THE MORPHOLOGICAL SIGNATURE OF NATURAL DISASTERS IN THE UPPER SAGUENAY FJORD AREA, QUÉBEC, CANADA

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ABSTRACT: The Saguenay Fjord area has been the locus of many disasters over the last few centuries. It includes the 1663 earthquake which is believed to have trigger many sub-aerial and submarine mass movements (landslides, rock slides) and the major flood disaster of 1996. This paper illustrates the evidence left by these disasters either as a geomorphological or sedimentological signature. Most of the examples are documented by multibeam surveys taken at different time since 1993.

RÉSUMÉ: Le fjord du Saguenay est un lieu où plusieurs catastrophes naturelles se sont produites au cours des derniers siècles. Cela comprend le séisme de 1663 qui a engendré plusieurs glissements tant aériens que sous-marins (sols et roches) ainsi que le déluge de juillet 1996. Cet article illustre les diverses évidences laissées par ces catastrophes naturelles tant sous la forme d'une signature morphologique que sédimentologique. La majeure partie des exemples présentés dans cet article sont faits à partir de levés multifaisceaux récoltés dans le secteur depuis 1993.

1. INTRODUCTION

The Saguenay area has been the locus of many natural disasters over the last 400 years. Well known are the 1663 St. Jean Vianney landslide (Lasalle and Chagnon 1968) which was triggered by a major earthquake, the St. Jean-Vianney landslide of 1971 (Tavenas et al. 1971), the 1988 earthquake and its related liquefaction phenomena and mass movements (Tuttle et al. 1990; Lefebvre et al. 1992, Schaffer and Smith 1987, Pelletier and Locat 1993), and the major flood event of 1996 (Pelletier et al. 1999). Signatures left by the various catastrophic events are either recorded in bedrock, soils, or in sediments in lakes or in the Saguenay Fjord.

The later event, the 1996 flood, was the cause for a detailed investigation of the fjord bottom. Since the fjord was largely contaminated with industrial material (Loring and Bewers 1978, Barbeau et al. 1981a, b), it was believed that the huge amount of "clean" newly deposited flood sediments would bury the old contaminated ones, thus providing a natural capping layer. A major goal of such investigations was the to test the stability of the newly deposited layer since the recurrence of new landslide events could lead to the exposure of the old contaminated materials. The first step for assessing slope stability is a good knowledge of the relief, so that bathymetric data from the fjord bottom was essential. Such data were already available from a survey carried out in 1993, but for monitoring purposes additional cruises were undertaken in order to collect new swath bathymetry data, as well as a complete set of geophysical data and various types of sediment samples.

The multibeam survey technology (Locat et al. 1999, Locat and Sanfaçon 2000) is the core of this manuscript. The degree of confidence with which we can map the most recent events that have occurred in the Saguenay Fjord can not be achieved without such a tool and this study therefore underlines its potential for integrating and understanding the recent geology of the upper Saguenay Fjord.

In this paper we present the signature left by the various catastrophic events, which have shaped the fjord bottom morphology. We will start by describing the overall fjord morphology, then follow with an analysis of the imprints left by the earthquake events of 1663 and 1988, and of the recent major flood of July 1996.

2. GEOLOGICAL PICTURE

The particular geological environment and Quaternary history of the Saguenay area is responsible for the origin of all of these phenomena. Of interest to us is the translation of these catastrophic events into gravitational phenomena which eventually leave a distinct signature such as a landslide (sub-aerial or submarine) or a turbidite deposit.

The Saguenay area is mostly composed of Precambrian rocks of metamorphoic origin. A few hundred millions years ago, the area was tectonically active and the Saguenay graben structure was formed (Hébert and Lacoste, 1998). The morphological evidence of this graben is shown in Figure 1 by a series of sub-parallel linear depressions in the bedrock. The main area of seismic activity is in the Charlevoix region (Figure 1). The most recent major event took place near Baie des Ha! Ha! in 1988 reaching 6.3 on the Richter scale, indicating that the area is seismically active.

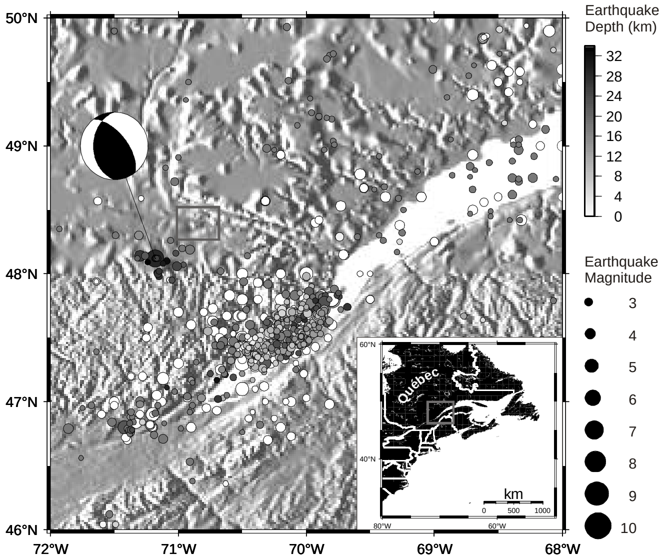

Fig.1: Shaded relief image of the study area illuminated from the west from GTOPO-30 topography (Earth Resources Information Systems Data Center, 1996) showing the main physiographic units along the St. Lawrence River. Earthquake epicentres from 1600 onwards are plotted from the Canadian national earthquake database (Natural Resources Canada, 1999) and clearly show the Charlevoix seismic zone. White dots generally correspond to old earthquakes for which the depth is unknown. The focal mechanism of the 1988 earthquake is also plotted.

During the Pleistocene, the area was covered by ice sheets several times with the last being the Wisconsinian glaciation (Lasalle and Tremblay 1978). Since the Saguenay graben is more or less oriented in the same direction as the glacial flow, it became a preferred path for ice flow and resulted in deep excavation of the bedrock. It is filled with as much as 1000 m of sediments (Syvitski and Praeg 1989, Locat and Syvitski 1991).

The final retreat of the Wisconsinian ice sheet, which took place about 10 000 years ago (Lasalle and Tremblay 1978) was followed by significant isostatic emergence varying from 140m on the north side of the graben to 120m the south side (Bouchard et al. 1983). The image of these events to keep in mind is that of a vanishing ice cap yielding tons of sediments being deposited in a retreating sea. The sedimentary environment was such that fine grained sediments were deposited in a brackish environment, rapidly uplifted and then leached of their salts (in the pore water). This resulted in the formation of quick clays. From existing data of terrestrial emergence in this region (Locat 1977), it is clear that most of the recent uplift took place in the first few thousand years immediately following glacial retreat. It is no surprise that such a geological combination yields a situation prone to major disasters: seismic activity (a way of dissipating stored strain energy due to glacial loading and unloading) and quick clays!

Although the recent major flood event of July 1996 is not related to the geology, the resulting impacts are, i.e. the geomorphology of the area and the sediments that were already in place. The impact of the flood may have been amplified by human inter-action related to reservoir management (Brooks and Lawrence, 1999), or land use practice. Nevertheless, such an event was not predictable and its signature in the fjord, so far, appears to be unique.

3. METHODOLOGY OF MULTIBEAM SURVEYS

The data presented in this paper is largely based on multibeam bathymetry acquired with the Simrad EM 1000 and EM3000 mounted on board the catamaran RV F.G. Creed and on the C.S.S. Puffin respectively. The EM1000 works at a frequency of 95 kHz, and may be operated in water depths between 3 and 1000 m. It uses 60 beams spaced 2.5°, thus covering a sector up to 150° or ~ 7.5 times the water depth. The beams are 3.3° and 2.4° width in the across and fore-aft direction respectively. The EM3000 operates in a similar manner to the EM1000 but is restricted to shallow waters not exceeding 100 m. It works around a centre frequency of 300 kHz using 127 beams spaced 1.02°, thus covering a sector of 130° or ~4.3 times the water depth. The beams are 1.5° width in the across and fore-aft direction. The EM1000 data were acquired at 15 kn speed using a ping rate of 200 ms, while EM3000 data were acquired at a speed of 12kn at a much higher rate of 40 ms. Both sets of data were positioned by means of differential GPS. The use of advanced techniques in multibeam data processing gives a vertical resolution of 0.25% of the water depth for features that span a horizontal distance of about 10%, the average beam footprint size (Huges-Clarke et al., 1996). The processing included sound velocity and tidal correction, and interactive swath editing.

Both systems, the EM1000 and EM3000, are also capable of providing a quantitative measure of the sea-floor backscatter intensity, which can be displayed in side-scan sonar like images (Huges-Clarke et al. 1996). These images are typically resolved to a higher resolution of about 5% the water depth. Both the bathymetric and backscatter data were acquired using Simrad's Mermaid software and processed using the Ocean Mapping Group of the University of New Brunswick's "Swathed" tools. The data was then imported into GMT (Wessel and Smith 1998) to generate bathymetric and backscatter 2-D and 3-D plots.

4. MORPHOLOGY OF THE UPPER SAGUENAY FJORD

The Upper Saguenay Fjord has a Y-shape with one arm of the Y being the Bras Nord and the other one being the Baie des Ha! Ha! (Figure 3). The fjord in that area has water depths ranging from 0 to 225 m and a width between 3 to 5 km. The Saguenay River flows into the Bras Nord while the Mars, Ha! Ha! and du Moulin rivers flow into the Baie des Ha! Ha!. The regular tide in the area is about 4 to 5 m.

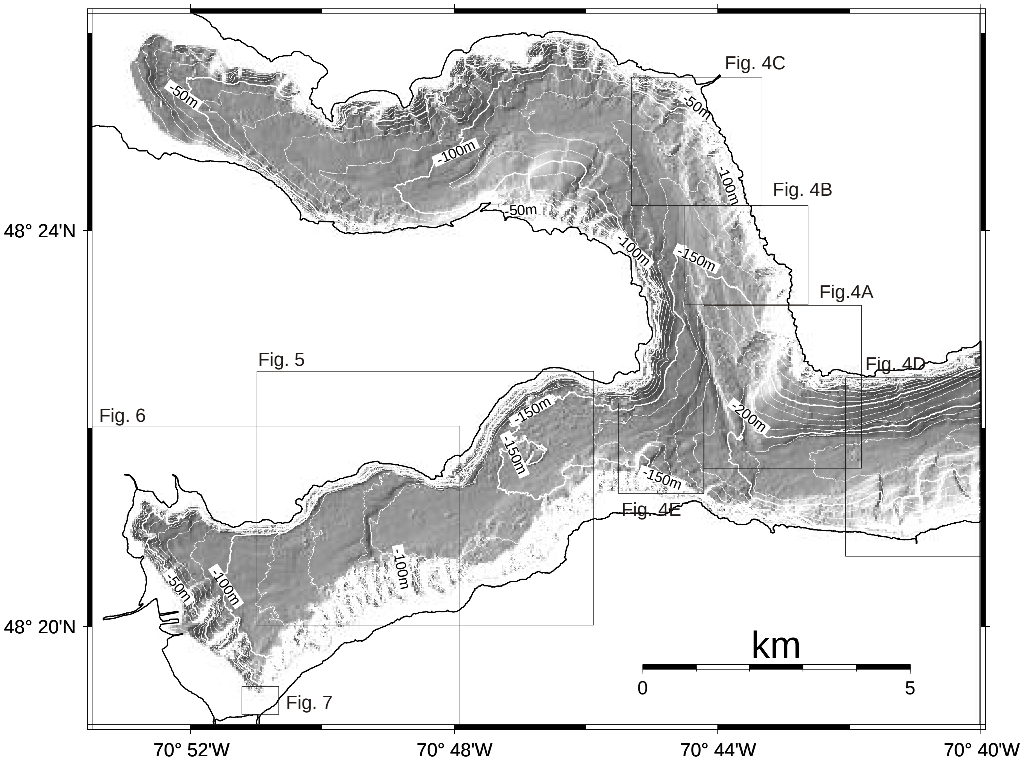

Fig. 2: Shaded image of the upper Saguenay Fjord constructed from swath bathymetry data illuminated from the north-west, with contours at 10 m interval.

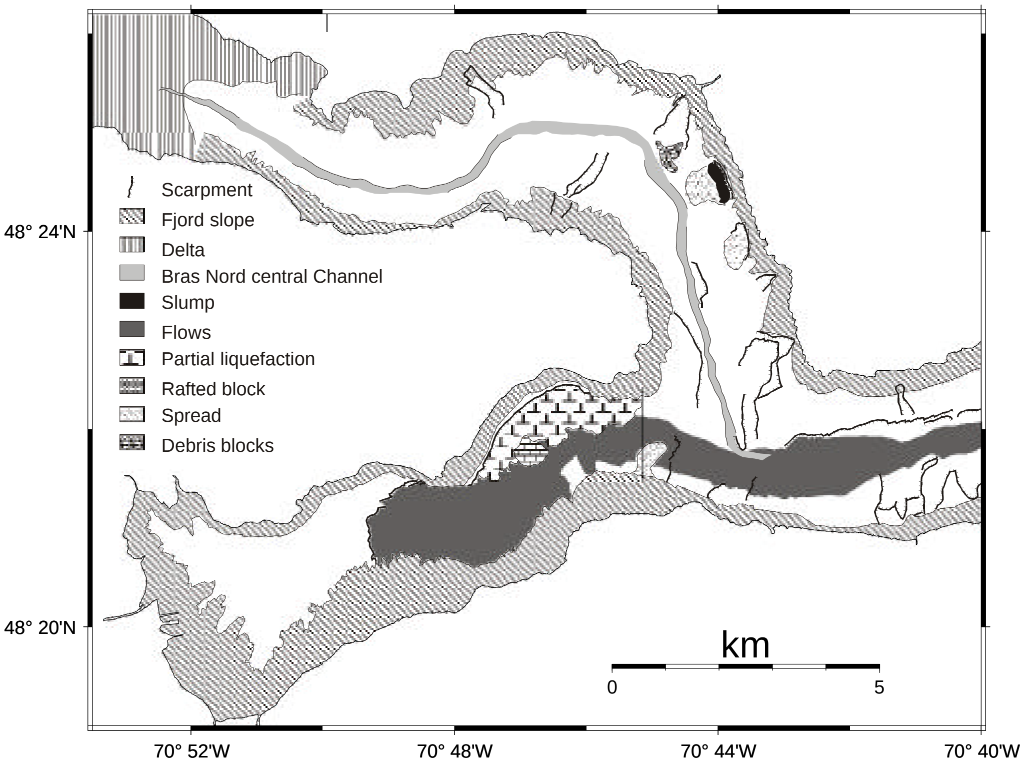

Fig.3: Geomorphological map of the Saguenay Fjord. Note profuse presence of scars and mass-wasting deposits.

The most active segment of the upper Saguenay Fjord is the Bras Nord where the accumulation rate is measured in centimetres per year at the delta (Locat and Leroueuil 1988, Perret et al. 1995) so that the Bras Nord is being filled more rapidly that the Baie des Ha! Ha!. The water depth in the Bras Nord ranges from about 10 m at the mouth of the Saguenay River to 200 m at the confluence with the Baie des Ha! Ha!. The Baie des Ha! Ha! itself has a water depth which rapidly descends to about 100 m near the head (at La Baie city) to 200 m downstream. The sea floor of the Baie des Ha! Ha! has a unique feature located near the centre, in the form of a sharp and more or less straight escarpment. Above it, the slope is 0.6° and below 0.2°.

The slopes on either side of the fjord are quite different, in particular in the Baie des Ha! Ha!, the northern escarpment is steep with slopes exceeding 40° while the south shore slope is gentler and gullied. The slope on the north side is controlled by the bedrock while the southern side is dominated by Quaternary sediments (Laflamme sea clays). The Bras Nord is bisected by a shallow channel which follows more or less the centre of the fjord, potentially acting as a conduit for mudflows or debris flows originating from the upper reaches of the fjord.

5. SIGNATURE OF THE 1663 EARTHQUAKE

5.1 The Epicentre of the 1663 Earthquake: in the Saguenay Area ?

The largest natural disaster that has taken place in the Saguenay fjord area is probably associated with the 1663 earthquake. The earthquake epicentre is believed to be located in the nearby Charlevoix seismic zone based on observations by Jesuits priests of the effects (Smith, 1962). However, recent discoveries, both morphological and structural, made in the Saguenay area, cast some doubt on this hypothesis and would favour an epicentre located in the Saguenay area.

Amongst the most striking onland features associated with this event is the Saint Jean Vianney I landslide (Lasalle and Chagnon, 1968), which contributed a huge amount of terrigenous input to the Saguenay fjord (Schaffer and Smith 1987). Other evidence includes the occurrence of a major rock avalanche located on the east margin of the Saguenay graben (Mont Éboulé slide, Locat et al. 1997) which, according to a ^{14}C date occurred less than 1000 years ago. In addition to these elements, very fresh mass movement morphologies and seismic traces (see Figures 3 and 4) in the Saguenay Fjord have been considered by Syvitski and Schafer (1996) as part of a major "basin failure" that they attribute to the 1663 earthquake. The final element to support the location of this earthquake in the Saguenay area is the recent discovery of a major active fault on the edge of the fjord which appears to be directly related to a submarine escarpment and a major liquefaction flow slide (Figure 5).

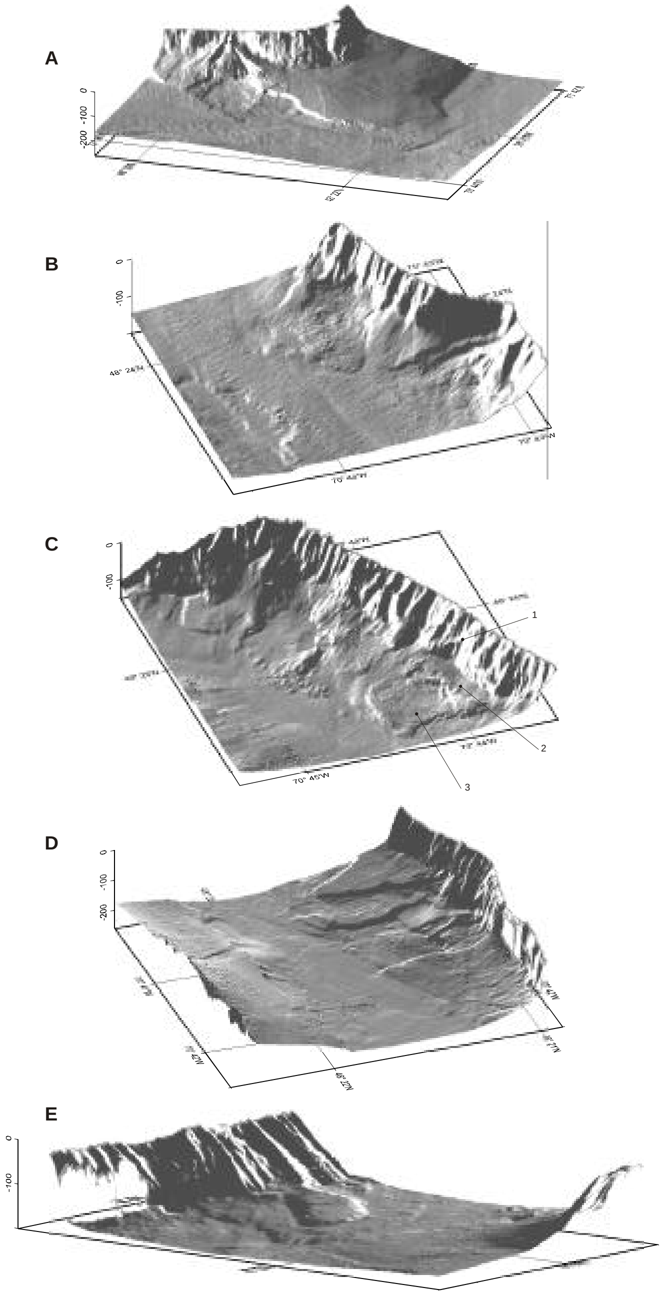

Fig. 4: Three-dimensional images of different landslide types encountered in the Saguenay Fjord. A. Flow (view is from N250°, 20° elevation, north illumination). B. Spread (note evidence of pressure ridges) (view is from N200°, 20° elevation, north-west illumination). C. Slump with, 1, main scarp, 2, head, and, 3, displaced mass in the form of spread (note also possible evidences of pressure ridges). Northwards is also a field of blocky debris (view is from N200°, 35° elevation, north-west illumination). D. Multiple complex headwall scarps in flow (view is from N290°, 30° elevation, north-west illumination). E. Spread (view is from N50°, 10° elevation, west illumination).Vertical exaggeration is ~2.5 in all cases. Locations are given in Figure 2.

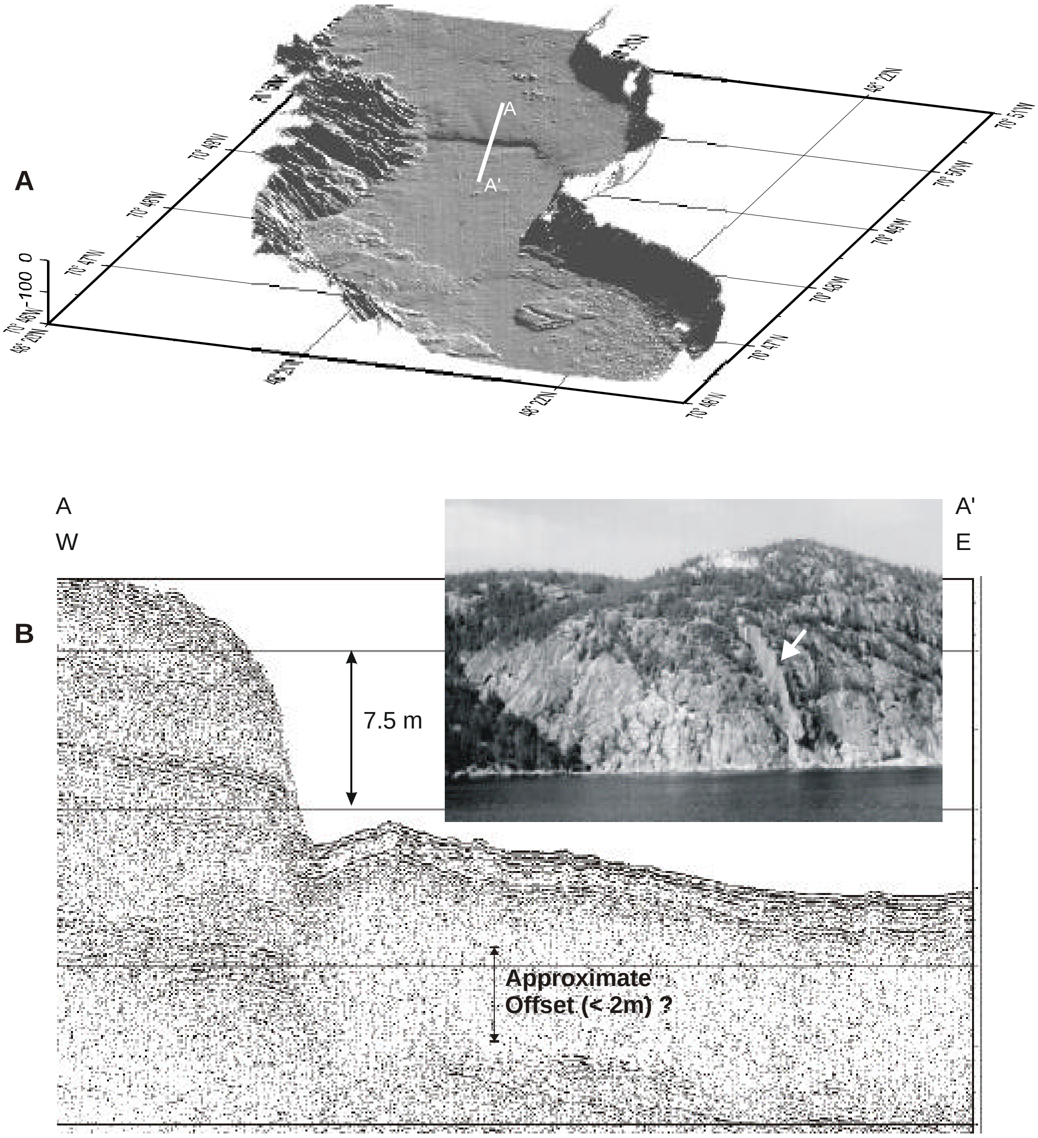

Fig. 5: Liquefaction event along the Baie des Ha! Ha! as seen from (A) a three-dimensional view of multibeam bathymetry data and (B) a seismic reflection profile along A-A'. Inset in B shows subaerial expression of the fault on the northern coast of the Baie des Ha! Ha!. Location is given in Figure 2.

5.2 Morphological Analysis

The multibeam data has shown the Saguenay Fjord to be a location where landslides take almost all of the possible forms and therefore provides a unique opportunity to study their morphology (Figures 2, 3 and 4). Along the fjord margins of both the Baie des Ha! Ha! and the Bras Nord, several features indicative of mass wasting are present. As already indicated in previous studies (Locat and Bergeron 1988, Pelletier and Locat 1993), a significant earthquake could have triggered these submarine mass movements. Other potential factors (see Hampton et al. 1996 and Locat and Lee 2000) are erosion, overloading by sedimentation and wave action.

The mass movements observed in Figure 3 can be divided into two main groups: (1) mass movements where only scars are left, i.e. the failed material has left the slide area and likely moved towards the centre of the basin as ponded material; and (2) those where most of the sediment involved in the slide remains within the slide area. The largest flow slide was mapped in the centre of Baie des Ha! Ha! extending down into the deeper part of the fjord (Figure 3). The upstream part of this flow slide is also shown in Figure 5a.

5.2.1 Flows

Along the fjord walls, several scars are observed without direct evidence of the deposits. These scars show a variety of morphologies ranging from arrow-shaped (Figure 4a), to elongated, to box-shaped (Figure 4d). In Figure 4a, the failed material has moved down a channel into the deeper part of the basin. The lateral escarpment on the east side of the slide is quite sharp and had already been mapped (Hampton et al. 1996). Here, the slide most likely involved both parts of the wall and more recent clayey sediments. In Figure 4d, where at least two scars are present, the failed masses are adjacent to the deepest part of the fjord where they are impounded.

The major flow slide of Figure 5a, covers about one half of the Baie des Ha! Ha! area. This slide is the most spectacular feature in this part of the fjord. It is limited in the upstream direction by a 7 to 8 metre escarpment, which can be traced on the adjacent northern flank of the fjord (Figure 5b). In the downstream area of the slide there is a rafted block, almost 1 km^2 in area, which shows signs of displacement or stretching (this block is visible in the lower part of Figure 5a as a split mass). Just around this block is a morphology which suggests that this part of the sea floor was only partially liquefied at the time of this event.

The swath data show a flat relief in the most distal parts of the fjord, indicating the ponding of sediment flows there (Figure 2). Such relief is especially manifest west of the scarp in the centre of Baie des Ha! Ha! Bay indicating deposition there of the liquefaction event (Figures 2 and 3). The sediments involved in this event travelled across the fjord bottom for a distance of about 10 km.

5.2.2 Slides and Spreads

Semicircular scars correspond generally with deposits visible at the foot of the scarp. Most of the depositional features show lobe-like morphologies with different aspect ratios (Figures4b, 4c and 4e). In the case of slumps, a crown headwall (Figures 4c, point 1) is present associated with a distinct slump head (Figure 4c, point 2) and the displaced mass (Figure 4c, point 3). In some cases, the displaced mass shows compression ribbons (Figures 4b and 4c), evidence of flowage. In the case of spreads no proximal headwalls are present.

Figure 4e shows a good example of a spread which was not confined within a channel. This slide extends over a length of about 1 km and the thickness is about 10m (Locat and Pelletier 1993). When it spread on the sea floor, it turned downstream following the gentle slope. The displaced mass appears to have detached from the wall of the fjord.

In general, slumps and spreads, usually originate at the base of the fjord walls where slopes are gentler, about 3°, but higher than those of the fjord bottom which do not exceed 0.2° (Figure 2), and they travel for distances not exceeding 1 km (Figure 3).

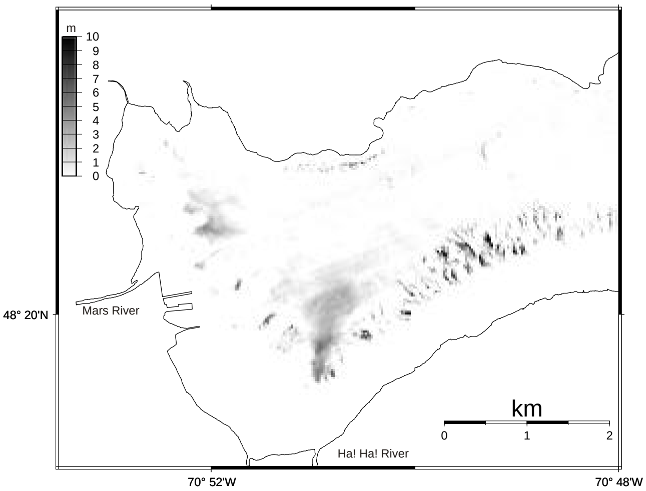

Fig. 6: Differential bathymetry between the surveys of 1993 and 1999 showing the large sediment accumulations at the mouth of the Mars river and especially at the mouth of the Ha! Ha! river.

6. THE JULY 1996 CATASTROPHIC FLOOD

In 1996 another major disaster occurred. After major rainstorms the flow rate in the Saguenay river increased to 5500m^3/s, while it normally transports 1600m^3/s (Gilbert, 1997). In the Ha! Ha! river, problems were accentuated by overtoping and erosion of an earthfill saddle dyke. Discharge estimates at the Ha! ha! river range from 1080 to 1260 m^3/s, an order of magnitude higher than the previous maximum instantaneous discharge of 114 m^3/s on May 9, 1983 (Brooks and Lawrence, 1999). Lapointe et al. (1998) also indicate that along the Ha! Ha! river valley 15 million tones of sediment were displaced. The ultimate destination of the sediments travelling along the Saguenay, Ha! Ha! and Mars rivers was the Saguenay fjord. There, a distinctive “flood bed” was deposited over the entire Baie des Ha! Ha! and part of the Bras Nord (Maurice et al., 2000). The largest accumulations occured at the mouths of the different rivers where sediment thickness in excess of 10 m were deposited as shown by the 1999-1993 differential bathymetry (Figure 6). The Ha! Ha! river delivered the largest amount of sediment to the Baie des Ha! Ha! forming an apron close to the river mouth extending ~1.5 km northwards over an area of about 2 km^2, from which a conservative volume of 8 million m^3 can be estimated. Considering a mean sediment dry density of 1 g/cm^3, this represents about 8 million tons of sediment, more than half the total sediment displaced by the Ha! Ha! river. The strength of the current entering the Baie des Ha! Ha! is illustrated by bed-forms shown on the EM3000 bathymetry data (Figure 7). The data show that the area located between the 1996 flood apron and the river mouth is occupied by several channels where dunes develop. These dunes have amplitudes of a few meters which tend to decrease distally while wave length tend to increase from about 8 m to more than 40 m (Figure 7).

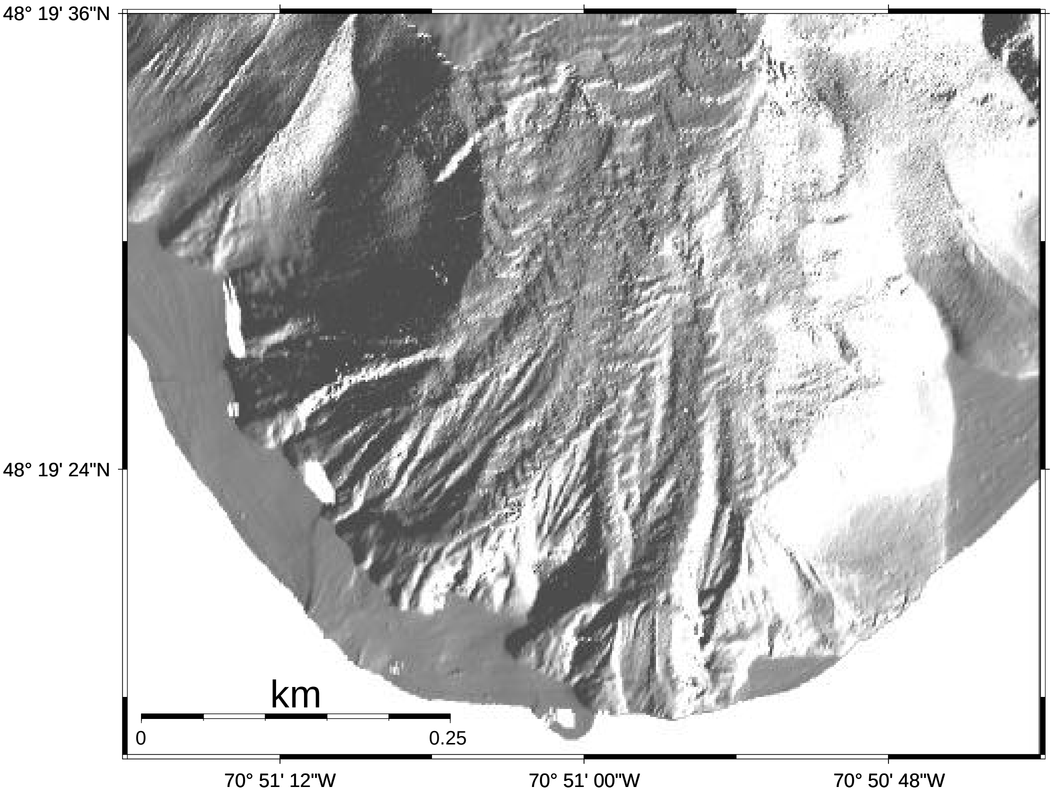

Fig. 7: Shaded relief image of high-resolution EM3000 data gridded at a 1 m interval showing sediment dunes along channels developed at the mouth of the Ha! Ha! river (illumination is from the north-west).

7. DISUSSION AND CONCLUSION

The above images and text showing the morphological signature of the various natural disasters that have occurred in the upper Saguenay Fjord illustrate how multibeam surveys have helped to significantly advance understanding of the different processes that took place in this fjord. This is another example (see also Locat and Sanfaçon 2000) of the necessity for access to these mapping techniques in order to fully integrate underwater features and geotechnical analyses.

The coupling of multibeam and seismic surveys in addition to geotechnical analyses of cores taken from the sea floor (Perret et al. 1995, Locat and Leroueil 1988) and landslide mapping (Locat et al. 1997) clearly support the argument that at least one major earthquake has occurred in this area. Furthermore, when the observations made earlier by Syvitski and Schafer (1996) from their own analysis of seismic and core data are added to those mentioned above, we believe that there is a strong argument to support the hypothesis that the epicentre of the 1663 earthquake was located in the Saguenay area rather than the Charlevoix area as originally proposed.

Finally, the above review illustrates the value of field observations and the use of recently developed technologies, such as multibeam bathymetry. It is hoped that it will serve as an example for a more widespread availability and use of these methods in Canada (Locat and Sanfaçon 2000).

8. ACKNOWLEDGMENTS

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