Landslides and Engineered Slopes: Protecting Society through Improved Understanding – Eberhardt et al. (eds)

Exploring the contrasting signatures of submarine landslides along the North Channel of the St. Lawrence Middle Estuary (Charlevoix), Québec, Canada

J. Locat, D. Turmel, F. Noël, C. Amiguet & P. Lajeunesse
Université Laval, Québec, QC, Canada

G. St-Onge & L. Terhzaz
Institut des sciences de la mer de Rimouski (ISMER), Rimouski, QC, Canada

ABSTRACT: The North Channel of the St. Lawrence Middle Estuary has been covered by multibeam surveys that have revealed numerous landslides signatures along both sides of the channel. In some parts of the estuary, the submarine coastline is covered by a drape of slide debris that varies in thickness. The landslide signature appears quite different so that slides on the North flank mostly result from slump and spread sometime leading to apparent compression ridges while the South flank is mostly covered by shallow spread failures. The very active erosion taking place in the channel, as shown by the active sand dunes, and the partial coverage of some slide debris, relative to others, suggests that they did not take place following a single event such as an earthquake.

1 INTRODUCTION

The coastline of the Charlevoix area represents the northern limit of the St. Lawrence Middle Estuary which extends over 200 km between Québec City and Tadoussac (Fig. 1, Dionne 1963). The Charlevoix area is known for its frequent earthquakes (Lamontagne 1987) associated with the Charlevoix Seismic Zone (CSZ) which has, in some occasions, generated sub-aerial slides in the area (Locat 2011). In the submarine environment, Praeg et al. (1990) mapped extensive zones of submarine mass movement signatures that were named 'slide toes'. The coastline of the Charlevoix being under strong touristic development, issues related to natural hazards, and earthquake-triggered landslides in particular, are of great interest and thus require a rational evaluation of the hazards and future risk for the people and the coastal infrastructures including roads and railroads. Recent (i.e., in 2006 and 2007) multibeam surveys carried out in the St. Lawrence Estuary have been interpreted by various authors (Amiguet 2007, Campbell et al., 2008, Poncet et al., 2009, Pinet et al., 2011, St-Onge et al., 2011) thus confirming and extending our knowledge about the extent of coastal and submarine mass movements along the coast of the Charlevoix area and their consequences.

This paper will further analyze the submarine failures along the North Channel that will illustrate the extent of the landsliding process and the various types of signatures which appear quite different on both sides of the North Channel of the St. Lawrence Middle Estuary.

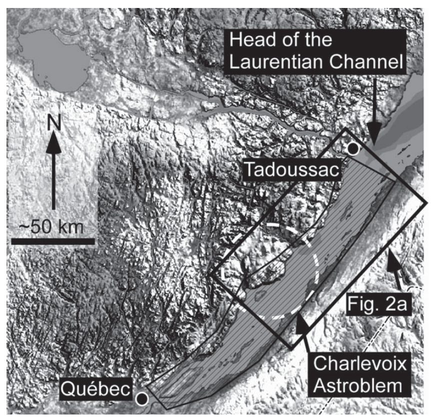

Figure 1. The St. Lawrence Middle Estuary (Dionne 1963, hatched) and the study area between Quebec City and Tadoussac including the Charlevoix astroblem region.

2 PHYSICAL SETTING

The St. Lawrence Middle Estuary extends from Québec City to the mouth of the Saguenay Fjord, i.e., a distance of about 200 km and has an increasing width from a few kilometers below

Île d'Orléans, just east of Quebec City, to about 20 km at the head of the Laurentian Channel near Tadoussac (Fig. 1).

The St. Lawrence Middle Estuary occupies a depression between Precambrian rocks to the North and Ordovician and Appalachian rocks under the seafloor and to the South. The main morphological characteristic of the Middle Estuary is the presence of two erosive (i.e., active) channels (North Channel and South Channel) and a flatter area near la Malbaie (LM in Fig. 2a) called Banc des Anglais. The main channels are also in line with a series of smaller sub-parallel channels which more or less follows the structural trend of the South Shore. Except for the North Channel, most of the Middle Estuary has depth of about 30 m. The North Channel contains two deep basins, one near Cap-au-Saumon (150 m; CAS, Fig. 2c) and the second near Île-aux-Coudres (90 m; IAC, Fig. 2a).

According to D'Anglejan et al. (1981) and D'Anglejan (1990), this asymmetrical profile of the Middle Estuary is responsible for the different tidal flow characteristics between the North and the South Channels. Flood flow dominates the North Channel versus ebb flow in the South Channel. Both flood and ebb flows have similar velocities with a maximum of 7 knots (3.5 m/s) between Île-aux-Coudres (IOC, in Fig. 2a) and St. Joseph-de-la-Rive (SJR, in Fig. 2a, Praeg et al., 1990).

The mixing of freshwater and sea water downstream from Quebec City creates the formation of a turbidity maximum between Île d'Orléans and Île-aux-Coudres with a sharp front seaward. It is maintained in suspension by water circulation, tidal and wave re-suspension in such a way that little sedimentation takes place in the Middle Estuary (D'Anglejan et al., 1981). The evidence suggests that most sediments in suspension introduced by the St. Lawrence drainage system into the Middle Estuary (Fig. 1) are transported downstream towards the Lower Estuary and the Gulf of St. Lawrence. This assumes a transport mechanism able to carry efficiently downstream a suspended load estimated at about 5×10^6 tons/year (Loring & Nota 1973).

Clearly, the St. Lawrence Middle Estuary is an erosive and high energy environment that will not easily preserve recent mass transport deposits. The erosion itself is largely responsible for the relatively high slope angles within the North Channel (D'Anglejan et al., 1981).

3 METHODOLOGY

The data used for the present study have been obtained by various methods. The seafloor

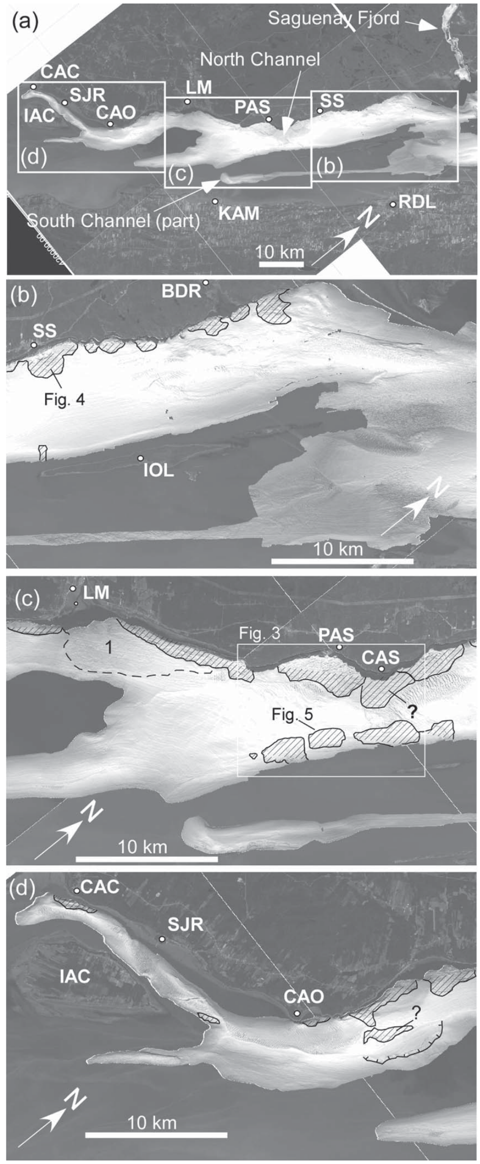

Figure 2. (a): Sectors covered with multibeam surveys in the North and South Channel of the St. Lawrence Middle Estuary. The main cities and study sites are also identified, from west to east along the north shore: Cap-aux-Corbeaux (COC), Île-aux-Coudres (IAC), St. Joseph-de-la-Rive (SJR), Cap-aux-Oies (CAO), La Malbaie (LM), Port-au-Saumon (PAS) and St. Siméon (SS); and along the south shore: Kamouraska (KAM) and Rivière-du-Loup (RDL). (b-d): aerial distribution of the various signatures related to submarine mass movements with slide debris and scars identified in hatched areas. In (c) site 1 corresponds to a major mound consisting of slide debris originating from the La Malbaie River, and CAS: Cap-au-Saumon. In (d), a long escarpment may represent an 'unfinished' slide.

morphology was acquired in 2006 and 2007 using a Kongsberg EM 1002 multibeam sonar survey system on board the CGCS Frederick G. Creed. The multibeam data were used to generate bathymetric images with either 5 or 10 m pixel resolution. The seismic survey reported here was carried using a SQUID 2000 sparker from Applied Acoustics at an energy level from 0.2 to 0.6 kJ operating at a frequency centered at 900 Hz with a vertical resolution of about 0.5 m. The seismic survey was carried out as part of a scientific cruise in May and June 2011 (Locat et al., 2011) on board the Coriolis II. The data analysis was performed using the Fledermaus software for the morphology, the Kingdom Suite and SeiSee softwares for 2D seismic analysis and ArcGIS for data integration.

4 GEOMORPHOLOGY AND STRATIGRAPHY

The geomorphology of the North Channel of the St. Lawrence Middle Estuary, as indicated by the multibeam data and from previous studies reported above, is mostly dominated by bedrock morphology, erosion features, bed load sediment transport landforms such as dunes (Bolduc et al., 2009) and landslides (Figs. 2 and 3).

The channel width is largely controlled by a bedrock striking more or less in a northeast direction, i.e., parallel to the coast line. For Praeg et al. (1990), this channel would correspond to an upstream extension of the glacially carved Laurentian Channel with a sill near Tadoussac and also near La Malbaie. A topographic cross section near Port-au-Saumon (PAS) is shown in Figure 3b illustrating the steeper slopes (20° and more) on the North side compare to the lower slopes angles to the South (2 to 10°).

Praeg et al. (1990) have mapped the sediment thickness in the North Channel and have identified two sedimentary basins with sediment thickness of 150 m near Île-aux-Coudres basin and about 350 m near La Malbaie. The sediment package in the study area involved up to 5 seismostratigraphic units representing various types of deposits from

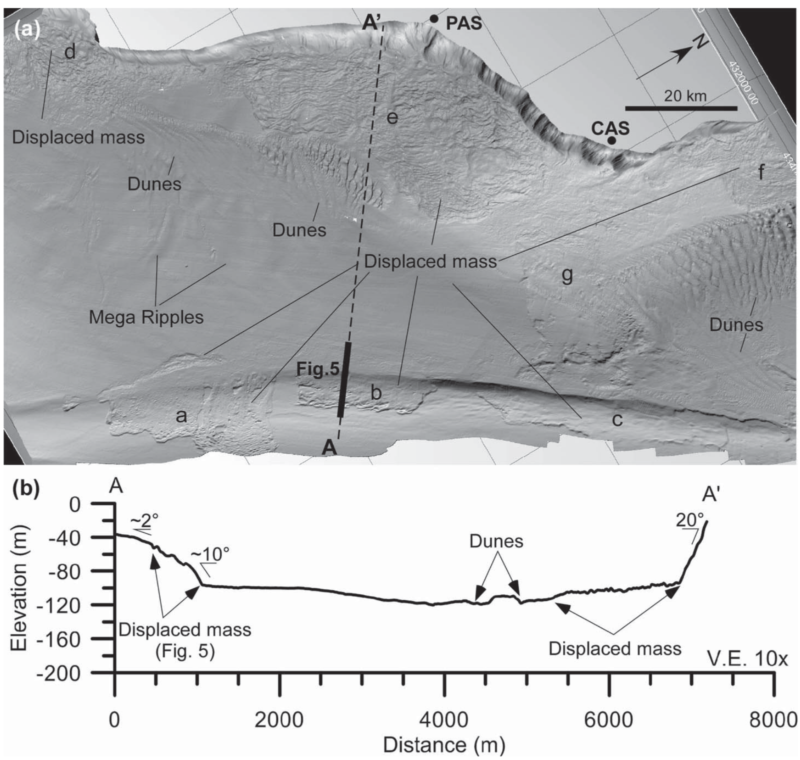

Figure 3. Contrasting the landslide morphology from both sides of the North Channel. Spread shallow failures are visible on the South side (a, b, and c) with spread flow and compression zones on the North side (d, e, f, g). Various types of dunes are visible on this image with some interesting mega-ripples. Note that the failure starting zone in slide 'c' appears more smoothed than in slide (a) and (b).

glacial ice-contact sediments to post-glacial marine muds, sands and gravels. Since our study deals mostly with landslide signatures, i.e., superficial landslides, the sedimentary units involved are mostly limited to glacial marine (unit 2 and 3) and postglacial estuarine and marine muds (unit 5 of Praeg et al., 1990).

5 MASS MOVEMENT INVENTORY

A detailed analysis of the multibeam data was carried out in order to identify various mass movement morphologies and the results are compiled in Figure 2. In most cases, the mass movement signatures could be easily mapped on the basis of their surface expression (e.g., Fig. 3).

From the Saguenay Fjord and upstream, mass movements are first noticed 10 km east of Baie-des-Rochers (BDR, Fig. 2b) and as far west as Cap-aux-Corbeaux (CAC, Fig. 2c). Except for the portion between La Malbaie and St. Siméon (Figs. 2a and 2b), most of the mass movements are found on the North flank of the North Channel. As it will be described below, mass movement signatures are also quite different from either side of the North Channel.

The size of landslides varies from less than 1 km^2 to close to 15 km^2 in the Port-au-Saumon area (PAS, Fig. 2c) with volumes reaching 150 M m^3. Submarine landslides are present at the mouth of almost every river along this stretch of the coast except at La Malbaie where they are replaced by a large accumulation of blocky and muddy debris most likely originating from sub-aerial slides (1 in Fig. 2c).

Due to limited space, only two slides, considered typical of either side of the North Channel will be describe in some details.

6 NORTH FLANK

The steep slopes along the North flank dip between 20 and 30° (Fig. 3b) and are cut into the bedrock (e.g., near Cap-au-Saumon, Figs. 2c, and 3a).

The North flank of the North Channel presents a large amount of submarine slides which are often close to inhabited areas (e.g., St. Siméon, Fig. 4). For a coastline, in the study area, which is about 125 km long (Fig. 2a), about 65% of it is covered by landslides debris extending up to 4 km offshore.

On the North flank of the North Channel, landslides are quite similar and reveal a series of deformed sub-parallel ridges similar to the 'finger print' morphology often seen on subaerial spread failures (Fig. 3a), which have stopped on slopes near 1° (see the topographic profile in Fig. 3b). In most locations, the multibeam survey being limited to a depth of 30 m, the starting zones of the landslides on the North flank are not clearly visible although they took place along a fairly steep failure surface (~10°, Fig. 4b). In some places, e.g., slide 'd' and 'e' in Figure 3a, the displaced mass has cut across the sandy bottom to stop against a dune field (west part of slide 'e' and slide 'f' in Fig. 3a).

The Saint-Siméon slide has been selected to illustrate the slide signature in this area of the North Channel. The displaced mass covers an area of 5 km^2. In Figure 3a, a half-moon large rotated block is visible. It is 1.2 km long by 450 m wide with an average thickness of 20 m (volume of nearly 11 M m^3). The remaining part of the displaced mass can be divided into two parts: (1) a disturbed zone showing a hummocky terrain more or less organized into ridges and (2) a second zone showing sub parallel ridges extending in a shape similar to compression ridges developed in two lobes (L1 and L2 in Fig. 4a). A box core taken on lobe L1 (Box, Fig. 4a) showed a mixture of stiff clay with boulders on the top (Locat et al., 2011). The stiff clay being much less erodible than silty or sandy sediments, it may explain why most of the slide debris originating from the North flank was preserved.

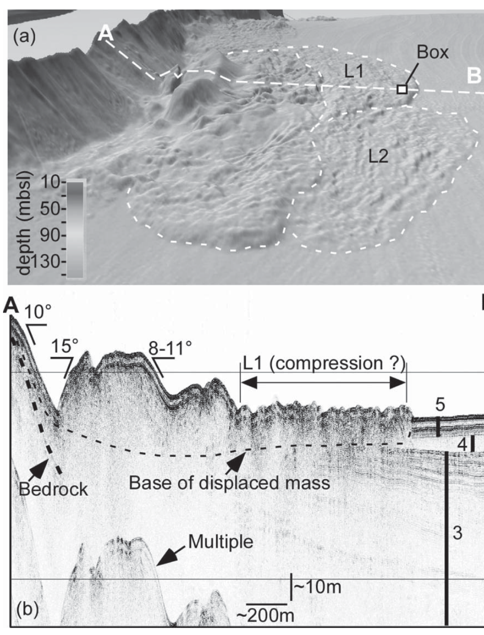

Figure 4. The St. Siméon slide (a) along the northern flank of the North Channel (see Fig. 2b for location) and a sparker seismic line (b) showing the thickness of the debris over the marine deposits.

The interpretation of the seismic survey line (Fig. 4b) suggests that the thickness of the large block is 20 m, while it would be 15 m for the disturbed zone and about 10 m for the lobes. Sliding surfaces may have been controlled by the inclined bedrock (sedimentary rocks) which would be similar to what has been proposed for the earthquake-triggered Saint-Joseph-de-la-Rive slide (Locat 2011).

7 SOUTH FLANK

The South flank of the North Channel presents a smaller amount of slide than the opposite side and most of them appear to be located in front of Cap-au-Saumon (CAS, Fig. 2c). The amount of debris at the toe of the failed slopes is often limited to few ridges (e.g., slide ‘a’ in Fig. 3a) which suggests that most of the debris were eroded away. In all cases, the starting zone can be well identified (slide ‘a’, ‘b’, and ‘c’ in Fig. 3a). Some slide, like slide ‘b’ in Figure 3a present a failure zone which appear draped by a thin layer of sand. This may indicate that slide ‘c’ took place before slide ‘b’ (Fig. 3a).

Slide ‘a’ in Figure 3b has been selected to illustrate the signature of the displaced mass on the South flank of the North Channel (Fig. 5).

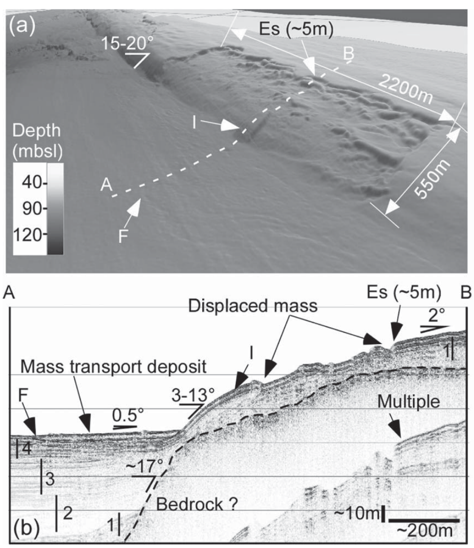

Figure 5. Shallow spread failures on the south side of the North Channel with head scarp (Es) more or less parallel to the slope direction (see Fig. 2c for location). Various slope angles are shown in (b) with seismic interpretation in showing the debris within the failure and some thin debris in the depositional zone at the toe of the slope. It appears that, at the toe, most of the slide debris were eroded away.

The local unfailed slopes show an increase in slope angle as the slope approaches the bottom of the channel with angles varying from 2° near the top close to 20° near the base of the slope (Fig. 5), where the slope is likely controlled by bedrock topography (e.g., Fig. 5b). The slide in ’a’ is typical of a spread failure with remnants of slices over the failure surface. The slide debris have been mostly evacuated from the toe of the slope or have only left a thin veneer of debris (Fig. 5b). From the geometry of the slide, and considering an estimated average thickness of 5 m (using the escarpment, Es in Fig. 5a and b, as a first estimate), the total volume of slide ‘a’ would be about 6 M m^3. The seismic line across the slide (Fig. 5b) may be used to suggest that the failure plane was more or less along or just above a high amplitude (sandy ?) reflector.

8 DISCUSSION

8.1 *Aggravating factors*

From our preliminary analysis of the North Channel of the St. Lawrence Middle Estuary, and the previous work reported above, it is possible to argue that the current erosive nature of the channel and the underlying bedrock morphology play a role in the instability of the submarine slopes in the area. They both contributed to maintain a steep slope more sensitive to environmental forcing such as earthquakes. Although not presented above, seepage forces along the contact between Quaternary sediments and the bedrock may also have been an aggravating factor. On the South flank, the widespread layering, as suggested by the seismic data, may also have provided potential planes for the development of the observed failures (see also Levesque et al., 2006).

8.2 *Triggering by earthquakes*

The well-known seismic activity of the Charlevoix area may be considered as the source of the earthquakes necessary to generate the observed mass movements (Locat 2011). If we were to consider hydrostatic conditions for the pore pressures, significant earthquakes would be necessary to generate failures in normally consolidated sediments lying on slopes as low as 5° (Locat et al., 2003). It could be speculated that the 1663 earthquake (M ~7.5, Locat 2011) may have triggered the observed failures, but the various degree of draping of the debris and the relative position of some displaced mass rather suggest that more than one earthquake has triggered the observed submarine and coastal failures. Dating these events is therefore very important, but challenging as the St. Lawrence Middle Estuary is such an erosive and bed load dominated transport environment. In some cases, it may be possible to use sequential multibeam surveys in order to use sand dunes or sand drift draping rates over the debris to estimate their relative age. Obtaining cores would also be an excellent way to ascertain the age of these slides, but the nature and the strength of the sediments in the St. Lawrence Middle Estuary presents a challenge to the existing piston coring technique available for the scientific community in Eastern Canada. It may require more powerful techniques similar to what has been used with the Marion Dufresne (French vessel) in 1999 (St. Onge et al., 2003).

8.3 *Landslide hazard*

Extensive landsliding already took place along the coastline (the North flank in particular). The timing of these slides is still unresolved, nor is the time and process required to regenerate unstable conditions in the failed areas. It would be interesting to evaluate if the remaining unfailed zone, which have not been disturbed by previous earthquakes, and the already failed zones, may be used to consider that the current slide hazards has been significantly reduced by these previous events. That is to say, what is the residual submarine slide hazard along the North Channel?

Another aspect of hazard assessment is to identify if any of these slide do interact with the sub-aerial part of the coast, as it has been shown in the Betsiamites area by Cauchon-Voyer et al. (2011). Ascertaining this hazard will first require shallow multibeam surveys where submarine slides have already been mapped and on land field investigations.

9 CONCLUDING REMARKS

From the above initial analysis of the submarine mass movement signatures in the St. Lawrence Middle Estuary the following preliminary conclusions can be made:

1. Submarine slide signatures significantly differs on both sides of the North Channel likely due to the type of sediments involved.
2. The erosive environment of the North Channel currently prevents the use of straightforward sedimentological techniques to estimate the age of the sliding events. It is expected that future developments will come by: detailed analysis of the morphology, sequential multibeam surveys, and targeted coring and dating in critical areas, and the development of specific radiogenic tools.
3. The extensive distribution of submarine landslides along the coastline requires further investigations in order to evaluate the potential for some of them to extend on land.
4. Ongoing analyses of the landslide distribution and architecture will also benefit our understanding of the type of failures involved and the triggering mechanism.
5. Further investigations are necessary in order to evaluate the current residual submarine slide hazard.

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