RESULTS FROM MULTIBEAM, SEDIMENTOLOGICAL AND GEOTECHNICAL DATA OF THE "SAGUENAY PROJECT"

Roger Urgeles, GRC Geociències Marines, Departament d'Estratigrafia, Paleontología i Geociències Marines, Universitat de Barcelona, Campus de Pedralbes, 08028 Barcelona (Catalonia), Spain
Jacques Locat, Département de géologie et de génie géologique, Université Laval, Pavillon Pouliot, Ste.-Foy (Québec), Canada

ABSTRACT
In July 1996 a major flooding of the Saguenay region caused the delivery of a large amount of sediments to the Saguenay Fjord, which buried the former contaminated sediments. Several multibeam and sampling surveys where triggered by the flood which aimed to understand the concealing ability of the newly deposited sediments. These surveys showed the effects of the flood on the Fjord bottom but also the existence of older mass movements. Nevertheless a dynamic slope stability analysis showed that the fjord sediments are stable within the recurrence interval of major earthquakes. The backscatter strength from the multibeam data also showed the evolution of the flood layer, though to represent the wiping out of benthic life and the subsequent recolonization of the flood layer by the benthos.

RÉSUMÉ
En juillet 1996, une crue majeure dans la région du Saguenay a causé le transport et la déposition d'une grande quantité de sédiments dans le fjord du Saguenay, recouvrant les sédiments contaminés présents. Plusieurs levés multifaisceaux et campagnes d'échantillonnage ont été réalisés pour vérifier la capacité de recouvrement de la nouvelle couche de sédiments. Ces travaux montrent les effets de la couche de crue sur le fond du fjord et aussi l'existence d'anciens mouvements de masse. Néanmoins, une analyse dynamique de la stabilité des pentes a montré que les sédiments du fjord sont stables à l'intérieur de l'intervalle de récurrence des séismes majeurs. Les données de rétrodiffusion obtenues à partir des données multifaisceaux montrent également l'évolution de la couche de crue, qui représente l'élimination de la faune benthique et la recolonisation subséquente de la nouvelle couche par le benthos

1. INTRODUCTION

The Saguenay flood of July 1996 (Brooks and Lawrence 1999) in Quebec (see location in Figure 1) carried a large amount of new sediments to the Saguenay Fjord. These sediments capped the older but contaminated sediments, which improved the overall environmental conditions of the Fjord. Such event triggered a new project, which aimed to understand several aspects of the newly deposited sediments in relation with their ability to conceal the former contaminated ones (Loring and Bewers 1978, Barbeau et al. 1981, Martel et al. 1987). Amongst these aspects an important topic was the stability of the newly deposited layer (Urgeles et al. 2002a). It was clear that, given the dilated history of seismic activity in the neighbouring areas (e.g. Charlevoix M_n 7 and Saguenay M_w 5.8 earthquakes of 1663 and 1988) (Chagnon and Locat 1988, Du Berger et al. 1991, Doig 1998), a dynamic approach was needed.

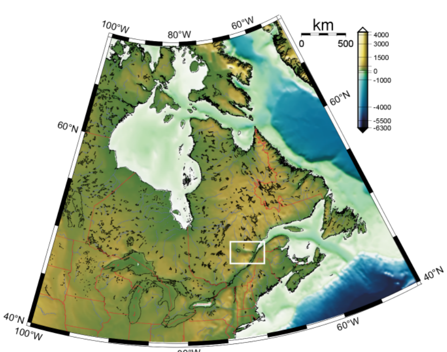

Figure 1. Location of the study area

One of the crucial data types that is needed for identifying previous failures, as well as for obtaining the true angles of the submarine slopes, that are necessary input to any slope stability equation is an accurate bathymetry. Hence, we obtained a complete data set of multibeam bathymetry of the Fjord floor. Such data brought evidence of several slope failures (Locat et al. 2000) thought to have occurred during the earthquake of 1663 (Locat et al. 2003), but in addition its derived backscatter strength made evident that changes occurred to the Fjord floor after the flood took place (Urgeles et al., 2002b). This paper briefly describes the major findings of the "Saguenay Project" obtained from the multibeam data, as well as from sedmentological and geotechnical analyses made on core samples.

2. RESULTS

2.1 Multibeam surveys: new morphological information.

The multibeam surveys have revealed the detailed morphology of the Saguenay Fjord (Locat et al. 2000) (Figure 2). In overall, it si seen that 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 increases to about 100 m near the head (at La Baie city) and to 200 m downstream. The slopes on either side of the fjord are quite different, in particular in the Baie des Ha! Ha!, the northern sidewall is steep with slopes exceeding 40° while the south shore slope is gentler and gullied.

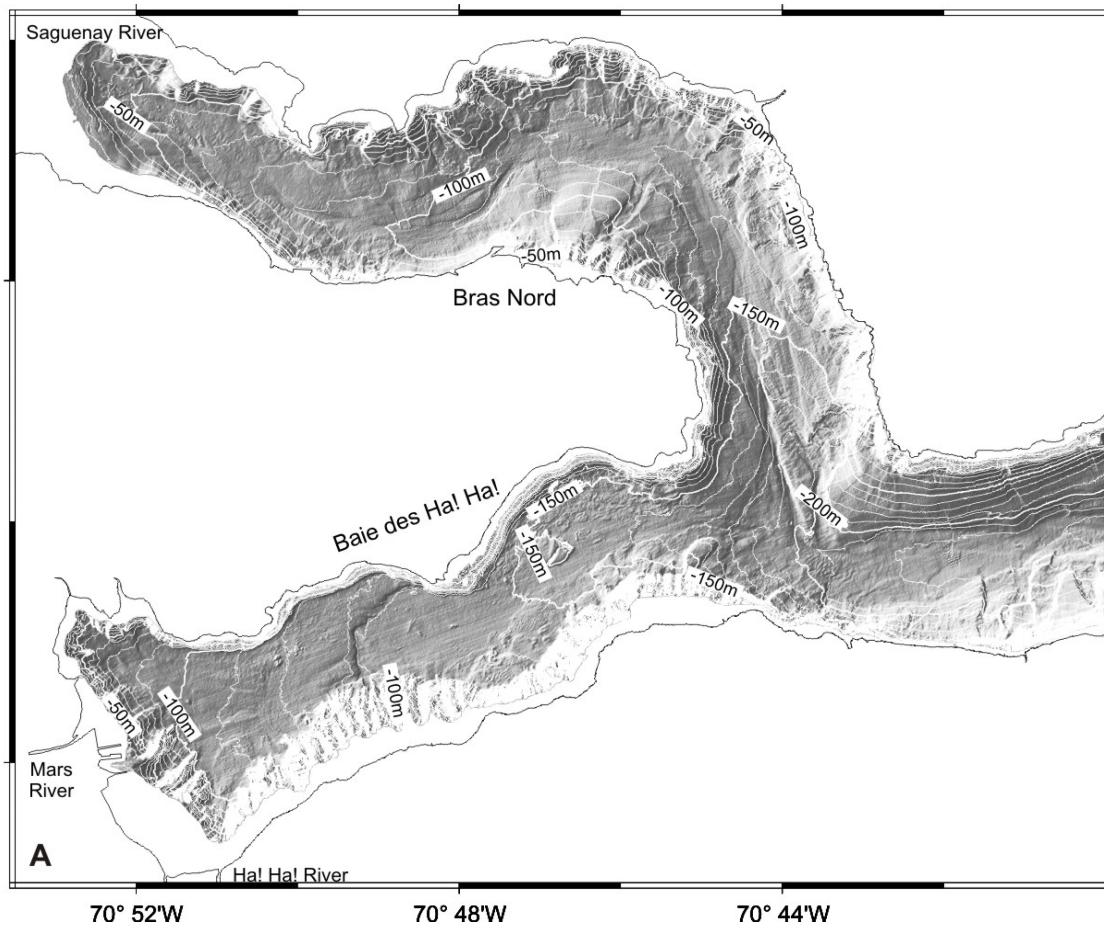

Figure 2. Bathymetry of the studied area with shaded relief illuminated from the West. Contours are also plotted at 5 m interval between 0 and 100 m depth and 10 m between 100 and 300 m depth. Box cores (inverted triangles) and Lehigh cores (stars) used in this study are also shown.

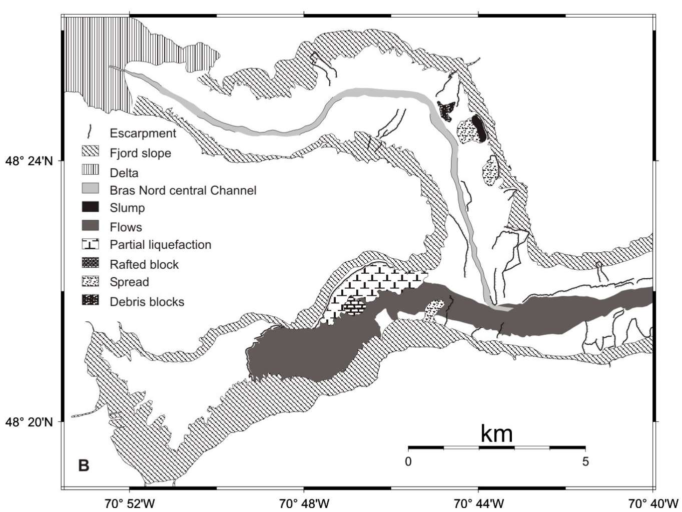

Figure 3. Geomorphological map of the Saguenay Fjord. Note abundance of escarpments and failure related deposits.

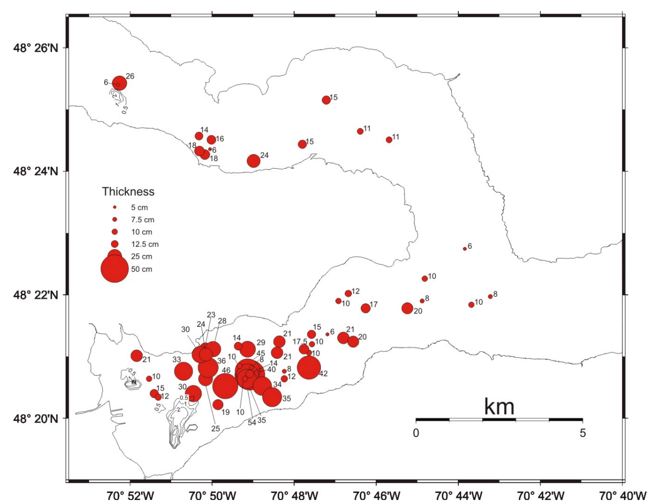

Figure 4: Thickness of the 1996 flood layer. Note that contours at the river mouths are in m as obtained from the 1999-1993 differential bathymetries, while thicknesses measured in samples (dots) are in cm.

From the slope stability point of view, it is clear that very fresh mass movements are present (Figures 2 and 3). Recently a major active fault on the edge of the fjord was discovered (Locat et al. 2000), which appears to be directly related to a submarine escarpment and a major liquefaction flow slide.

The mass movements that can be observed along the fjord margins of both the Baie des Ha! Ha! and the Bras Nord, 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.

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. The sediments involved in this event travelled across the fjord bottom for a distance of about 10 km.

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. Amongst these, 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°, and they travel for distances not exceeding 1 km. As already indicated in previous studies (Locat and Bergeron 1988, Pelletier and Locat 1993, Locat et al. 2003), the source of these mass-movements appears to be a significant earthquake.

The imprint of the recent flood of 1996 is also visible on the swath bathymetry data. As a previous survey had already been carried out in 1993, the differential bathymetry between that of 1999 and that of 1993 show that the largest sediment accumulations occurred at the mouths of the different rivers where thicknesses are in excess of 10 m (Figure 4). 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.

2.2 Backscatter strength from multibeam surveys: A tool for monitoring the evolution of the 1996 flood layer?

As mentioned earlier a multibeam survey had already been collected in 1993 before the flood took place. Two additional surveys were conducted in 1997, shortly after the flood, and in 1999, all them with a Simrad EM1000 multibeam echosounder (Figure 5). Surprisingly the backscatter strength recorded by the system was not exactly the same in these three surveys. An overall decrease seems associated with the flood event and major sediment input to the Fjord. A backscatter strength difference of ca. 5 dB is found when comparing the 1993 and 1997 data, while present overall backscatter strength is similar to that of 1993 (Urgeles et al. 2002b) (Figure 5).

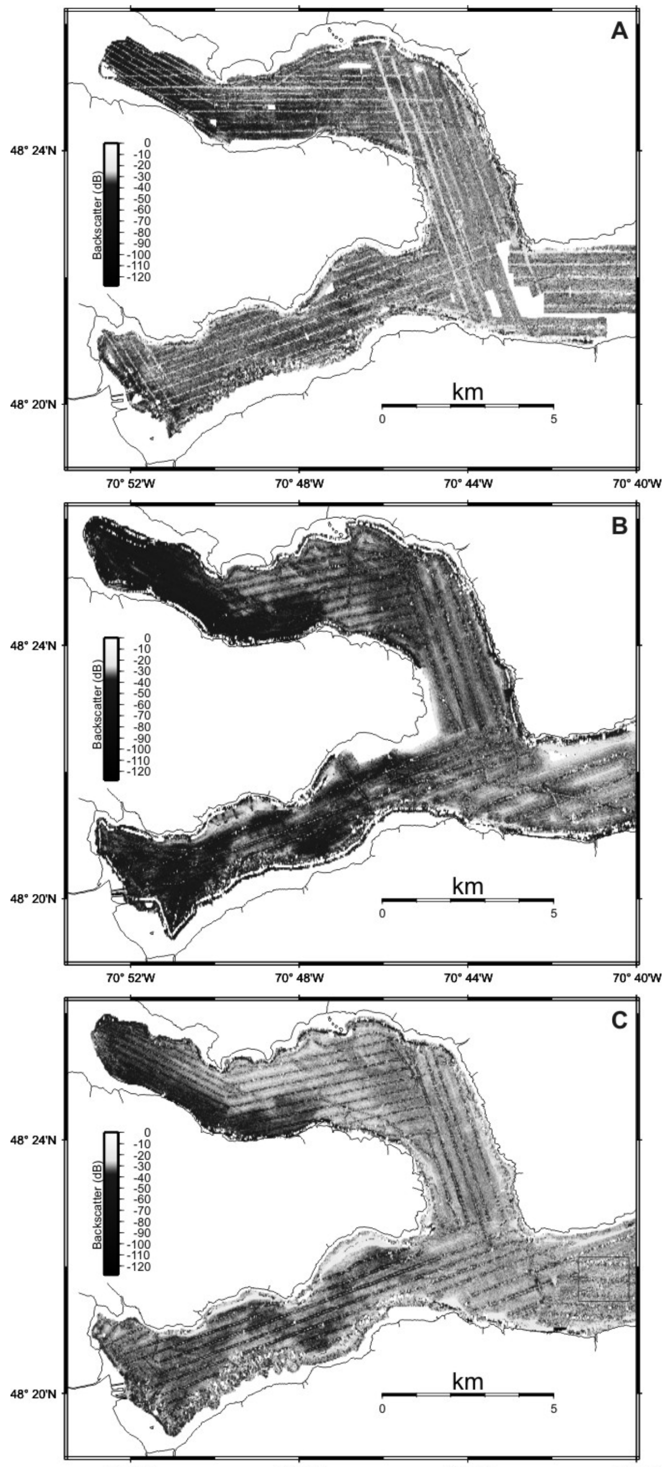

Figure 5. Series of backscatter strength maps derived from the multibeam echosounder for A. 1993, B. 1997 and C. 1999.

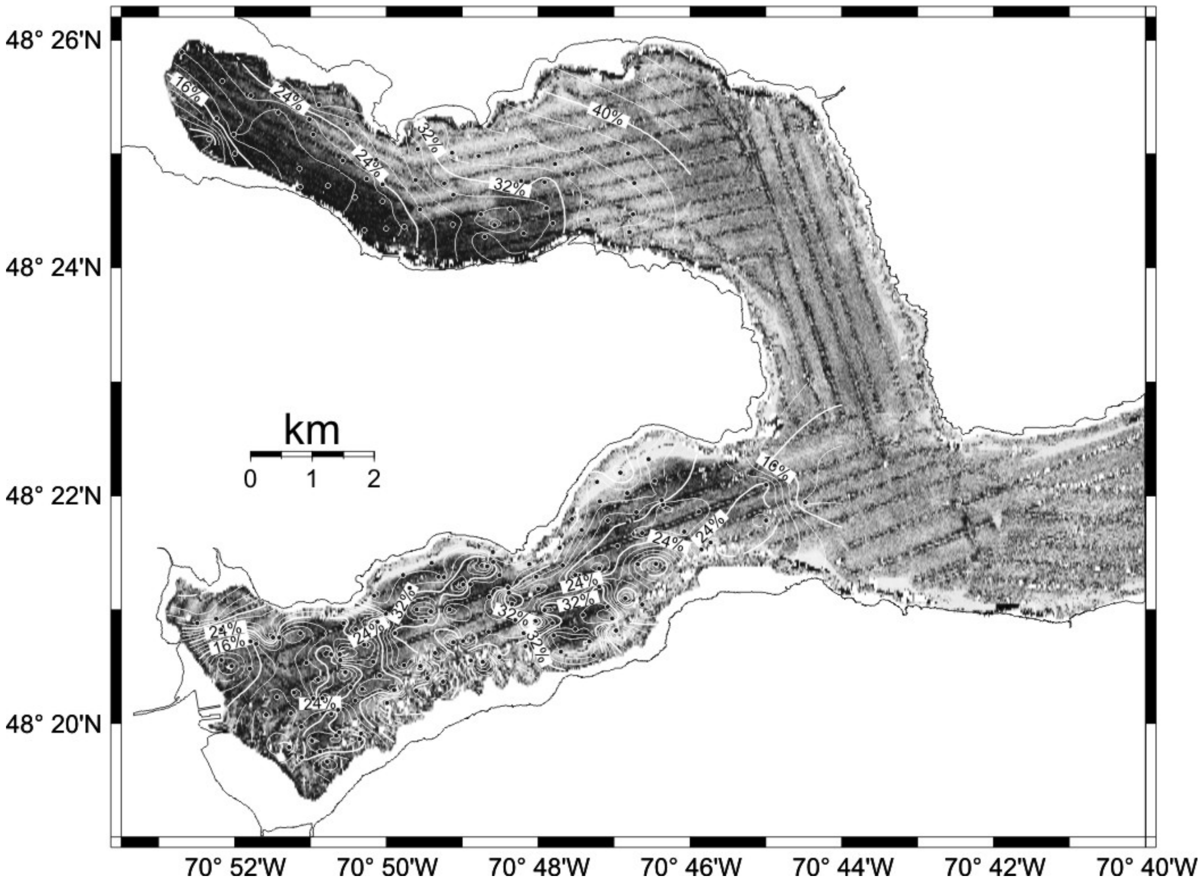

Figure 6. Isocontours of clay content superimposed on the backscatter strength map of 1999. Note, especially for the Bras Nord, how the isocontours mimic quite well the low backscatter patches.

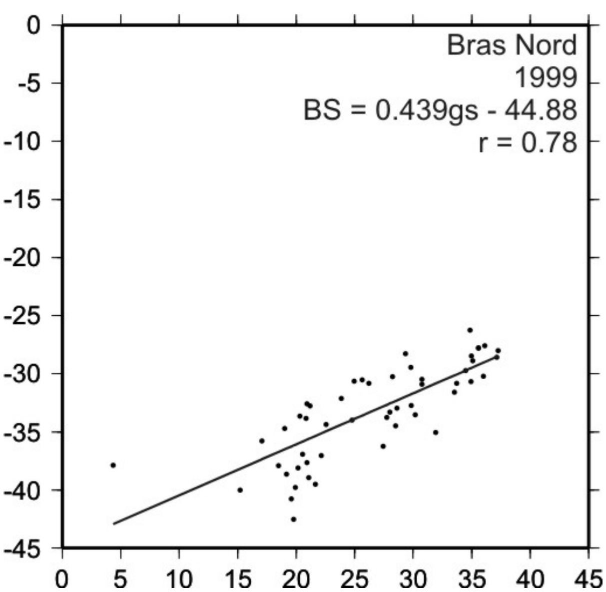

Figure 7. Backscatter strength as measured in 1999 correlated to clay content (%).

The mean backscatter strength measured in 1999 is around –31 dB. Within a single year measurement, several zones can be delimited which rely on acoustic differences of 2 to 3 dB (Figures 5 and 6). The zones presenting the lower backscatter are located at the river mouths and more proximal areas, while the high backscatter areas appear in more distal settings.

In order to investigate the observed differences through time and space a series of grab samples were collected, on which water content and grain size analysis were carried out. It appeared that there was little relation between water content and, thus, density and backscatter strength. On the other hand, the sediments with lower clay contents appeared to show the lowest backscatter strength (Figures 6 and 7). The observed relation is however opposed to that usually observed (backscatter strength usually increases with increasing grain size).

From these relations it was hypothesized that the main factor controlling the present distribution of low and high backscatter patches, was the interaction between sedimentary input and sediment reworking by organisms (Urgeles et al. 2002b). This hypothesis considered that, in the Saguenay Fjord, the roughness induced by bioturbation is higher than the roughness associated with the graininess of the sediment. This hypothesis is also supported by

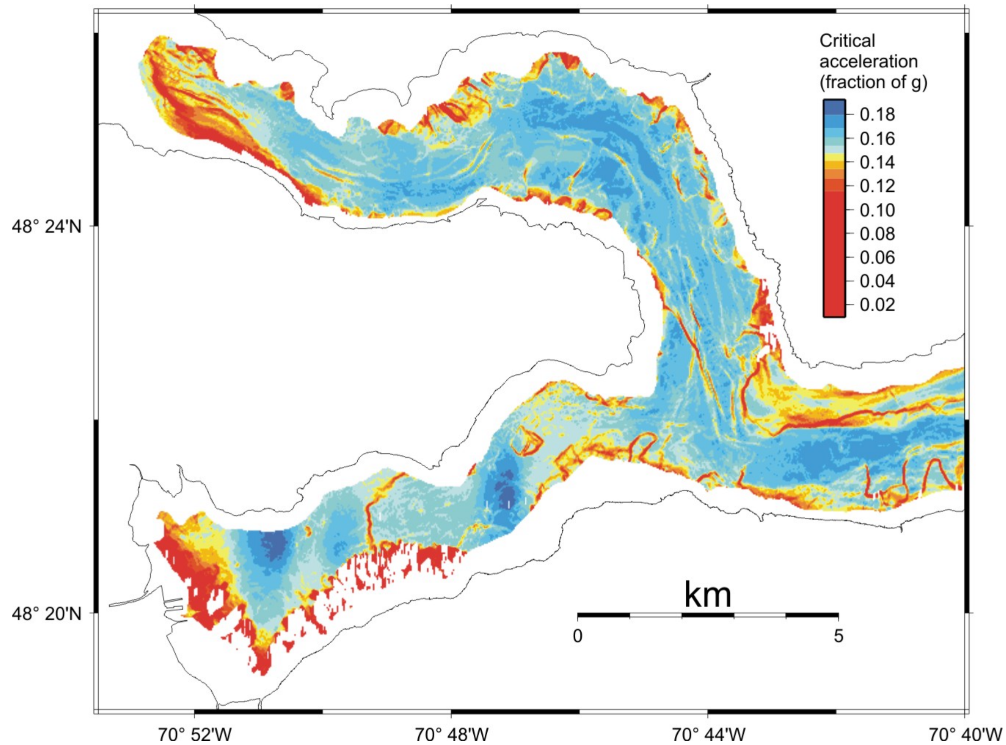

Figure 8. Calculated critical horizontal earthquake acceleration (as a fraction of g) to cause shallow seated landslides in the Saguenay Fjord.

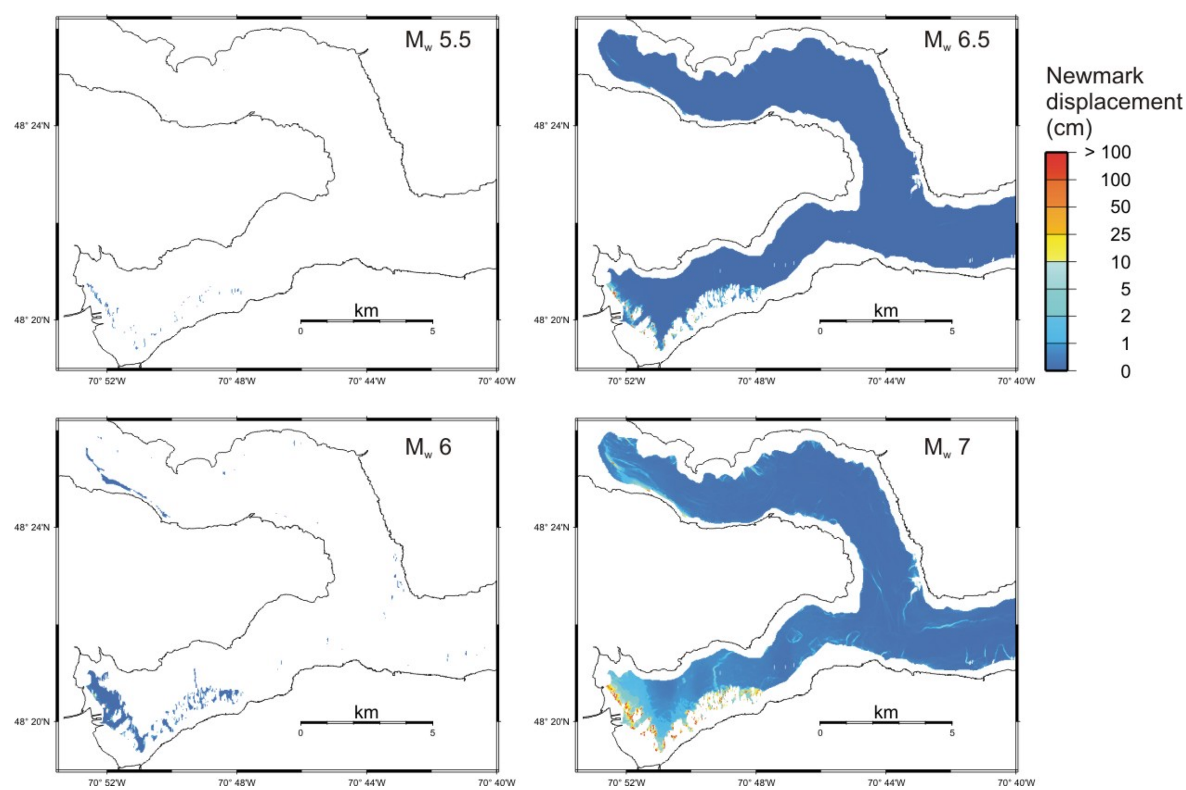

Figure 9. A series of calculated Newmark displacements for increasing earthquake magnitudes. Simulations were run with an epicenter corresponding to that of the 1988 Saguenay earthquake.

published data (Pelletier et al. 1999; Montety et al. 2000), which show a profound effect of the 1996 flood event on the Fjord benthos.

As a result it was concluded that the observed temporal variations in backscatter strength reflected variations in roughness associated to bioturbation, thus, the impacts of the flood on the benthos (1997 data) and its subsequent recovery (1999 data).

2.3 Multibeam surveys and geotechnical data: stability of the 1996 layer.

Since the Saguenay Fjord is an area of high seismicity it is compulsory that a dynamic analysis is carried out in order to evaluate the stability of the 1996 flood layer, that would, in case of failure, expose the old contaminated sediments. To this effect a Newmark (1965) analysis on a spatial basis was carried out. This involved three major steps: A, seismic shaking characterization through the generation of synthetic ground motions (Boore 1996), B, assessment of the seismic landslide susceptibility (Figure 8) through correlation of measured water content to cyclic stress ratio available relationships (Lee et al. 1999), and finally, C, integration of the two factors into an analysis of seismic landslides hazard that is expressed as permanent displacement (Figure 9).

The results showed that major displacements were only expected in certain regions of the Fjord for moment magnitudes larger than 6.75 (Urgeles et al. 2002a). The areas that appeared most likely to fail under such earthquakes are the head regions of the Baie des Ha! Ha! and the delta of St. Fulgence in the Bras Nord (Figure 9). As noted previously, some authors (e.g., Locat et al., 2000, 2003) believe that the Mn ~7 earthquake of 1663 might have had its epicentre somewhere nearby the epicentre of the 1988 Saguenay earthquake. It is clear from these results that if such an earthquake was to take place now, it would pose a major hazard to the stability of the flood layer. However, earthquakes of such magnitudes do not appear to be frequent in the Saguenay Fjord region. Lake sediment cores representing some 3000 yr of sediment accumulation of the area nearby the Saguenay Fjord have shown the occurrence of “abnormal” silt layers attributed to seismic shaking events prior to the 1988 earthquake (Doig 1998). The silt layers, much thicker and more widely distributed than the one associated with the 1988 event, were believed to be generated by earthquakes of local origin of magnitudes ranging between 6 and 7. From this data Doig (1998) estimated a recurrence interval for magnitude ~ 6 earthquakes of 350 to 1000 yr. Thus, it would appear from this recurrence interval range that failure of the flood layer in the near future is highly unlikely.

The analyses also showed that amplification due to specific soil conditions was an important parameter to take into account, if reliable earthquake magnitudes are to be linked with landslides in the study area. Such amplification will efficiently control the ground motion characteristics and, thus, the onset of landslides triggering.

It was finally concluded that major displacements that could induce failure were only expected from earthquake moment magnitudes of 6.5 or larger. And therefore, the 1996 flood layer appears to be seismically stable.

3. ACKNOWLEDGEMENTS

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