1938 for the upper estuary.

7) Differences from existing earthquake catalogues

Readers may find that the current list of significant earthquakes is different from previous earthquake catalogues. Here are some differences and the rationale behind these changes.

1. False events

There are 16 instances of false or 'ghost' events of which 15 are currently listed in the GSC earthquake catalogue. These false entries occur when historical accounts are misinterpreted or when human errors (typographic mistakes) are made. All false events have dates before 1924 and there is only two instances of earthquakes of magnitude 4.0 and larger. Earthquakes that were identified by Gouin (2001) as false events are:

1. A pseudo-earthquake that was supposed to have occurred between the two voyages of Jacques Cartier in Canada (1534-1535). This possibility was discarded by Gouin (1994). This 'ghost' event is not included in our list and does not appear in the CEEF file. It is, however, still present in some pre-1994 literature, and in some derived post-1994 literature that referred to those.
2. 16631116 ML 3.7: false event: Gouin (2001) p. 240.
3. 18590000 0000 ML 3.0: false event: Gouin (2001) p. 518
4. 18691200 ML 4.0: False event near Baie-St-Paul Gouin (2001)
5. 18701026 0000? ML 3.7: mix-up with 18701020 main shock Gouin (2001)
6. 18730226 ML 2.4: false event according to Gouin (2001)
7. 18740731 0900 ML 3.7 and 18740803 ML 3.7: wrong region (not in LSL: should be St-Basile-de-Portneuf, SW of Quebec City) and event (in fact series of events) is doubtful.
8. 18790407 ML 3.0 is a false event. There is a possible mix-up with 18810407: there is a double entry in database; same event repeated twice…
9. 18801124 ML 3.0: false event in Quebec City; Gouin (2001)
10. 18801230 ML 3.0: fictitious event; referred to 18801129
11. 18841122 ML 3.0: second event could be fictitious (Gouin, 2001)
12. 18870215 1830 ML 3.0: false event
13. 19061221 ML 3.0: false event (Gouin, 2001)
14. 191002 ML 5.0: false event; not reported locally; it was probably the 19100225 event that got reported twice (Gouin, 2001).
15. 19150806 ML 3.0: false event in Quebec City (Gouin, 2001).
16. 19230927 ML 2.4: false event in Quebec City (Gouin, 2001).

2. **New events and modified information for some events**

The works of Gouin (2001) for Quebec has brought to light new information on many pre-instrumental earthquakes. Numerous epicentres and origin times were modified.

1. An event was previously listed as 1831-07-14. According to Gouin (2001), no earthquake occurred on that date (contrary to Smith, 1962). Consequently, it is listed as 1831-07-07 or 1831-07-08 since it occurred during the night without any indication of the time of occurrence.
2. For the event on 1842-11-07: according to Gouin (2001), the earthquake occurred on 1842-11-07 not on 1842-11-09 (contrary to Smith, 1962). There are reports written on Nov. 07 for this earthquake.
3. The earthquake of 1880-11-29 was wrongly listed as 1880-11-28 in Dawson and in Smith (Gouin, 2001).
4. 18181011 0000: should be 18180911 according to Gouin (2001)
5. 18701226 should be end of December according to Gouin (2001)
6. 18710216 should be 18710210 or 18710217 (Gouin, 2001)
7. 18710520 should be 18710521 Note by the author: The magnitude should be at least 5: felt in QC, Montreal, Ontario, US; epicentre placed near Quebec City in Smith (1966) should be Niagara-on-the-Lake according to Gouin
8. 18720109: formerly located in Charlevoix, new location near Quebec City (Gouin, 2001)
9. 18820226 could be 18820219 but remains doubtful Gouin (2001)
10. 19070411 should be 190704 (sometime in April, unknown date) Gouin (2001).
11. 19140412 should be 19140413.

7- The catalogue

The accompanying catalogue consists of all database entries prior to 1920 and of magnitude ≥ 4.0 earthquakes after 1920. The author has chosen to list all earthquakes prior to 1920 since these earthquakes, mostly known from felt information, are generally poorly located and their magnitude very approximate. For those reasons, readers should exercise caution is using these pre-1920 epicentres and magnitude values.

Post-1920 earthquakes can have two earthquake solutions. The first one, generally with minimum comments, is the solution that appeared in the Canadian Earthquake Epicentre File (CEEF). The other, generally with some description and seismic phases, is a recomputed solution, from Adams et al. (1989) or from Stevens (1980), with comments added by Lamontagne for some Charlevoix earthquakes.

The meaning of the various fields is given in the file npf_format.txt.

1. Events that could have had an impact on the sediments

In addition to the catalogue, Tables 3 and 4 presents some characteristics of these moderate to large events. Since about 1980, epicentre precision has been better than ± 10 km, and within the Charlevoix Seismograph Network better than 2 km since 1977. As one goes back in time, the precision decreases in direct correspondence with the decreasing number of stations.

1663: Probably the largest earthquake felt in Quebec. The epicentre is, the author believes, very approximate (a few hundreds of kilometres) and is mainly based on its impact. The most important impact is the number of terrestrial landslides triggered by the event. Its estimated magnitude makes it the largest earthquake of the catalogue. The large magnitude is supported by the numerous aftershocks felt in Quebec City and in the Laurentians. Based on the land movement impact of this earthquake, Locat (2008) suggests a higher magnitude for this event (M 7.6) and a location closer to the Saguenay region. EPRI (1994) lists it as M_w 6.7.

In Duchesne et al. (2003), the possible acceleration sustained by the Outardes Bay area in 1663 was compared to how the earthquake was felt in Boston, MA (800 km epicentral distance). It is mentioned that the earthquake was felt so strongly in Boston that tops of several stone chimneys were broken (GSC web site, 2001). This interpretation is not supported by the evidence in Gouin (2001) about the felt information along the Atlantic Coastline:

New England

Lalemant and Marie de l'Incarnation heard from travellers arriving from New England that the earthquake was felt in New England:

* « *Ce 29. de juillet, il est arrivé à notre port de Québec une barque de la Nouvelle Angleterre. Les personnes qui sont descendues de ce vaisseau disent qu'étant à Buston … le lundi gras à cinq heures et demie, ils eurent le tremblement de terre comme nous l'avons eu ici, et qu'il redoubla plusieurs fois* … » (Marie de l'Incarnation in *Ouri*; Letter CCIV, p. 698)

At Boston, they felt the main shock and other aftershocks.

Williams in 1785 (ed. 1785, I, pp. 263-264) gave information on what happened at Boston during the main shock. He told his readers of authors mentioning that the earthquake was felt in New England, of the accompanying noise, of houses oscillating, of « pewters falling from their shelves ... », etc. In reading his report, <u>we have the impression that information from Canada and from New England are rather mixed up. The reader can not know which effect belongs to which part of North America</u>.

Based on interpretations of other secondary sources, Mather *et al.* (1927) estimated the intensity to be at Boston VII (RF[2]), i.e. VI (MM[3]). We do not

[2] RF : Rossi-Forel intensity scale
[3] MM : Modified-Mercalli intensity scale

believe that the original documents authenticate these conclusions. **They suggest a much lower intensity.**

Consequently, Boston should not be used as an example of the ground shaking in the Lower St. Lawrence.

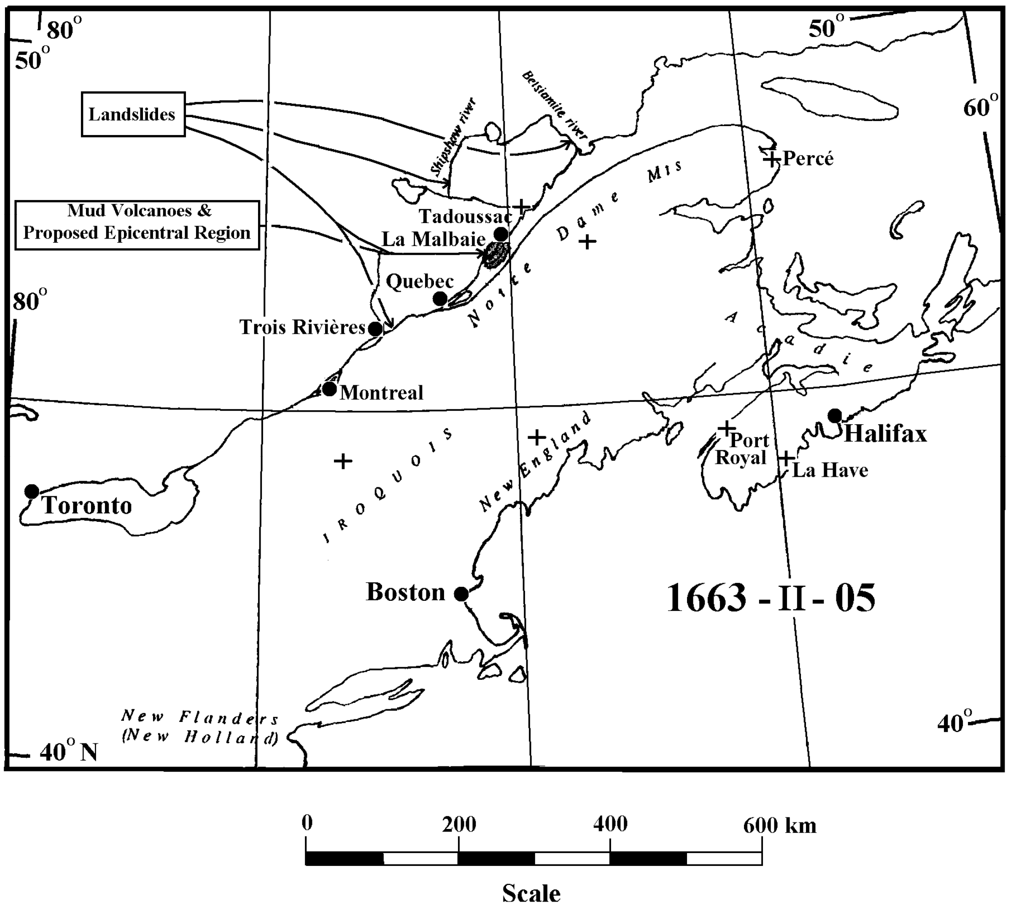

Figure 11: Map of the regions and sites represented by the names they had in 1663, and the epicentral area for the earthquake on February 5, 1663. The sites where the information comes from are indicated by: a full circle (●) for known intensities, a cross (+) for unknown intensities. Source: Gouin (2001).

1791: Earthquake most probably from the Baie-St-Paul-Isle aux Coudres area where damage was the greatest (broken chimneys). It is the author's opinion that the event was notably smaller than the **M** 5.8 Saguenay earthquake: not felt in Montreal, Ontario, New

Brunswick or the U.S. Based on the limited damage and small felt area, its magnitude may only be **M** 5½. EPRI (1994) lists it as M_w 5.5.

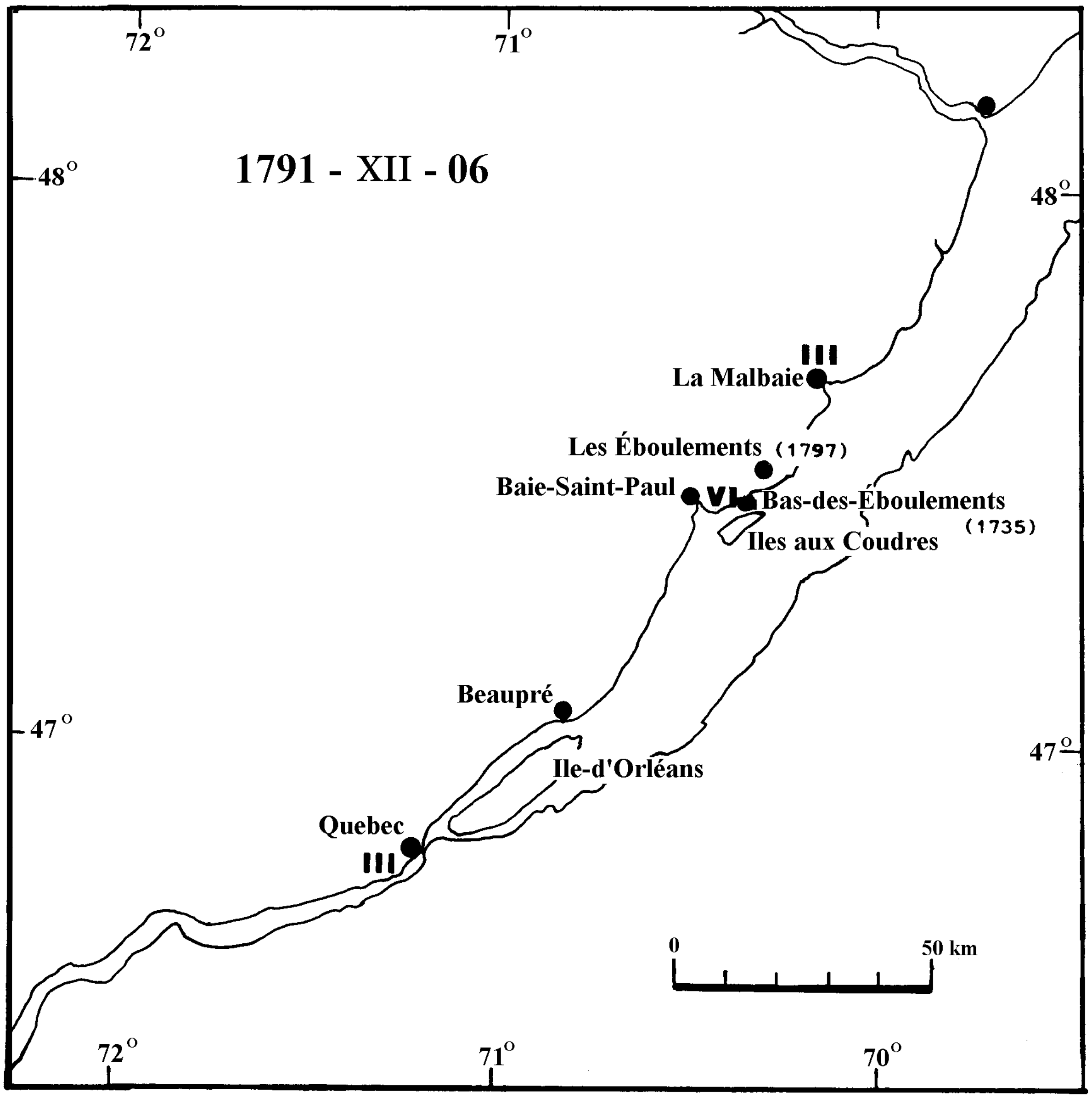

Figure 12. Distribution of the intensities of December 6, 1791. The date that follows Les Éboulements (1797) is the date for the construction of the third church; in 1791, the church and the village were at Bas-des-Éboulements. The chapel, in masonry, was from 1735. Source : Gouin (2001).

1860: Earthquake most probably located in Charlevoix since most of the damage was witnessed there. The Quebec City newspaper “Le Canadien” of 19 October 1860 reports that on the St. Lawrence River, the event was felt by at least one ship. One must note that for a sufficiently strong earthquake, P-waves can be felt on water. The excerpt below is a description of how it was felt at La Traverse, near Ile aux Coudres, and near Kamouraska. Except for the seismic P-waves, nothing that could indicate submarine mass movement at depth or release of gas is reported.

> *Le capitaine D. Wilson, du navire Great Britain, se trouvant dans la traverse, ressentit la commotion souterraine de 6 h. du matin et croyant que son vaisseau avait touché, il consigna le fait dans son livre de loc.*
>
> *On nous rapporte que le capitaine d'un navire en marche vis-à-vis de l'Île aux Corneilles, située devant Kamouraska, ayant été réveillé par la commotion sous terraine, crut que son vaisseau avait touché, et s'élança sur le pont, ordonnant au pilote de faire jeter l'ancre immédiatement. Pour toute réponse, celui-ci fit jeter la sonde qui marqua 12 brasses d'eau.*

EPRI (1994) lists it as M_w 6.1.

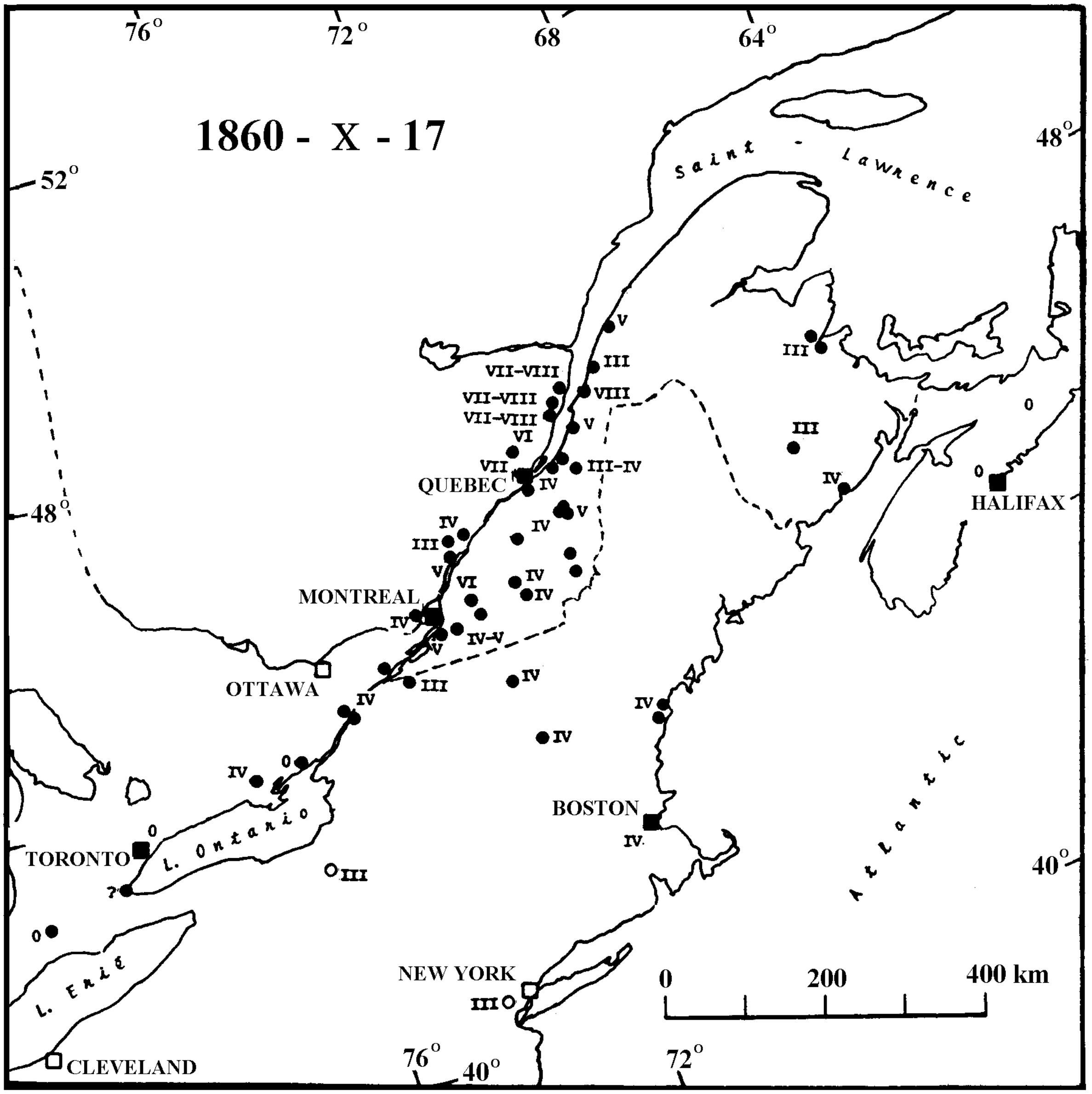

Figure 13: Distribution map of the sites mentioned in contemporary documents as being shaken or not by the tremors. The sites found in contemporary documents are marked by full circles (●) and the sites found in non-contemporary documents are marked by open circles (○). The reference points are marked by full squares (■), three points such as Ottawa Cleveland and New York are marked by an open square (□). Source : Gouin (2001).

1870: A large earthquake with an estimated magnitude of 6 ½ with an epicentre probably near Baie-St-Paul based on maximum damage and reported liquefaction, which is usually in the near field. EPRI (1994) lists it as M_w 6.6. This earthquake was felt on the St. Lawrence near Isle aux Coudres (Gouin, 2001).

On the St. Lawrence River, the event was felt by at least one ship. For a sufficiently strong earthquake, P-waves can be felt. The excerpt below describes its intensity at La Traverse, near Ile aux Coudres. Except for the seismic P-waves, nothing indicative of a submarine mass movement at depth or release of gas is reported.

La Traverse [on St. Lawrence]

> * " *The ship Sarawak, Capt. Richardson, ... reports: " Oct. 20, at 11:40 a.m., experienced three shocks ... while in the Traverse -the first lasted about two minutes, the second half a minute, and the third five seconds. The ship shook from stem to stern.* "

Quebec Daily Mercury –Oct. 22, 1870.

- **Location of La Traverse (The Crossing)**

  * " *Beyond Rivière du Sud is a channel named La Traverse, which deserves mention from the circumstance of the river being here 13 miles across; yet the Isle aux Coudres, the shoal of St. Rock, and another called the English Bank, intercept the fair way so much, that this passage which is the usual one the pilots choose, is not more than 17 to 1800 yards between the two buoys that marks the edge of the shoals.* " (Bouchette, Topographical Description of Lower Canada, 1815, p. 49)

The Morning Chronicle - Commercial and Shipping Gazette – October 22nd, 1870, reports:

> *EARTHQUAKE - The Purser of the steamer Clyde reports that the shock of earthquake was very violent along the whole of the North Shore.*

It appears that part of Cap Trinité collapsed into the Saguenay River

> *Near Cape Trinity, a mass of rock of more than four hundred feet in length, has been detached from the lofty banks and precipitated into the river Saguenay.*

Quebec Daily Mercury –Oct. 22, 1870.

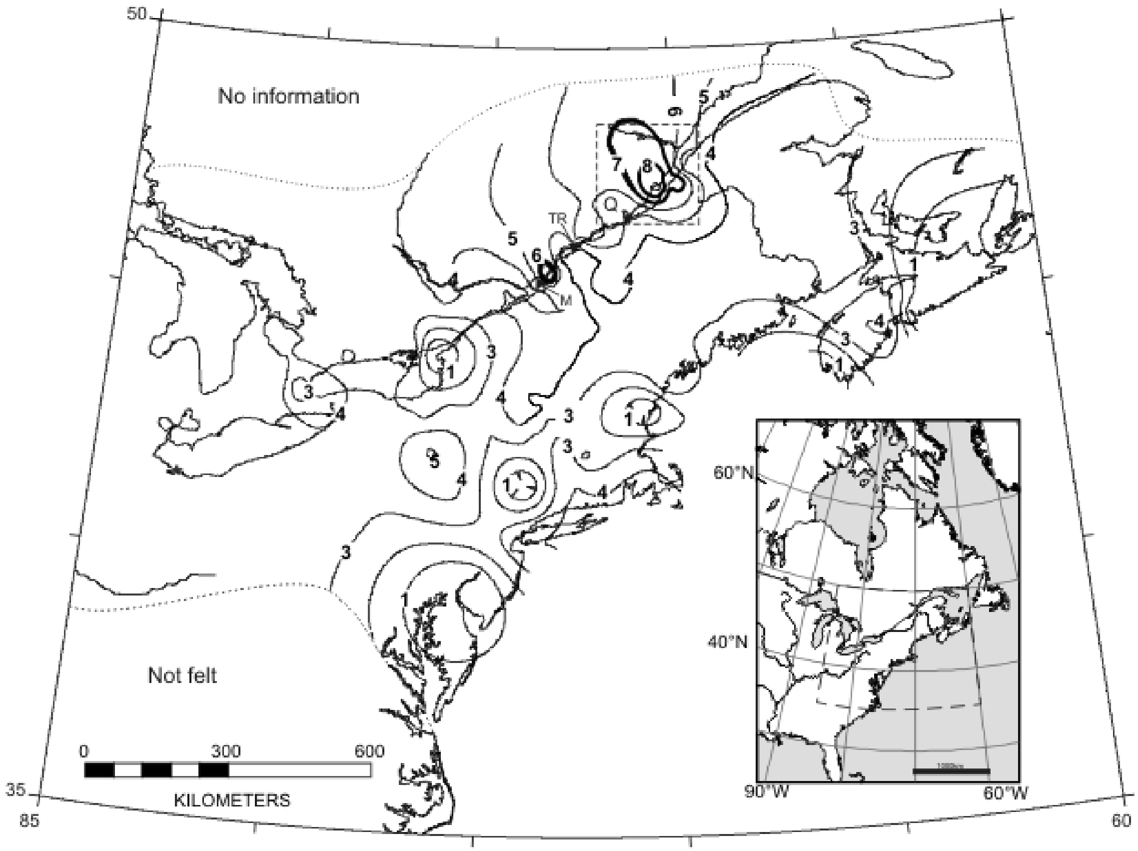

Figure 14: Isoseismals (MMI) of the 1870 earthquake (Lamontagne et al., 2008).

1925: Event well located near Ile aux Lièvres based on seismograph data (Stevens, 1980). This earthquake is located within a few kilometres and its focal depth is about 10 km. The description of the impact can be found in Hodgson (1950) and the revised isoseismals in Cajka (1999).

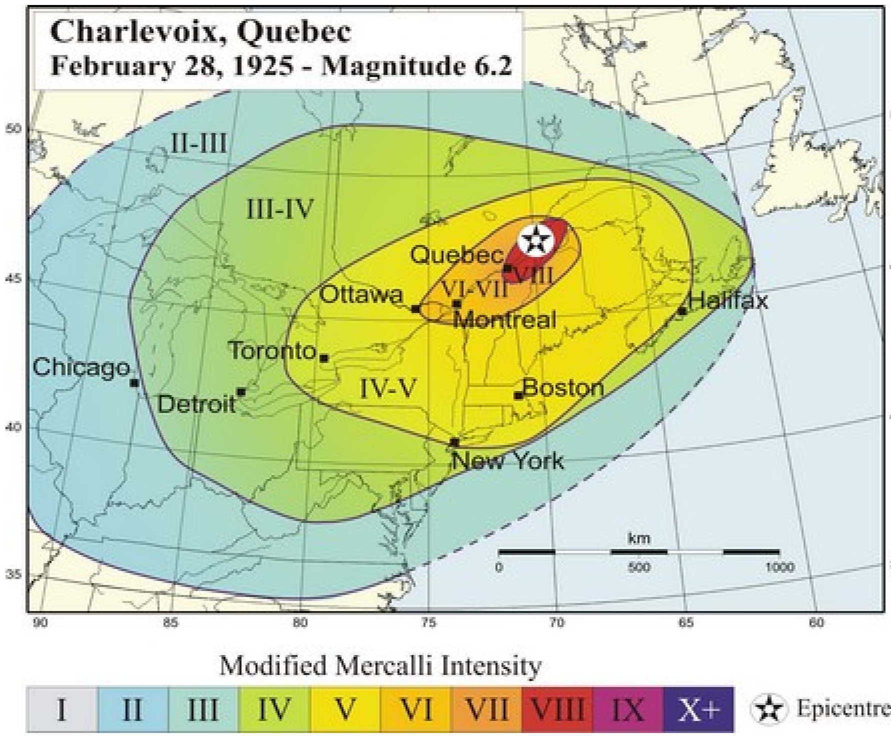

Figure 15: Isoseismals of the 1925 Charlevoix earthquake (modified from Cajka, 1999).

1988: The Saguenay earthquake was well located with a network of modern seismographs and its epicentre was 35 km south of Saguenay (Chicoutimi), Qc. The earthquake caused a series of landslides that are described in Lefebvre et al., 1992. None of these mass movements were reported for water-covered areas. At the time of the earthquake, the media reported cases of gas release in some lakes near the epicentres (Lamontagne, pers. recollection). There were also cracks at the surface of ice-covered lakes (Lamontagne, pers. recollection).

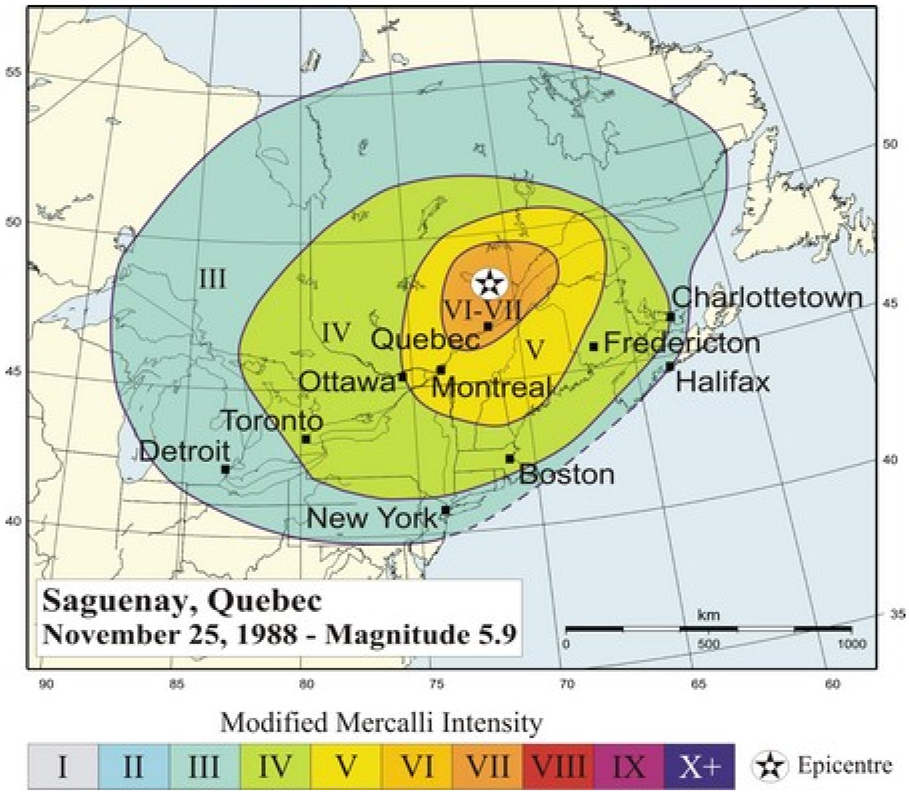

Figure 16: Isoseismals of the 1988 Saguenay earthquake (Cajka and Drysdale, 1996).

Moderate events

1831-07-07 or 08(?) Night Charlevoix-Kamouraska, Qc; Magnitude around 5.0

This event does not have a very accurate location. However, the fact the damage was maximum at La Malbaie and that five aftershocks were felt there, suggest that the epicentre of the main shock was most probably nearby. Considering the number of aftershocks and the damage, the magnitude of the main shock must have been at least **M** 5.5. EPRI (1994) lists it as M_w 4.8. Gouin (2001), using the felt area magnitude relation of Nuttli and Zollweg (1974), finds that the corresponding $m_b(Lg)$ magnitude would have been about 4.6. We find this magnitude too low, since earthquake damage is usually not associated with an earthquake as small as that.

Interestingly, for this earthquake it is reported that, at Kamouraska:

Un navigateur nous a rapporté, le lendemain matin, que le fleuve avait été saisi, en ce moment, d'un bouillonnement général. » *Le Canadien*, Québec, 20 juillet 1831

Which Gouin (2001) interprets as : *It was reported that the waters of the St. Lawrence were suddenly agitated; the exact site where the sailor was is not indicated but it could not practically be far from the quay at Kamouraska.*

During an earthquake, it is generally reported that a strong shock is felt (due to the arrival of the strong Primary (P) waves; the secondary (S) waves do not propagate through water. The term *bouillonnement* may signify that the waters of the Saint-Lawrence were made as boiling by the shock; could it be due to a submarine landslide or to the release of sediment-trapped gas?

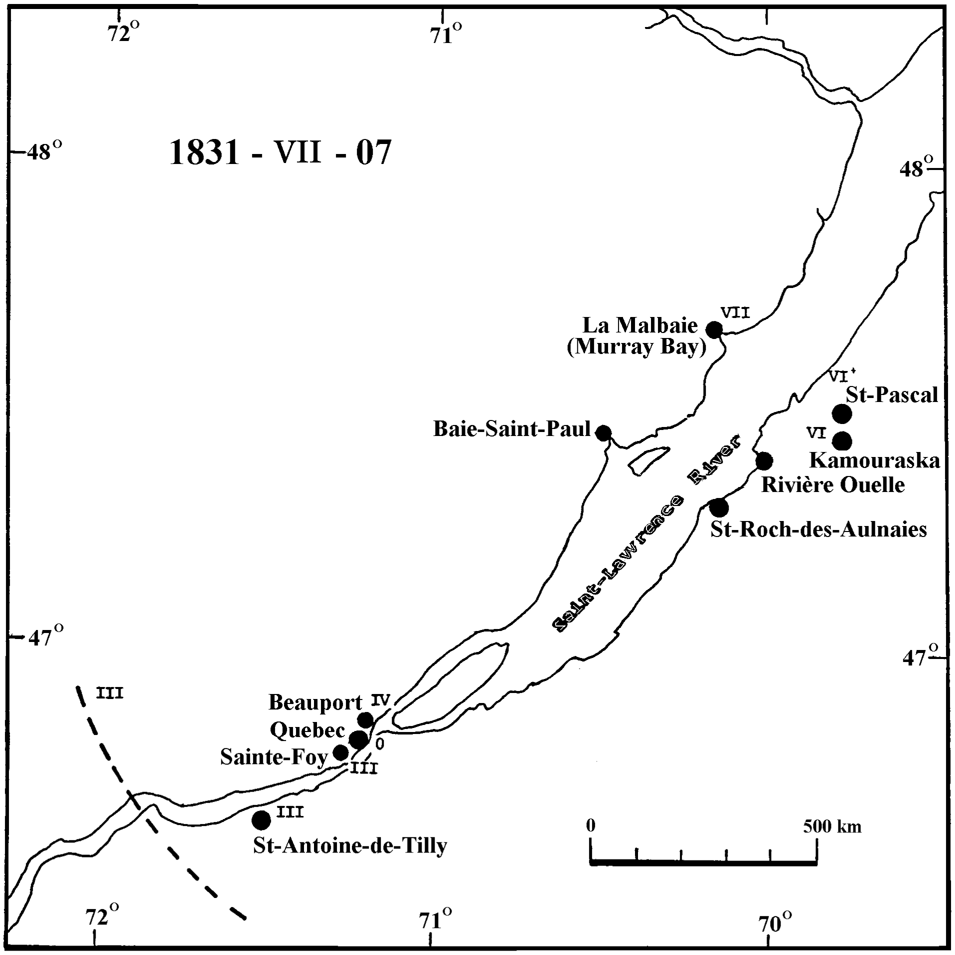

Figure 17: The full circles (•) indicate the sites mentioned in contemporary newspapers and the Roman numerals the intensities inferred from newspapers. The dotted line, at lower and left of this map, represents the probable limit of perceptibility for the tremors south-west of the perturbed area. Source : Gouin (2001).

1872-01-10 01:00 Quebec City Region Magnitude around 5.0

The earthquake was strongly felt in Quebec City suggesting an epicentre in the region. The shock was felt on the ice bridge where many cracks were created. EPRI (1994) lists it as M_w 4.6.

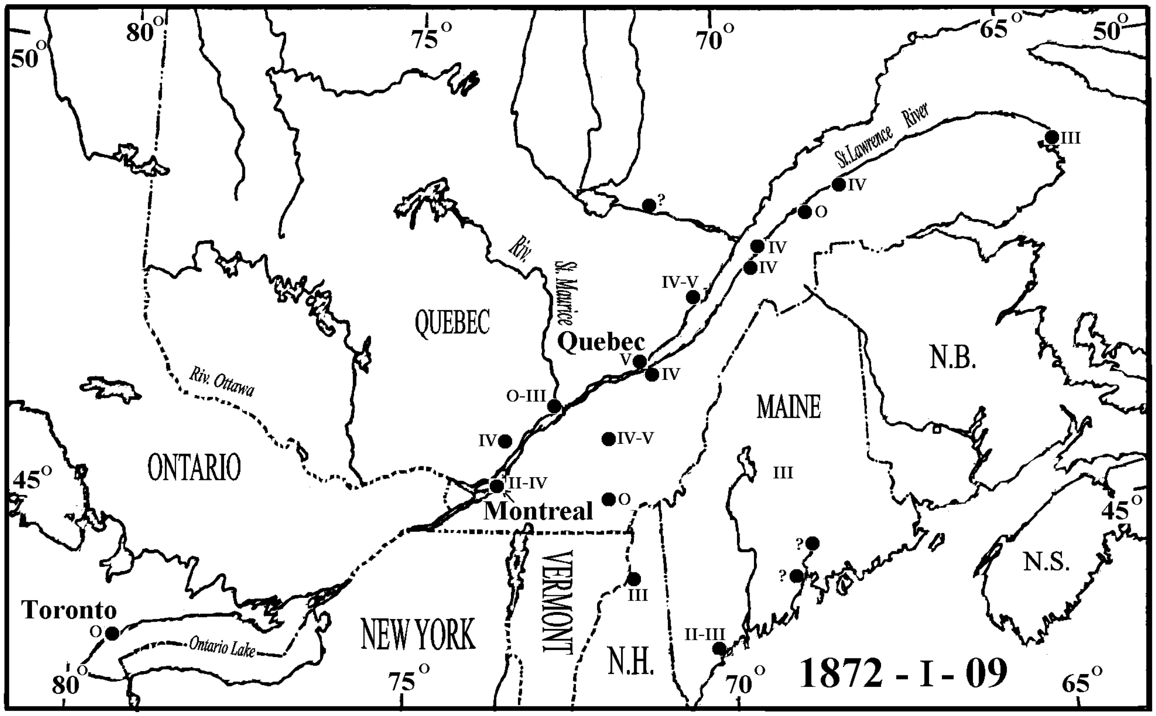

Figure 18: Isoseismals of the January 9, 1872 earthquake.

1880-11-29 Morning Quebec North Shore Estimated Magnitude around 5.5

This earthquake caused some damage to chimneys at Pointe-aux-Anglais suggesting an earthquake potentially nearby with a magnitude of at least 5.

Instrumentally-recorded earthquakes with magnitudes ≥ 5

The earthquakes below were all recorded by seismographs and their locations and magnitudes are fairly accurate.

1924-09-30 03:54 Charlevoix-Kamouraska Magnitude 5.4; Stevens (1980). EPRI (1994) lists it as M_w 5.2.

1931-01-08 00:13 Charlevoix-Kamouraska Magnitude 5.5; Stevens (1980). EPRI (1994) lists it as M_w 4.9.

1939-10-19 11:53 Charlevoix-Kamouraska Magnitude 5.6; Stevens (1980). EPRI (1994) lists it as M_w 5.3.

1952-10-14 22:03 Charlevoix-Kamouraska Magnitude 5.3; Stevens (1980). EPRI (1994) lists it as M_w 4.5.
1979-08-19 22:49 Charlevoix-Kamouraska Magnitude 5.0; Hasegawa and Wetmiller (1980). Schulte and Mooney (2008) list it as M_w 4.8.
1997-11-06 02:34 Quebec City (Cap-Rouge) Magnitude 5.1; Nadeau et al., 1998. Schulte and Mooney (2008) list it as M_w 4.8.
2005-03-06 06:17 Charlevoix-Kamouraska Magnitude 5.4.

8- Possibilities of submarine landslides and tsunamis during historical earthquakes

There are a few historical accounts that suggest submarine mass movements, gas releases (venting) and even a tsunami caused by earthquakes.

- **Earthquake of 1831-07-07 or 08(?)**

In Kamouraska, it is reported that:

Un navigateur nous a rapporté, le lendemain matin, que le fleuve avait été saisi, en ce moment, d'un bouillonnement général. » [12]

During an earthquake, it is generally reported that a strong shock is felt (due to the arrival of the strong Primary (P) waves; the secondary (S) waves do not propagate through water. The term *bouillonnement* may be interpreted as the waters of the Saint-Lawrence looked as they were boiling by the shock; this can be due to a submarine landslide or to the release of sediment-trapped gas.

- Saguenay Cap-Trinité 1870

According to some newspapers, a 100 m (300 feet) section of the Cap Trinité collapsed into the Saguenay River during the 20 October, 1870 earthquake. No submarine data exist to illustrate the impact of this rockslide beneath the Saguenay River.

- The Charlevoix-Kamouraska earthquake of 1925

According to the Montreal newspaper *La Patrie* (*/data/LaPatrie-2mars1925p1.pdf),* the icebreaker Mikula, which was anchored near Cap-au-Saumon at the time of the March 1st, 1925 Charlevoix-Kamouraska earthquake felt the earthquake strongly and was covered with a large sea wave.

"…De plus, il se trouvait au Cap-au-Saumon lorsque le tremblement de terre se produisit et la secousse sur le fleuve, à cet endroit, fut telle que le navire faillit sombrer. La mer s'ouvrit sous la coque du vaisseau <u>pendant que des vagues gigantesques</u> le couvraient tout entier. … »

Strangely, another interview with the Captain does not mention such a wave. Elsewhere, near Rimouski, it was found that the ice had disappeared between the mainland and an island (Fig. 19). Search for the log book of the Mikula was not successful. M. Lamontagne contacted a few residents of Charlevoix who lived through the 1925 earthquake. No one had heard of a series of waves hitting the shore line.

Near Rimouski, the ice covered St. Lawrence River became ice-free following the earthquakes, which only happens in April on other years (Figs. 19; 20). The link with the earthquake or a possible underwater mass movement remains unclear.

aucun dégât à enregistrer.

UNE DEBACLE PARTIELLE

(Du correspondant de la PRESSE)

Rimouski, 4. — La première vibration du sol se fit sentir vers neuf heures et vingt minutes, samedi soir. Dès le début, il était difficile d'identifier ce frémissement comme un tremblement de terre. La secousse proprement dite qui suivit immédiatement ne laissa plus de doute, car elle fut d'une intensité telle que pendant plusieurs secondes les maisons se comportèrent comme des vaisseaux sur une mer agitée. Il est surprenant qu'on n'ait aucun désastre ou accident grave à enregistrer. Ce fut une danse générale de menus objets: les horloges s'arrêtèrent, les câdres sur les murs quittèrent leurs crochets; la vaisselle dans les armoires s'entrechoqua.

La secousse eut un furieux effet sur le fleuve, comme on put le constater, dimanche matin. Le champ de glace, qui existait depuis le commencement de l'hiver entre la terre ferme et l'île Saint-Barnabé, s'était complètement disloqué; et on peut actuellement voir une partie du fleuve libre de glace là où, en temps normal, pareille chose ne se produit que dans le mois d'avril.

Un autre tremblemnet de terre un peu moins violent se fit sentir dans la nuit, exactement 5 heures après le premier.

Figure 19: Description of the effects of the 1925 earthquake near Rimouski (La Presse).

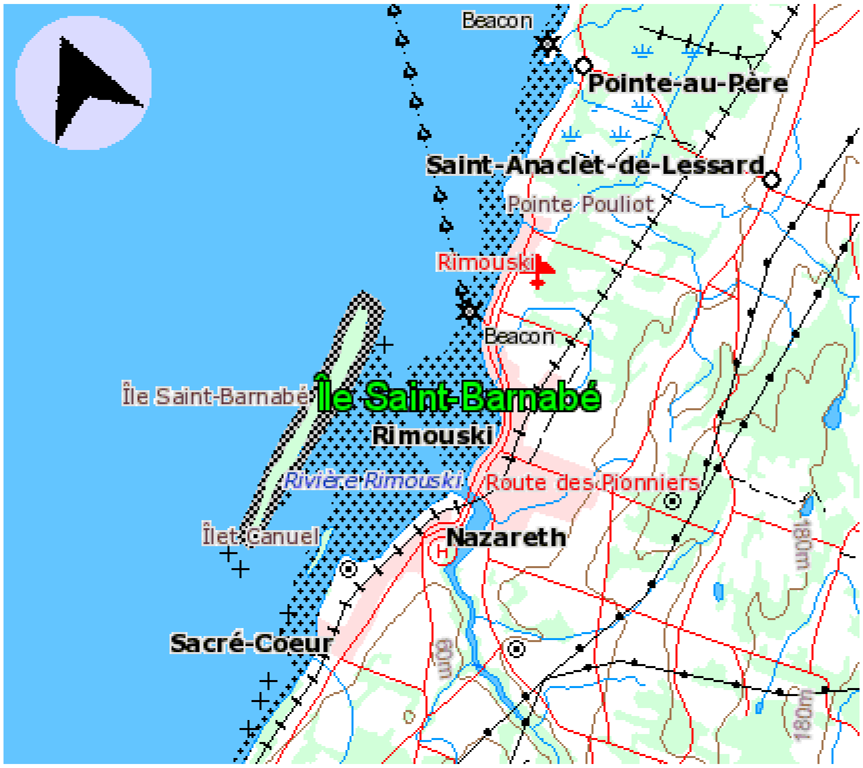

Fig. 20 Location of Ile Saint-Barnabé, near Rimouski, Qc.

The Lower St. Lawrence earthquake of 16 March, 1999

Two events occurred, one was a possible undocumented snow avalanche near Mont-Saint-Pierre and one was a possible sand bank slide near Port-Cartier (undocumented). The earthquake and its aftershocks is found in Lamontagne et al., 2004. There is no means of verifying if underwater movements occurred.

9- Paleoearthquakes

Four types of studies suggest prehistoric earthquakes in an area centred on Charlevoix. Readers are referred to the references for more information.

1- Lake disturbances (Doig, 1986, 1990, 1991, 1998; Ouellet, 1997).
2- Liquefaction features (Tuttle et al., 1990)

3- Sub-areal landslides (Locat et al., 1993; Fillion et al., 1991)
4- Submarine landslides beneath the Saguenay River (Locat et al., 2003; Urgeles et al., 2002).

10- Conclusions and recommendations

The topography of the area reveals numerous scars left from past mass movements on land (sub-aerial) and at the bottom of the River (submarine). We have documented the known earthquakes that had the potential (location and magnitude) to trigger some of these landslides. There are about 80 earthquakes in our revised database for the period 1608-1925, with magnitude ≥ 3 (estimated or calculated) that have occurred near or in the estuary of the St. Lawrence River (i.e. between Quebec City and Baie-Comeau, Quebec). We know that this catalogue is far from complete in terms of events that could have triggered a submarine landslide. Until dates are obtained from the submarine landslides, a correlation with a known seismic event remains uncertain. Historical descriptions provide accounts of potential mass movements seen at the surface ("boiling" of the St. Lawrence River and a possible tsunami wave).

11- Acknowledgments

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Table 1: Factors contributing to the initiation of submarine landslides (Modified from Masson et al., 2006)

Historically documented worldwide	**Potentially found in St. Lawrence Estuary**
Earthquakes	**Yes**
Hurricanes or cyclic loading	**Yes**
Loading or oversteepening of slopes	**Yes**
Underconsolidation (overpressures)	**Yes**
Rainfall (where landslides have a subareal extension)	**Yes**
Slope parallel weak layers in bedded sequences	**Yes**
Suggested (but less well documented):	
Gas Hydrate dissociation and venting	**Yes**
Sea-level change	**Yes**
Volcanic activity	**No**

Table 2: Completeness table, parameter table and source zone maps (Source: Adams and Halchuk, 2003)

A) H Model

Eastern Zones, H Model Completeness Table

Zone	2.5	2.6	2.8	2.9	3.0	3.2	3.3	3.4	3.6	3.8	4.0	4.1	4.2	4.3	4.8	5.3	5.8	6.3	6.8	7.2	7.3
BSL			1975	--	--	--	1963	--	--	--	--	--	--	1938	1928	1900	--	1850			
CHV			1968	--	--	--	1963	--	--	1938	--	--	--	1928	1920	1880	1790	1660			
GNS			1975	--	--	--	1963	--	--	--	--	--	--	1938	1928	1900	--	1850			
SAG			1975	--	--	--	1963	--	--	1938	--	--	--	1928	1920	1880	--	1850	--	--	1660
SEB			1982	--	--	--	1975	--	--	1963	--	--	--	--	1953	1900	--	1850			
TAD			1975	--	--	--	1963	--	--	1938	--	--	--	1928	1920	1880	1790	1660			
TRR			1975	--	--	--	1963	--	--	1938	--	--	--	1928	1920	1880	1790	1660			

B) R model

Zone	2.5	2.6	2.8	2.9	3.0	3.2	3.3	3.4	3.6	3.8	4.0	4.1	4.2	4.3	4.8	5.3	5.8	6.3	6.8	7.2	7.3
IRB			1982	--	--	--	1975	--	--	1963	--	--	--	--	1953	1900	--	1850			
IRM			1975	--	--	--	1963	--	--	--	--	--	--	1938	1928	1900	1790	--	1850		
LAB			1982	--	--	--	1975	--	--	1963	--	--	--	--	1953	1900	--	1850			

C) Completeness (Basham et al., 1982)

Zone	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5
CHV	1968	1963	1937	1928	1920	1900	1800	1660	1660	

LSL	1975	1963	1963	1937	1937	1937	1900			
EBG	--	1963	1963	1956	1937					

Abbreviations of source zone names

BSL - BAS SAINT LAURENT East H
CHV - CHARLEVOIX East H
ECM - EASTERN CONTINENTAL MARGIN East R
GNS - GULF OF ST. LAWRENCE - NORTH SHORE East H
IRB - IAPETAN RIFT BACKGROUND East R
IRM - IAPETAN RIFT MARGIN East R
LAB - SOUTHERN LABRADOR East R
LSP - LAURENTIAN SLOPE East H
NAI - NORTHERN APPALACHIANS INTERIOR East R
NAN - NORTHERN APPALACHIANS East H
SAG - SAGUENAY East H
SEB - SOUTHEAST CANADA BACKGROUND East H
SGL - SOUTHERN GREAT LAKES East R
SLE - SOUTH SHORE LAKE ERIE East H
TRR - TROIS-RIVIERES East H

Table3: Large earthquakes (M ≥ 6)

Date	Time (U.T.)	Region	Lat	Lon	Précision (km)	Mag	Land slide	Damage	Maximum MMI	Description	References
1663-02-05	22:30	Charlevoix-Kamouraska, Quebec	47.6	-70.1	200	7	Yes	Yes	IX	Epicentre most likely in the Charlevoix-Kamouraska Seismic Zone, Quebec; Felt in most of New France (Quebec City, Trois-Rivières, Montréal) and parts of New England (Boston) and New Amsterdam (New York City). Some damage to masonry in Quebec City, Trois-Rivières and Montréal. Landslides reported in the Charlevoix region, and along the St. Lawrence, Shipshaw, Betsiamites, Pentecôte, Batiscan and Saint-Maurice rivers. Numerous aftershocks felt in Quebec City during the following months.	Gouin (2001)
1791-12-06	20:00	Charlevoix-Kamouraska, Quebec	47.4	-70.5	50	6	No	Yes	VII	Felt strongly in Charlevoix, Quebec, and in Quebec City. Damage to houses and churches in Baie-Saint-Paul, Les Éboulements and on Île aux Coudres.	
1860-10-17	11:15	Charlevoix-Kamouraska, Quebec	47.5	-70.1	30	6	No	Yes	VIII	Widely felt in Quebec and felt as far as New Brunswick, eastern Ontario and New England. Damage in the epicentral region on both shores of the St. Lawrence River: North Shore: Baie-Saint-Paul; La Malbaie; South Shore: Rivière-Ouelle. Also felt strongly in Quebec City.	
1870-10-20	16:30	Charlevoix-Kamouraska, Quebec	47.4	-70.5	30	6½	Yes	Yes	IX-X	Felt over most of the Province of Quebec, in Ontario, New Brunswick, and in New England. Considerable damage to houses in Charlevoix, especially in Baie-Saint-Paul, Les Éboulements and along the South Shore	

										of the St. Lawrence River. Damage to chimneys reported in lower town in Quebec City. Possible rock slide along the Saguenay River.	
1925-03-01	02:19	Charlevoix-Kamouraska, Quebec	47.8	-69.8	15	6.2	Yes	Yes	VIII	Charlevoix-Kamouraska Seismic Zone, Quebec, near Île aux Lièvres. The earthquake was felt over most of eastern Canada and northeastern U.S. It caused damage to unreinforced masonry (chimneys, walls) in the epicentral region on both shores of the St. Lawrence, and in Quebec City, (including damage to port facilities), Trois-Rivières and Shawinigan. Possible liquefaction near Saint-Urbain, Quebec. Numerous felt aftershocks followed.	Location: Stevens (1980); magnitude: Bent (1992)
1988-11-25	23:46	Saguenay Region, Quebec	48.12	-71.18	10	5.9	Yes	Yes	VIII	Laurentides Fauna Reserve, south of Saguenay (Chicoutimi), Quebec. Preceded by a foreshock 2½ days before. Damage caused to unreinforced masonry at Jonquière, Chicoutimi, La Baie, Charlevoix region, Montmagny, Quebec City, Sorel and Montreal-East. Liquefaction of soft soils in the Ferland-et-Boilleau area. Eleven cases of soil movements reported. Only one felt aftershock.	North et al., 1990

Table 4; Moderate earthquakes (5 ≤ M < 6.0)

Date	Time (U.T.)	Region	Lat	Lon	Précision (km)	Mag	Landslide	Damage	Max MMI	Description	Reference
1831-07-07 or 08(?)	Night	Charlevoix-Kamouraska, Quebec	47.6	-70.1	30	5.0	No	Yes	VII	"At La Malbaie, Quebec, damage to walls (wide crack), chimneys thrown down or displaced. Also felt in Quebec City."	Gouin (2001)
1872-01-10	01:00	Quebec City	46.8	-71.2	30	5.0	No	Yes	V	Quebec City Region; Vibrations cracked a wall in the lower town and made objects fall.	Gouin (2001)
1880-11-29	Morning	Quebec North Shore	49.5	-67.0	40	5.5	No	Yes	V-VI	"In Pointe-aux-Anglais, Quebec, many chimneys and windows were reported broken. Also felt in the Charlevoix region."	Gouin (2001)
1924-09-30	03:54	Charlevoix-Kamouraska	47.8	-69.8	10	5.5	No	Yes	V	"Felt over most of the St.Lawrence Valley from Ottawa, Ontario, eastward through Quebec, New Brunswick and northern Maine. No damage reported. "	Location: Stevens (1980); Description: Gouin (2001)

1931-01-08	00:13	Charlevoix-Kamouraska	47.3	-70.4	10	5.4	No	Yes	V	"Felt in Charlevoix, Quebec City, Montreal and Ottawa. Minor damage (fallen objects) reported."	Location: Stevens (1980)
1939-10-19	11:53	Charlevoix-Kamouraska	47.8	-69.8	10	5.6	No	Yes	VII	"Chimneys damaged in Rivière-Ouelle, Rivière-du-Loup, Saint-Urbain and La Malbaie, Quebec. There, some brick walls were cracked. In Rivière-du-Loup, the plaster from the ceiling of church fell and many store windows were broken. Small ground fissures reported in Tadoussac. Felt over most of eastern Canada. "	Location: Stevens (1980)
1952-10-14	22:03	Charlevoix-Kamouraska	47.8	-69.8	10	5.3	No	Yes	VI	"Dishes were jarred and some store windows broken in Rivière-du-Loup, Quebec. Felt in most of the St. Lawrence Valley, northern Maine and northern New Brunswick Rockfall reported at Cap-aux-Corbeaux, near Baie-St-Paul. Powerblack out in Baie-St-Paul. "	
1979-08-19	22:49	Charlevoix-Kamouraska	47.67	-69.9	5	5.0	No	Yes	VI	"Felt in Charlevoix, Kamouraska, and Saguenay regions. Damaged three chimneys.	Location: Hasegawa and Wetmiller (1980)
1997-11-06	02:34	Quebec City	46.80	-71.42	5	5.1	No	Yes	VII	"Quebec City Region, near the Cap-Rouge suburb. Felt in Quebec City, Charlevoix, and Saguenay regions. Also reported felt in Ottawa Valley, Montreal, Maine, and northern New York State. Minor damage reported in a school of the Quebec City region."	Location and description: Nadeau et al. (1998)

2005-03-06	06:17	Charlevoix-Kamouraska	47.75	-69.73	5	5.4	No	No	IV-V	"Near Rivière-du-Loup. No damage but felt strongly in the regions of Charlevoix, Saguenay and Quebec City. Felt as far as the Ottawa valley, Montreal, Fredericton, New Brunswick, and Boston, Mass. " Natural Resources Canada	Earthquakescanada.ca

Figure captions

Figure 1: Location map of the study area (polygon) and of some geographic locations mentioned in text. In addition, the submarine landslides are shown (areas in blue).

Figure 2: Earthquakes of the period 1600-1925 currently in the GSC catalogue. The study area is the black polygon. Seismograph stations of the CNSN (as of 2008) are black inverted triangles.

Figure 3. Earthquakes of magnitude 4 and larger for the period 1600-2007 from the GSC catalogue. The study area is the black polygon. Seismograph stations of the CNSN (as of 2008) are black inverted triangles.

Figure 4. Earthquakes of magnitude 2.0 and larger for the period 1980-2007. The concentration of earthquakes in Charlevoix-Kamouraska and in the Lower St. Lawrence Seismic Zone is evident.

Figure 5. Significant earthquakes of eastern Canada (Lamontagne et al. 2008).

Figure 6. Seismic zones according to the historical seismicity (“H” model) as developed by Adams and Halchuk (2003) for seismic zoning purposes. The acronyms are explained in Table 2. The red polygon is the study area.

Figure 7. Figure 6. Seismic zones according to the historical seismicity (“R” model) as developed by Adams and Halchuk (2003) for seismic zoning purposes. The acronyms are explained in Table 2. The red polygon is the study area.

Figure 8. Completeness years for magnitude 6.3 in the different zones of the seismic zoning model “H”.

Figure 9. Completeness years for magnitude 4.8 in the different zones of the seismic zoning model “H”.

Figure 10. Completeness years for magnitude 4.0 in the different zones of the seismic zoning model “H”.

Figure 12 to 19: in main text.

Appendix 1: Modified Mercalli Intensity Scale (Wood and Neumann, 1931)

I. Not felt -- or, except under especially favorable circumstances.

Under certain conditions, at and outside the boundary of the area in which a great shock is felt:

- sometimes birds, animals, reported uneasy and disturbed;
- sometimes dizziness or nausea experienced;
- sometimes trees, structures, liquids, bodies of water, may sway; doors may swing, very slowly.

II. Felt indoors by few, especially on upper floors, or by sensitive or nervous persons.

Also, as in grade I, but often more noticeably:

- sometimes hanging objects may swing, especially when delicately suspended;
- sometimes trees, structures, liquids, bodies of water, may sway, doors may swing, very slowly;
- sometimes birds, animals, reported uneasy and disturbed;
- sometimes dizziness or nausea experienced.

III. Felt indoors by several, motion usually rapid vibration.

- Sometimes not recognized to be an earthquake at first.
- Duration estimated in some cases.
- Vibration like that due to the passing of light or lightly loaded trucks or heavy trucks some distance away.
- Hanging objects may swing slightly.
- Movements may be appreciable on upper levels of tall structures.
- Rocked standing motor cars slightly.

IV. Felt indoors by many, outdoors by few.

- Awakened few, especially light sleepers.
- Frightened no one, unless apprehensive from previous experience.
- Vibration like that due to the passing of heavy or heavily loaded trucks.

- Sensation like heavy body striking building or falling of heavy objects inside.
- Rattling of dishes, windows, doors; glassware and crockery clink and clash.
- Creaking of walls, frame, especially in the upper range of this grade.
- Hanging objects swung, in numerous instances.
- Slightly disturbed liquids in open vessels. Rocked standing motor cars noticeably.

V. Felt indoors by practically all, outdoors by many or most: outdoors direction estimated.

- Awakened many, or most.
- Frightened few -- slight excitement, a few ran outdoors.
- Buildings trembled throughout.
- Broke dishes, glassware, to some extent.
- Cracked windows -- in some cases, but not generally.
- Overturned vases, small or unstable objects, in many instances, with occasional fall.
- Hanging objects, doors, swing generally or considerably.
- Knocked pictures against walls, or swung them out of place.
- Opened, or closed, doors, shutters, abruptly. Pendulum clocks stopped, started, or ran fast, or slow.
- Moved small objects, furnishings, the latter to slight extent.
- Spilled liquids in small amounts from well-filled open containers.
- Trees, bushes, shaken slightly.

VI. Felt by all, indoors and outdoors.

- Frightened many, excitement general, some alarm, many ran outdoors.
- Awakened all.
- Persons made to move unsteadily.
- Trees, bushes, shaken slightly to moderately.
- Liquid set in strong motion.
- Small bells rang -- church, chapel, school, etc.

- Damage slight in poorly built buildings.
- Fall of plaster in small amount.
- Cracked plaster somewhat, especially fine cracks; chimneys in some instances.
- Broke dishes.
- Fall of knick-knacks, books, pictures.
- Overturned furniture in many instances.
- Moved furnishings of moderately heavy kind.

VII. Frightened all -- general alarm, all ran outdoors.

- Some, or many, found it difficult to stand.
- Noticed by persons driving motor cars.
- Trees and bushes shaken moderately to strongly.
- Waves on ponds, lakes, and running water.
- Water turbid from mud stirred up.
- Incaving to some extent of sand or gravel stream banks.
- Rang large church bells, etc.
- Suspended objects made to quiver.
- Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary buildings, considerable in poorly built or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, etc.
- Cracked chimneys to considerable extent, walls to some extent.
- Fall of plaster in considerable to large amount, also some stucco.
- Broke numerous windows, furniture to some extent.
- Shook down loosened brickwork and tiles.
- Broke weak chimneys at the roof-line (sometimes damaging roofs).
- Fall of cornices from towers and high buildings.
- Dislodged bricks and stones.
- Overturned heavy furniture, with damage from breaking.
- Damage considerable to concrete irrigation ditches.

VIII. Fright general -- alarm approaches panic.

- Disturbed persons driving motor cars.
- Trees shaken strongly -- branches, trunks, broken off, especially palm trees.
- Ejected sand and mud in small amounts.
- Changes: temporary, permanent; in flow of springs and wells; dry wells renewed flow; in temperature of spring and well waters.
- Damage slight in structures (brick) built especially to withstand earthquakes.
- Considerable in ordinary substantial buildings, partial collapse: racked, tumbled down, wooden houses in some cases; threw out panel walls in frame structures, broke off decayed piling.
- Fall of walls.
- Cracked, broke, solid stone walls seriously.
- Wet ground to some extent, also ground on steep slopes.
- Twisting, fall, of chimneys, columns, monuments, also factory stacks, towers.
- Moved conspicuously, overturned, very heavy furniture.

IX. Panic general.

- Cracked ground conspicuously.
- Damage considerable in (masonry) structures built especially to withstand earthquakes:
- threw out of plumb some wood-frame houses built especially to withstand earthquakes;
- great in substantial (masonry) buildings, some collapse in large part; or wholly shifted frame buildings off foundations, racked frames;
- serious to reservoirs; underground pipes sometimes broken.

X. Cracked ground, especially when loose and wet, up to widths of several inches; fissures up to a yard in width ran parallel to canal and stream banks.

- Landslides considerable from river banks and steep coasts.
- Shifted sand and mud horizontally on beaches and flat land.

- Changed level of water in wells.
- Threw water on banks of canals, lakes, rivers, etc.
- Damage serious to dams, dikes, embankments.
- Severe to well-built wooden structures and bridges, some destroyed.
- Developed dangerous cracks in excellent brick walls.
- Destroyed most masonry and frame structures, also their foundations.
- Bent railroad rails slightly.
- Tore apart, or crushed endwise, pipe lines buried in earth.
- Open cracks and broad wavy folds in cement pavements and asphalt road surfaces.

XI. Disturbances in ground many and widespread, varying with ground material.

- Broad fissures, earth slumps, and land slips in soft, wet ground.
- Ejected water in large amount charged with sand and mud.
- Caused sea-waves ("tidal" waves) of significant magnitude.
- Damage severe to wood-frame structures, especially near shock centers.
- Great to dams, dikes, embankments, often for long distances.
- Few, if any (masonry), structures remained standing.
- Destroyed large well-built bridges by the wrecking of supporting piers, or pillars.
- Affected yielding wooden bridges less.
- Bent railroad rails greatly, and thrust them endwise.
- Put pipe lines buried in earth completely out of service.

XII. Damage total -- practically all works of construction damaged greatly or destroyed.

- Disturbances in ground great and varied, numerous shearing cracks.
- Landslides, falls of rock of significant character, slumping of river banks, etc., numerous and extensive.
- Wrenched loose, tore off, large rock masses.
- Fault slips in firm rock, with notable horizontal and vertical offset displacements.

- Water channels, surface and underground, disturbed and modified greatly.
- Dammed lakes, produced waterfalls, deflected rivers, etc.
- Waves seen on ground surfaces (actually seen, probably, in some cases).
- Distorted lines of sight and level.
- Threw objects upward into the air.