SUBMARINE MASS MOVEMENTS IN THE BETSIAMITES AREA, LOWER ST. LAWRENCE ESTUARY, QUÉBEC, CANADA

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Abstract

A complex submarine geomorphology was revealed from multibeam bathymetry and seismic reflection surveys conducted between 2001 and 2006 in the Lower St. Lawrence Estuary offshore Betsiamites River, Québec, Canada. In this paper, we describe the submarine morpho-sedimentology of an area of ~500 km^2 with focus on the consequences of three mass movement events. A chronology suggesting the ages for the failures is established. A major landslide scar is characterized by two large channels on the shelf and a sediments fan in the Laurentian Channel. This landslide is dated around 7.25 kyr cal BP. Morphological observations and sediment core analyses allow us to identify a least two different recent (*i.e.,* less than 1 kyr BP) debris flow accumulations on the shelf and in the Laurentian Channel. Two different ^{210}Pb-dated debris flow deposits were identified and associated to two recent earthquake episodes: (1) the AD 1663 (M~7) earthquake and (2) AD 1860 (M~6) or AD 1870 (M~6.5) earthquakes. The 1663 debris flow deposit is associated with a subaerial landslide observed on shore.

1. Introduction

Investigating submarine mass movements in order to evaluate slope stability for a region is required when carrying out risk assessment related to natural hazards. With the development of coastal and offshore activities there is an essential need to improve our understanding of the factors maintaining slope stability and those triggering mass movements. Submarine mass movements are widespread geomorphological processes found in many different oceanographic settings (Canals *et al.*, 2004; Locat and Lee, 2002). In Québec, comprehensive analyses of submarine mass movements have mostly been carried out in the Saguenay Fjord (Levesque *et al.*, 2006; St-Onge *et al.*, 2004; Locat *et al.*, 2003; Urgeles *et al.*, 2002). In the St. Lawrence Estuary (Figure 1), no exhaustive study has been undertaken with the primary goal of understanding submarine mass movements. As part of the COSTA-Canada project (COntinental slope STAbility) (Locat and Mienert, 2003), intensive field work was carried out in the St. Lawrence Estuary between the Betsiamites and Manicouagan deltaic systems (Cauchon-Voyer, 2007; Locat *et al*., 2004; Duchesne *et al.,* 2003) and led to the recognition of significant evidence of submarine mass movements west of the Betsiamites River mouth (Figure 1). Considering the amount of historical earthquakes known to have disturbed the landscape across Eastern Canada since the last deglaciation (Levesque *et al.*, 2006; St-Onge *et al.*, 2004; Aylsworth *et al.*, 2000; Shilts et Clague, 1992; Smith, 1962) and the extent of the regional disturbance observed in the Betsiamites – Rimouski area (Figure 1), it would be expected to identify more than one failures in the area. Therefore, morphological, sedimentological, and seismostratigraphic analyses of the seafloor

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integrated with results from St-Onge *et al.* (2003) on the Holocene magnetic and sedimentological sequences of the St. Lawrence Estuary will provide basis for a chronology for the failure events.

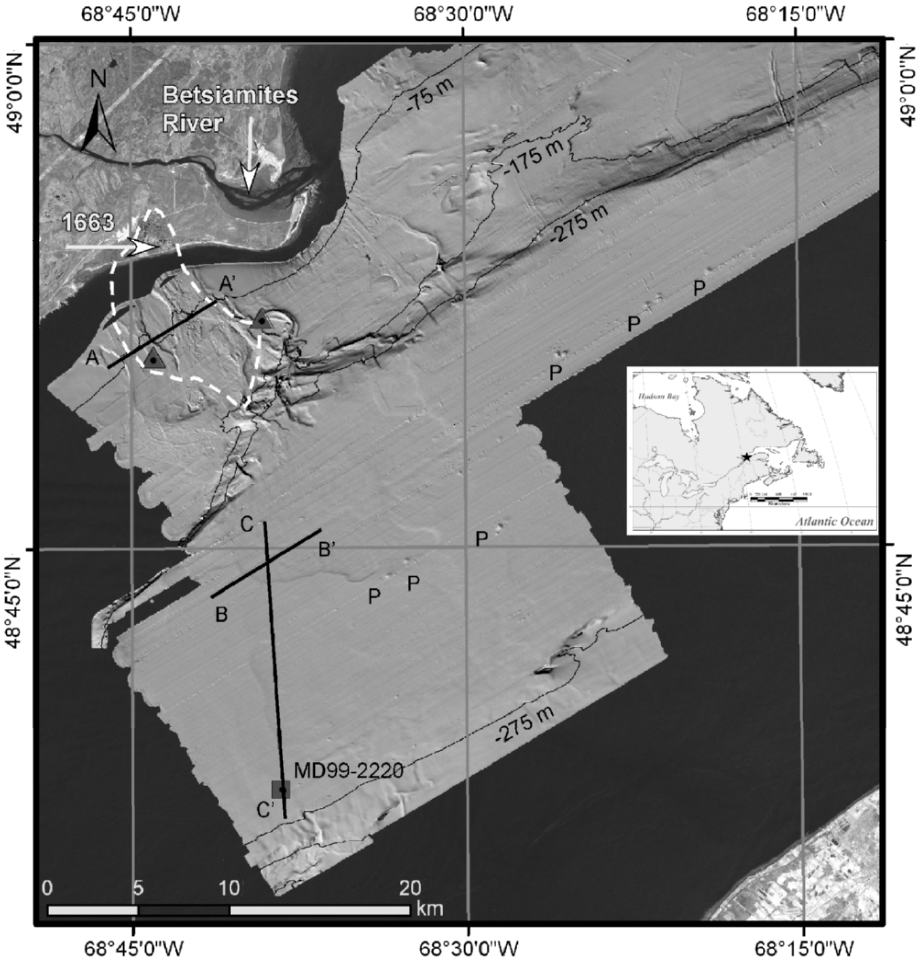

Figure 1. Sun illuminated map of the study area. The white dashed line indicates the location of the subaerial landslide scar and submarine debris associated to the 1663 earthquake. Gray triangles indicate position of two ^{210}Pb dated box cores presented in Figure 5. Notice the location of the Betsiamites River and the MD99-2220 coring station, indicated by the gray square. The black lines correspond to the position of the three high resolution profiles presented in this paper (A-A' Figure 3; B-B' and C-C' Figure 4). The letters P indicate the locations of large pockmarks.

2. Data and Methods

Bathymetric data was acquired using a SIMRAD EM1000 multibeam echosounder (Figure 1). The seismic reflection profiles presented in this study were obtained with an EG&G chirp system (2-12 kHz). 34 cores (box, Lehigh and piston) were recovered from 15 sampling stations between years 2003 and 2006. Low field volumetric magnetic

susceptibility (k) and wet bulk density and porosity were measured on board using a GEOTEK multi-sensor core logger (MSCL). Digital X-ray images of all cores were obtained with computerized co-axial tomography (CAT-Scan) with a pixel resolution of 1 mm. Sedimentation rates were derived from ^{210}Pb measurements within sediments of two box cores (Figure 5) following routine procedures at the GEOTOP-UQAM-McGill research center (*e.g.*, Zhang, 2000).

3. Regional morphology

The study area is located along the North Shore of the Lower St. Lawrence Estuary, 400 km northeast of Québec City (Figure 1). On land, a subaerial landslide scar with an area of 6.5 km^2 can be observed, west of the Betsiamites River (Figure 1). With an area of 6.5 km^2 and a volume of more than 300 millions m^3 it is one of the largest historical subaerial landslides identified in Québec. It has been suggested by Bernatchez (2003) that this landslide was triggered by the earthquake (M~7) that shook the province of Québec in AD 1663 (Smith, 1962). The water depth in the study area ranges from the shoreline down to 375 m in the Laurentian Channel, a long U-shaped glacial valley (Loring and Nota, 1973). The shelf is a sub-horizontal surface and has an average width of 10 km and a maximum slope of 2°. shelf break occurs between 150 and 200 m water depth. A wide variety of landforms are revealed from seafloor investigation (Figure 2). We define four (4) main types of geomorphological features: mass movement morphologies, paleochannels, pockmarks, and undisturbed seafloor. A paleo-submarine channel and its meander are identified on the shelf, east of the landslide scar (Figure 2). This submarine channel is not currently related to the modern Betsiamites River discharge (Figure 1). This paleochannel is probably a vestige of the progradation of the deltaic system during the last sea level regressive phase (Hart and Long, 1996). Pockmarks were identified on the shelf and in the Laurentian Channel regions. On the shelf, they are concentrated at water depths ~ 140 m (Figure 2). Their diameters range between 50 and 75 m and depths from 2 to 4 m below surrounding seafloor. In the Laurentian Channel, the pockmarks are significantly larger, some having diameters of up to 400 meters and forming depressions reaching 12 m (Figure 1).

4. Mass movements morphologies

4.1 7.25 KYR CAL BP EVENT

In the study area, mass movements have modified the shelf, slope, and Laurentian Channel. On the shelf, an area of 70 km^2 was modified by mass movements (Figure 2).
It stretches for 10 km from the shoreline to the shelf break. The landslide scar on the shelf is characterized by three main distinctive features: (a) a landslide scar with two large channel, (b) buttes of remnant deposits and (c) recent and shallow landslide debris (Figure 2).

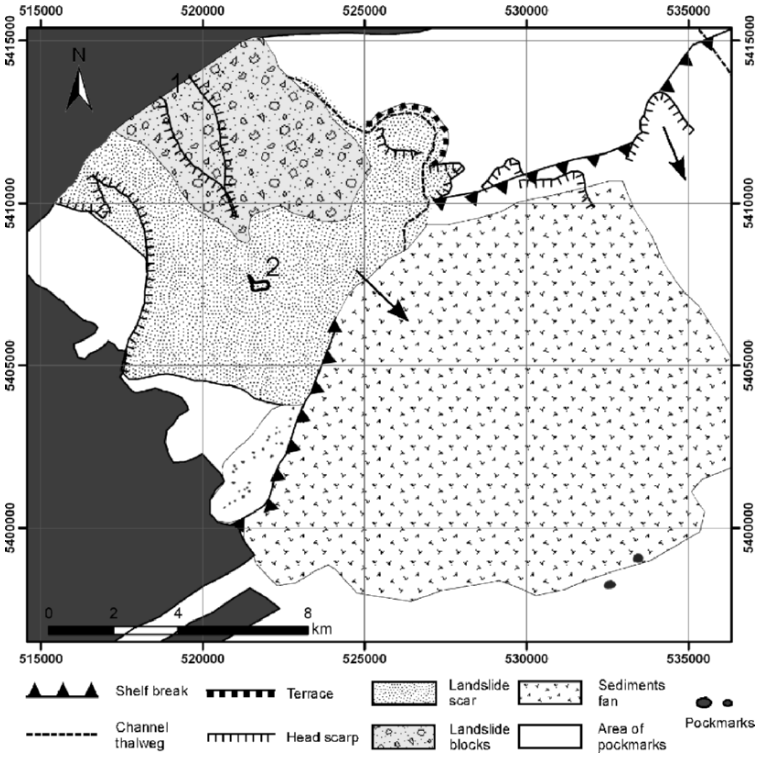

Figure 2. Geomorphological interpretations of the area, with focus on the mass movement morphologies. Arrows indicate landslide flow direction. 1 and 2 refer to the buttes, see text for explanation.

At least four different events modified this area of the shelf (Figure 3) and three of them were dated. An event created the two large channels separated by a butte of remnant stratified deposits (Figure 3). Sequential analysis of the seismic configuration of the reflectors at the base of the channels allows us to interpret them as being formed synchronously as a sliding mass. The West landslide channel has a width ranging from 2 to 3 km and a length of 5 km. The slope of the West landslide channel floor is 1°. The western flank heights of the West landslide channel ranges from 12 to 18 m, with average slope of 12°. For the eastern flank, heights range between 10 to 20 m with average slopes of 5°. The East landslide channel width varies from 2 to 4 km, has a length of 5 km, and a floor slope of 1°. The morphology of the eastern flank of the East landslide channel is irregular due to mass wasting processes.

Two buttes with steep flanks and flat tops are observed within the landslide scar (1 and 2 on Figure 2). They are remnant deposits of stratified sediments (above R2 on Figure 3). A continuous stratified sequence is interpreted on the seismic profiles (Figure 3) of butte 1, implying that it was kept mostly intact when the landslide channels were formed. Butte 1 extends over 5 km^2 with a maximal length and width of 4.5 km and 1.6 km, respectively (Figure 3). The average slope of the top of butte 1 is 1°. Butte 2 was kept intact within the lower section of the landslide scar (Figure 2).

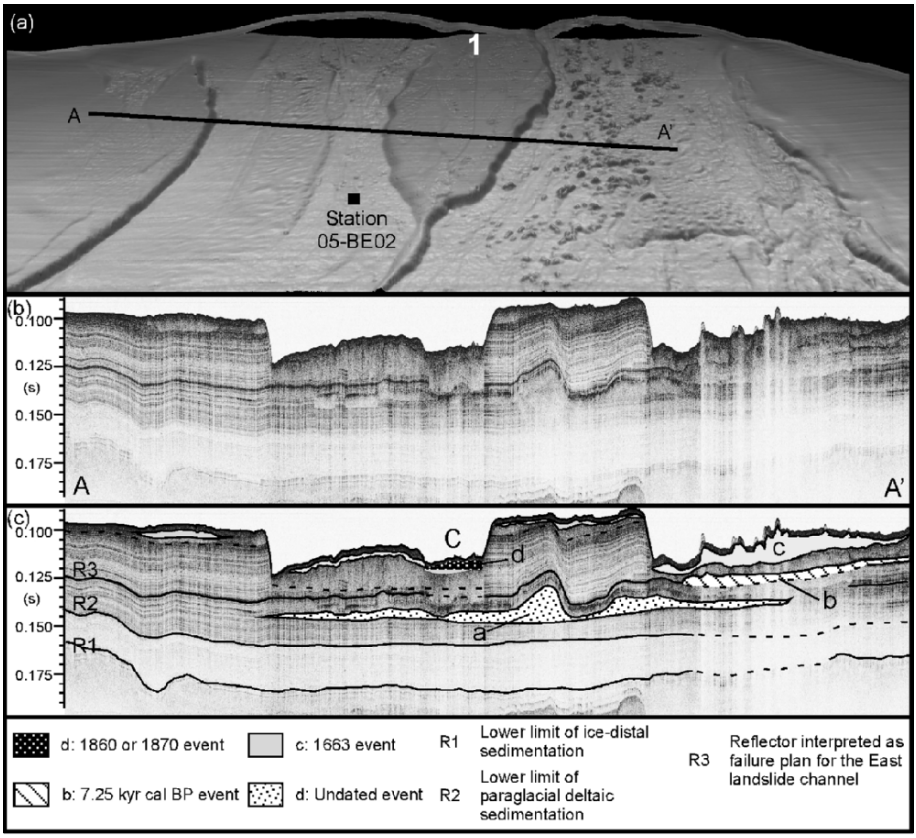

Figure 3. (a) 3D shaded bathymetry relief of the landslide channels and butte 1. View is looking north-west. Vertical exaggeration is 5x. Position of the 7.4 km long seismic profile A-A' is shown. (b) High resolution seismic A-A'. Scale is in second (two-way travel time). (c) Interpretations. Letter C indicates the position of a shallow landslide channel (event of AD 1860 or AD 1870) in the 1663 debris. R1 is interpreted as the lower limit of ice-distal sedimentation. R2 is interpreted as the lower limit of paraglacial deltaic sedimentation. Notice that both the undated and landslide channels events occurred within this unit of highly stratified sediments.

In the Laurentian Channel, traces of this event are interpreted in the seismostratigraphic sequence. In fact, a large sediment fan is observed at a water depth of 350 m (Figure 2). The fan has an area of 115 km^2 and a maximum diameter of 15 km. Seismic reflection profiles allow us to interpret this fan as the result of accumulation of debris (Figure 4). The last debris flow is buried under an average of 15 m of postglacial hemipelagic sediments, which implies that the fan is currently inactive. With an average thickness of 9 m, the debris flow has an estimated volume of 1 km^3. A high amplitude seismic reflector is interpreted as the upper boundary of the debris flow deposit, indicated by S1 in Figure 4 and extends out of the limit of the debris fan. A correlation to date this event can be done with the work of St-Onge *et al.* (2003) who established from 17 AMS ^{14}C dates an age model for core MD99-2220 sampled in the Laurentian Channel, ~ 15 km from the study area (Figure 1).

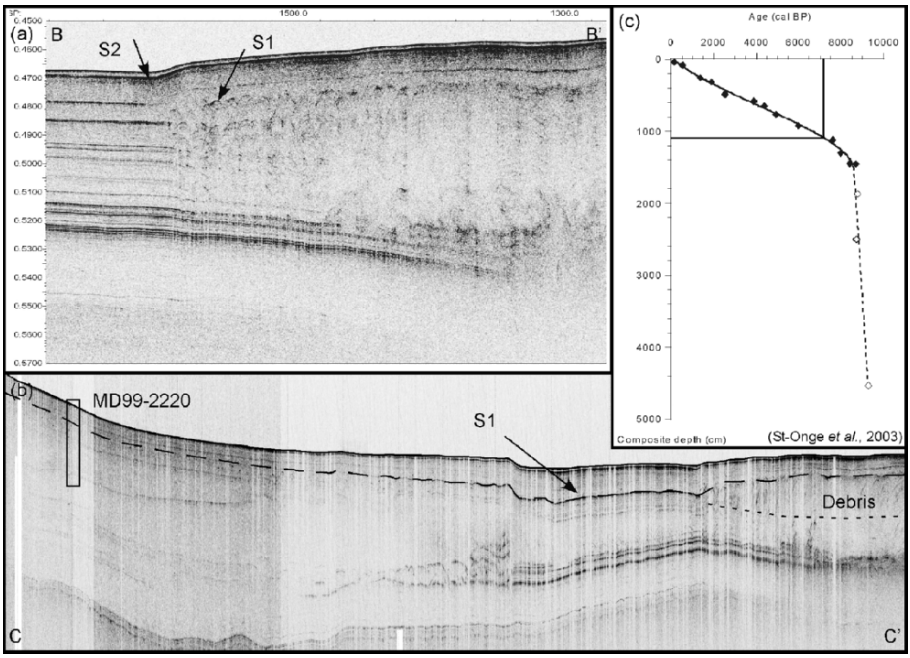

Figure 4. (a) High resolution profile B-B' across the debris fan in the Laurentian Channel. S2 refers to the reflector interpreted as related to the 1663 event. (b) High resolution seismic profile C-C' providing spatial correlation between the debris fan and the sampling location of core MD99-2220. C-C' is 15 km long, vertical exaggeration is 28x. The dashed line indicates the position of reflector S1 that links the debris flow to the age model. (c) Age model (St-Onge *et al.,* 2003).

S1 is observed at a depth of 1100 cm, leading to an age estimate of about 7250 cal BP (Figure 4). This age estimate is consistent with many observations linking glacio-isostatic rebound and earthquake-triggered landslides close to the study area. For example, St-Onge *et al.* (2004) suggested that at least 4 rapidly deposited layers possibly caused by earthquakes occurred in the Saguenay Fjord between 6800 and 7200 cal BP. Similarly, Aylsworth *et al.* (2000) associated observations of very disturbed terrain in a flat erosional plain in the Ottawa Valley to earthquake deformations and liquefaction of sensitive clays that occurred ca. 7060 yr BP.

4.2. RECENT EVENTS

Morphological observations and high resolution seismic interpretations led us to establish that more than one recent landslide (*i.e.,* less than 1000 years old) have occurred in the area. The floor of landslide channels East and West adjacent to the shoreline is covered with a chaotic layer having a rough surface and transparent seismic attributes (Figure 3). It is interpreted as recent debris flow deposits. The East landslide channel debris are a continuity of the subaerial landslide (Figure 1). It is covered by large rafted blocks impeding seismic penetration (Figure 3). The blocks extend downslope 8 km from the shoreline. Small wood branches, bark, and peat were found in the sediments recovered from the submarine debris, which attests of their subaerial provenance.

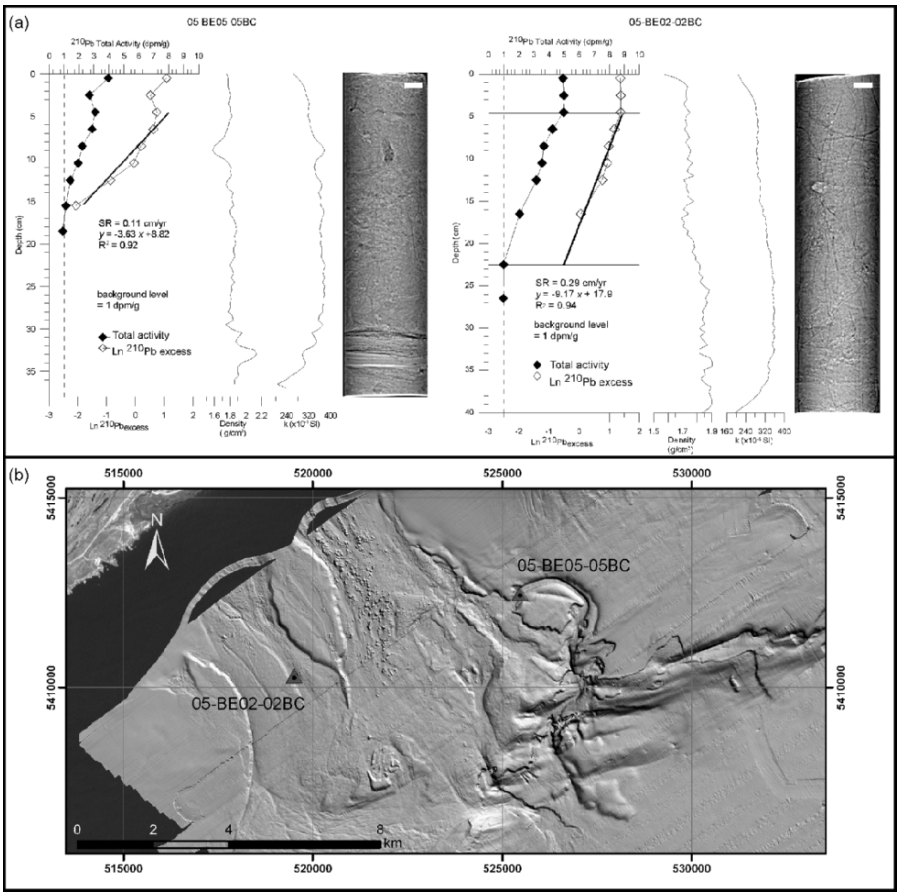

Figure 5. (a) ^{210}Pb measurements in box cores 05-BE05-05BC and 05-BE02-02BC. Regional ^{210}Pb supported value is from Zhang (2000). Bulk density, magnetic susceptibility profiles and CAT-Scan images are presented (white bar represents 2 cm). Active mixing occurs in the upper 4.5 cm of both cores. For box 05BC, SR = 0.11 cm yr^{-1} (R^2= 0.92). Notice the sand bed at 30 cm, associated with the 1663 event. For box 02BC, SR = 0.26 cm yr^{-1} (R^2= 0.94). (b) Sun illuminated indicating position of sampling stations.

Analysis of the sediments physical properties recovered from a box core (05-BE05-05BC) sampled in the meander area (Figure 5) led to the identification of recent homogenous hemipelagic sedimentation and of a sand bed associated to a debris flow (Figure 5). The debris flow deposit was identified at 30 cm bsf and 5 cm of compaction was recorded when the core was sampled, implying that the debris flow at this location is buried under a minimum of 35 cm of hemipelagic sediments. Using the sedimentation rate of 0.11 cm yr–^{1} calculated from the slope of the ln (^{210}Pb$_{excess}$) (Figure 5), the debris flow buried under 35 cm is dated at about AD 1685, suggesting it could have been triggered by the 1663 earthquake. This recent event is also observed within the sediments of the Laurentian Channel. In fact, a high amplitude reflector was interpreted at an average depth of 1 m in the sediments (S1 on Figure 4). The layer was sampled with gravity coring and interpreted as a rapidly deposited layer (RDL) following a landslide event. Using the ^{210}Pb derived sedimentation rate of 0.28 cm yr^{-1} determined

by St-Onge *et al.* (2003) on box core AH00-2220, we can estimate a date of occurrence at AD 1646, which can reasonably be linked to the AD 1663 earthquake. As described previously, many landslides elsewhere in Québec are related to the 1663 earthquakes (Saguenay Fjord, Levesque *et al.*, 2006 and St-Onge *et al.*, 2004; Saint-Jean Vianney, Lasalle and Chagnon, 1968) as it is also suggested for the Betsiamites subaerial landslide (Bernatchez, 2003).

In the West channel, the AD 1663 landslide debris were subsequently eroded by another landslide that produced the shallow channel seen at the surface, as indicated by the letter C in Figure 3. ^{210}Pb measurements were performed on the sediments of a box core recovered within this channel. The debris flow was not identified in the 40-cm long ^{210}Pb-dated box but identified at a depth of 30 cm within a different gravity core from this same coring station. Based on the sedimentation rate estimated at this station (0.29 cm yr^{-1}; Figure 5), a depth of 40 cm would lead to AD 1872 for the event whereas a depth of 45 cm to AD 1855. Despite the fact that we can not provide a precise date, it nevertheless discards the hypothesis that this last event is associated with the AD 1663 earthquake. Two significant earthquakes were recorded in the Charlevoix Seismic Zone (CSZ) (Smith, 1962): a first one on October 17, 1860 (M~6) and a second one on October 20, 1870 (M~6.5). The epicenters for the 1860 and 1870 events are evaluated at 180 km and 200 km from the Betsiamites area.

5. Discussion and conclusion

The recurrence of slope instability within the Betsiamites – Rimouski area could be attributed to seismic activity due to glacio-isostatic rebound. As the area is located within the Lower St. Lawrence Seismic Zone (LSZ) and close to the Charlevoix Seismic Zone (CSZ), it is expected that seismicity will influence the occurrence of slope instability. However, other factors reducing slope stability such as highly stratified deposits, groundwater seepage, and possible gas escape are found in the Estuary. In combination with earthquakes they cumulate to create a less stable environment. As seen in Figure 3, the failure plan of the landslide channel is interpreted in a unit of dense stratified seismic reflectors. These highly variable seismic attributes could indicate different sediments composition, such as the alternation of silty and sandy layers. The layer identified by R3 in Figure 3 could have developed in a weak layer that would undergo liquefaction when subject to an earthquake and thus result in slope failure. Such liquefaction has likely occurred for the slide in the East landslide channel (Figure 3), as little sediments remained on the failure plane.

In our chronology, we were able to link 3 main events (7250 cal BP, AD 1663, and AD 1860 or 1870) to slope instability (*i.e.*, not to catastrophic river discharge), and to differentiate them from one another based on a sequential stratigraphy point of view and on ^{210}Pb or radiometric dates. Our analysis has raised many other questions such as the tsunamigenic potential of these events and the treat of future similar events elsewhere in the Estuary. There is thus a need to pursue our research to clearly define the mechanisms responsible for slope failures and to describe post-failure behavior in order to assess the risk of slope instability in the St. Lawrence Estuary.

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7. References

Aylsworth, J.M., Lawrence, D.E. and Guertin, J., 2000. Did two massive earthquakes in the Holocene induce widespread landsliding and near-surface deformation in part of the Ottawa Valley, Canada? Geology, 28(10): 903-906.

Bernatchez, P., 2003. Évolution littorale holocène et actuelle des complexes deltaiques de Betsiamites et de Manicouagan-Outardes : synthèse, processus, causes et perspectives, Université Laval, Sainte-Foy, 460 pp.

Canals, M., et al., 2004. Slope failure dynamics and impacts from seafloor and shallow sub-seafloor geophysical data: case studies from the COSTA project. Marine Geology, 213 (1-4): 9-72

Cauchon-Voyer, G., 2007. Morpho-sédimentologie et mouvements de masse au large de la Rivière Betsiamites, estuaire du Saint-Laurent, Québec, M.Sc. Thesis, Université Laval, 196 pp.

Duchesne, M.J., Long, B.F., Urgeles, R. and Locat, J., 2003: New evidence of slope instability in the Outardes Bay delta area, Québec, Canada. Geo-Marine Letters 22, 233-242.

Hart, B.S. and Long, B.F., 1996. Forced regressions and lowstand deltas: Holocene Canadian examples. Journal of Sedimentary Research, 66(4): 820-829.

Lasalle, P., and Chagnon, J.-Y., 1968. An ancient landslide along the Saguenay River, Québec. Canadian Journal of Earth Sciences, 5(1):548 -549.

Levesque, C.L., Locat, J., and Leroueil S., 2006. Dating submarine mass movements triggered by earthquakes in the Upper Saguenay Fjord, Québec, Canada. Norwegian Journal of Geology, 86: 231-242.

Locat, J. and Lee, H.J., 2002. Submarine landslides: advances and challenges. Canadian Geotechnical Journal, 39(1): 193-212.

Locat J., Levesque C., Locat P., Cauchon-Voyer G., Leroueil S., Godin A., Sanfaçon, R., 2004. Aperçu des mouvements de masse sous-marins au large de la rivière Betsiamites, estuaire du Saint-Laurent, Québec, Canada, Conférence Canadienne de Géotechnique, Québec.

Locat, J. and Mienert, J. (Editors), 2003. Submarine Mass Movements and their Consequences 1st International Symposium. Kluwer Academic Publishers, Dordrecth, The Netherlands, 540 pp.

Loring, D.H. and Nota, D.J.G., 1973. Morphology and Sediments of the Gulf of St. Lawrence, Bulletin of the Fisheries Research Board of Canada 182, Ottawa, 147 pp.

Shilts, W.W. and Clague, J.J., 1992. Documentation of Earthquake-Induced Disturbance of Lake-Sediments Using Subbottom Acoustic Profiling. Canadian Journal of Earth Sciences, 29(5): 1018-1042.

Smith, W., 1962. Earthquakes of eastern Canada and adjacent areas, 1534-1927, 26. Publications of the Dominion Observatory, Ottawa, pp. 271-301.

St-Onge, G., Mulder, T., Piper, D.J.W., Hillaire-Marcel, C. and Stoner, J.S., 2004. Earthquake and flood-induced turbidites in the Saguenay Fjord (Québec): a Holocene paleoseismicity record. Quaternary Science Reviews, 23(3-4): 283-294.

St-Onge, G., Stoner, J.S. and Hillaire-Marcel, C., 2003. Holocene paleomagnetic records from the St. Lawrence Estuary, eastern Canada: centennial- to millennial-scale geomagnetic modulation of cosmogenic isotopes. Earth and Planetary Science Letters, 209(1-2): 113-130.

Urgeles, R., Locat, J., Lee, H.J. and Martin, F., 2002. The Saguenay Fjord, Québec, Canada: integrating marine geotechnical and geophysical data for spatial seismic slope stability and hazard assessment. Marine Geology, 185(3-4): 319-340.

Zhang, D., 2000. Fluxes of Short-lived Radioisotopes in the Marginal Marine Basins of Eastern Canada. Ph.D Thesis, Université du Québec à Montréal, Montréal, 193 pp.