# The Betsiamites-Colombier slides along the St. Lawrence Estuary: linking a 7250 years BP submarine slide to a 1663 coastal landslide

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ABSTRACT
The case of the Betsiamites-Colombier slides is one of the large submarine mass movements in Canada for which some detailed geotechnical investigations were also undertaken, largely because of the slide extension onto the coastal area. It resulted from at least two major slide events which mobilized an estimated total volume of 2000 million $m^3$ (2 $km^3$) of sediments. Linkage between offshore and onshore geophysical investigations with borehole data and in situ testing allows reconstruction of the architecture of the Betsiamites River delta area and leads to the identification of the main failure events. A first landslide dated at 7250 cal BP mobilized a volume of 1300 million $m^3$ over an area of 54 $km^2$: the Betsiamites submarine slide event. It prepared the ground for the second major slide event of February 5$^{th}$ 1663 slide: the Colombier slide. This slide involved four successive failure phases: one submarine (flow) and three subaerial (two flow slides and a spread), for a total volume of about 530 million $m^3$ over an area of 20 $km^2$. The Colombier landslide event is among the largest documented historic landslides in Canada. The presence of submarine scars, left by the early Holocene event, acted as predisposition factors for the development of the failure while the earthquake of 1663 was the main triggering of the Colombier slide.

RÉSUMÉ
Le cas des glissements de Betsiamites-Colombier constitue l'un des plus grands glissements pour lequel une étude géotechnique détaillée existe, rendue possible parce que ce glissement implique aussi une partie terrestre. Cette grande signature est le résultat de deux glissements de terrain totalisant un volume total de sédiment de 2000 millions de $m^3$ (2 $km^3$). Le lien entre les investigations géophysiques marines et terrestres ainsi que les données de forages ont permis la reconstruction des principaux événements. Un premier glissement, daté de 7250 cal BP a mobilisé un volume total de 1300 millions de $m^3$ sur une superficie de 54 $km^2$ : l'événement de Betsiamites. Cet événement a de plus préparé le terrain pour le deuxième qui s'est produit le 5 février 1663 : l'événement de Colombier. Cet événement comprend quatre phases dont une marine (écoulement) et trois subaériennes (2 écoulements et une étalement) pour un volume total de 530 millions de $m^3$ sur une superficie de 20 $km^2$. Le glissement de Colombier est un des plus grands glissements historiques qui ait été documenté. La présence d'escarpements sous-marins, laissés par l'événement holocène, a agi comme facteur de prédisposition pour le glissement de Colombier alors que le séisme de 1663 en aurait été le déclencheur principal.

## 1 INTRODUCTION

The North Coast of the St Lawrence Estuary (Quebec, Canada) exhibits many areas with subaerial and submarine landslide scars. The largest scars are identified in the vicinity of the Betsiamites River delta, close to the municipality of Colombier, about 400 km northeast of Québec City (Fig. 1). The Betsiamites-Colombier slides scar extends over more than 64 $km^2$ continuously in the subaerial and submarine environments. Detailed analyses of the morphology and lithostratigraphy of the Betsiamites-Colombier slides area showed that this landform resulted from two separate major landslide events (Bernatchez 2003; Cauchon-Voyer et al. 2008; Cauchon-Voyer et al. 2011).

The first major submarine event landslide, thereafter named Betsiamites slide event, dated at 7250 cal BP, mobilized a minimum volume of 1300 million $m^3$ (1.3 $km^3$). The triggering of the slide is not known but has been assumed to be from an earthquake (Cauchon-Voyer et al. 2008). The deposition of the debris for this early Holocene slide was dated by mapping seismic reflections from the top of the debris accumulation to the location of core MD99-2220 ~15 km away in the Laurentian Channel where a chronostratigraphy is available (St-Onge et al. 2003; Cauchon-Voyer et al. 2008).

The second major event, the Colombier slide, took place in 1663 both in the submarine and subaerial environments and is found just upslope of the 7250 cal BP Betsiamites slide scar. It was triggered by the 1663 earthquake. Following a morphostratigraphic analysis of the area, it is also concluded that the Colombier slide involved four successive failure phases: one submarine and three subaerial (Cauchon-Voyer et al. 2011).

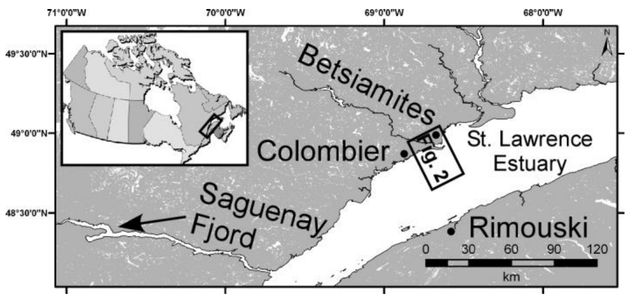

Figure 1. Map of the study area

The 1663 earthquake first triggered a submarine slide, which reached the shoreline and led subsequently to three subaerial failure phases: two flowslides in sensitive clayey material and one subaerial lateral spread. The four failure phases, which have influenced the subaerial and submarine domains in 1663, have mobilized a total volume of more than 530 million $m^3$ over an area of 20 $km^2$. The volume involved solely in the 3 subaerial failure phases is estimated at 385 million $m^3$. The debris of the 1663 Colombier slide event, i.e., those that evacuated the subaerial scar, accumulated in the 7250 cal BP Betsiamites submarine landslide scar. According to Cauchon-Voyer et al. (2008), although these two slide events are more than 6800 years apart, the relative difference in sea levels was less than 10m compare to the actual sea level.

The purpose of this paper is to present this well documented case history of a large landslide scar in Eastern Canada known to have been the results of a sequence of submarine and subaerial movements with a 1663 slide partly rooted in a 7250 y BP slide event scar. Such a study also has a great interest for evaluating the threat for coastal highways and infrastructures due to submarine mass movements and their consequences. By doing so, this paper presents a rare example of the coupling of both marine and subaerial geo-investigation techniques.

## 2 METHODS

The analysis follows the integration of an extensive subaerial and submarine dataset (Figure 2) The subaerial digital elevation model (DEM) of the landslide area was derived at a 1 m resolution from airborne laser scanning (LIDAR) and hypsometric lines at 1 m contour interval obtained from photogrammetry on 1:15000 aerial photos. The submarine DEM is derived from high-resolution bathymetric surveys. A 5.2 km-long subaerial seismic reflection survey was carried out on the current beach and allowed the definition of the coastal seismostratigraphy (Cauchon-Voyer et al. 2011). In addition, more than 750 km of seismic reflection survey allows the reconstruction of a seismostratigraphic model of the submarine seafloor and underlying deposits. Methodological details on the subaerial LIDAR, submarine bathymetric surveys, and subaerial and submarine geophysical data can be found in Cauchon-Voyer et al. (2008; 2011).

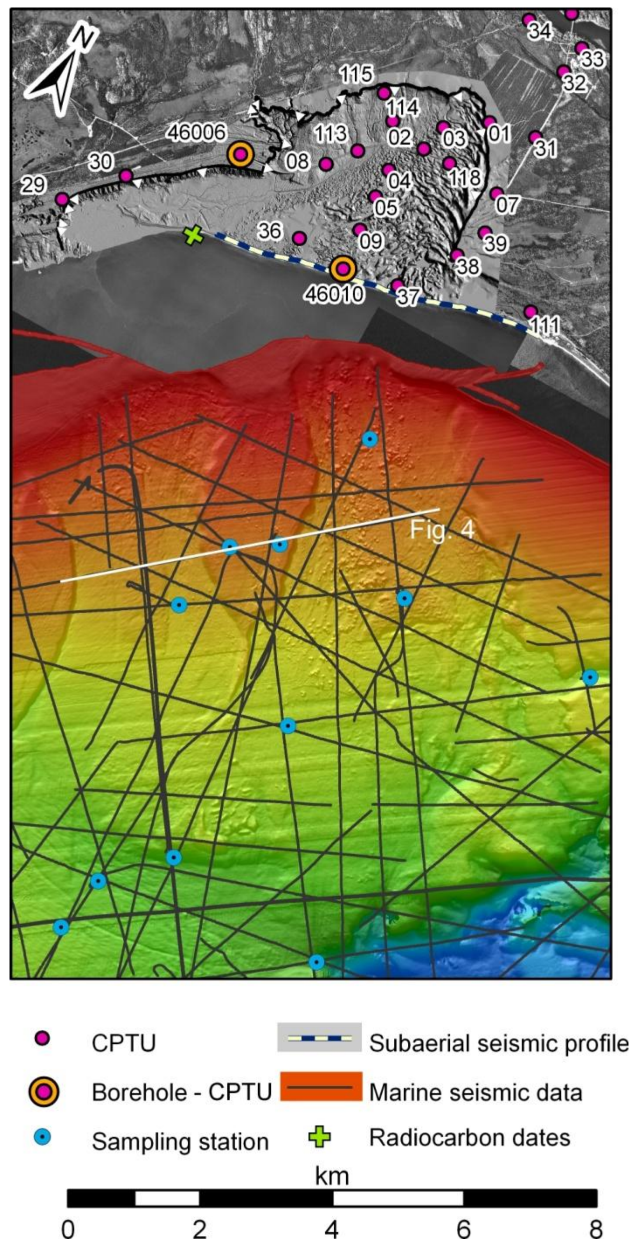

Figure 2. Investigation carried out in the subaerial and submarine area of the Betsiamites-Colombier slides. Numbers refer to CPTUs and 46006 and 46010 to boreholes.

Two (2) boreholes were drilled in the area (see location on Figure 2). Borehole 46010, to a depth of 58.9 m, is located in the accumulation zone of the Colombier subaerial landslide scar at a distance of 75 m behind the shoreline. One of the objectives for this borehole was to tie the coastal stratigraphy to the marine stratigraphy and also to provide a geotechnical description of the main stratigraphic units. Borehole 46006, to a depth of 54.4 m, was drilled 400 m behind the escarpment of the Colombier subaerial landslide scar at an elevation of 47.6 m to characterize the main units involved in the 1663 slide. Samples were recovered and natural water contents, grain size distribution, shear strength measured with the Swedish fall cone, Atterberg limits, and preconsolidation pressures were subsequently measured. Thirty-eight (38) piezocone tests with pore water pressure measurement (CPTU) were carried out on land (Figure 2).

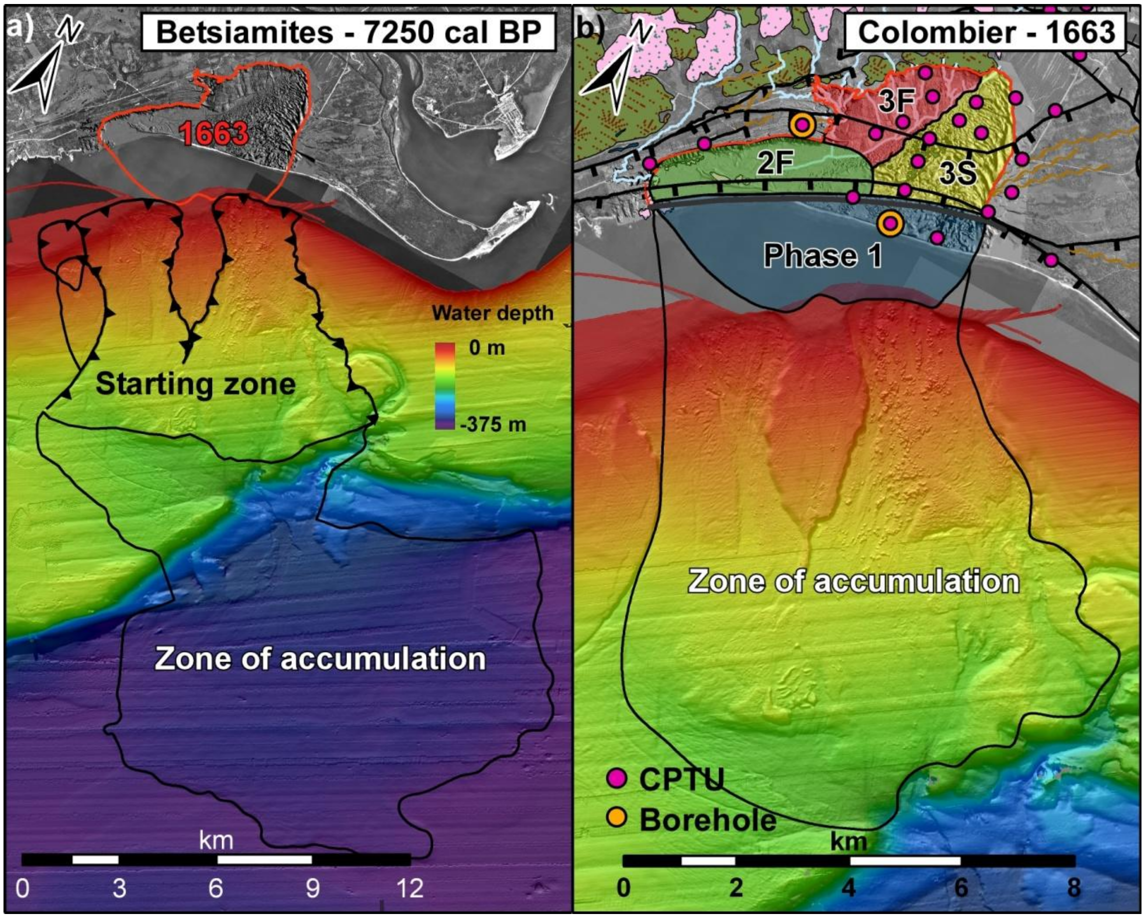

Figure 3. Boundaries of the Betsiamites-Colombier slides (see Figure 2 for symbols definition).

The linkage between the various units is based on a seismo-stratigraphic model proposed by Syvitski and Praeg (1989) for the St. Lawrence Estuary that are described in details by Cauchon-Voyer et al (2008) and summarized as follows. From the base to the top we find: unit 1: made of ice contact sediments (e.g. till), unit 2 consisting of ice proximal sediments (coarser unit, e.g. glacio-fluvial), unit 3 made of ice distal sediments (fine-grained), unit 4 being paraglacial sediments consisting of highly stratified sediments deposited during time of rapid sedimentation and finally unit 5 consisting of post-glacial sediments mostly fine grained.

## 3 AN HISTORY OF LANDSLIDES

The Betsiamites-Colombier slides impacted both the subaerial and submarine environments. Figure 3 presents the boundaries of both slides, their starting and accumulation zones. In the following paragraphs we will present the history of these two slides in an attempt to illustrate how the Betsiamites slide prepared the ground for the Colombier slide. We will also describe how the 1663 Colombier slide developed in the four phases leading to the actual scar morphology.

### 3.1 The 7250 cal BP Betsiamites slide event

The Betsiamites slide left a 54 $km^2$ landslide scar on the shelf, with two main topographic depressions: the West and the East depressions, separated by an intact butte with steep flanks and flat top (Fig. 3). The scar was later partly filled with debris of the 1663 Colombier slide that are well seen on the seafloor (Fig. 3b) and also on the seismic profile (Fig. 4). It is assumed that the Betsiamites submarine scar resulted from one event dated at 7250 cal BP, and it may have resulted from more than one failure phase, which is not possible to distinguish at this time. Both depressions have widths ranging from 2 to 4 km, lengths of 7 km, and floor slopes of about 1°. The height of the flanks to the seafloor of both depression ranges from 12 to 20 m. The butte is 5 $km^2$ in area with a maximum length and width of 4.5 km and 1.6 km respectively (Fig. 3). The average slope of the top of this butte is 1°. The depressions and the butte are overlain by 3 to 10 m of the Colombier subaerial landslide debris (Fig. 4). The scar of the Betsiamites slide extends from -10 m to -140 m.

At the time of the large submarine failure, relative sea level had reached more or less its present level (Dionne 2001; Bernatchez 2003). A seismic reflection analysis (Cauchon-Voyer et al., 2008) demonstrated that the failure surface developed along a well defined layer (R1, Fig. 4) within the stratified clayey silt and thin sand layers unit (unit 4 in Figs. 4 and 5).

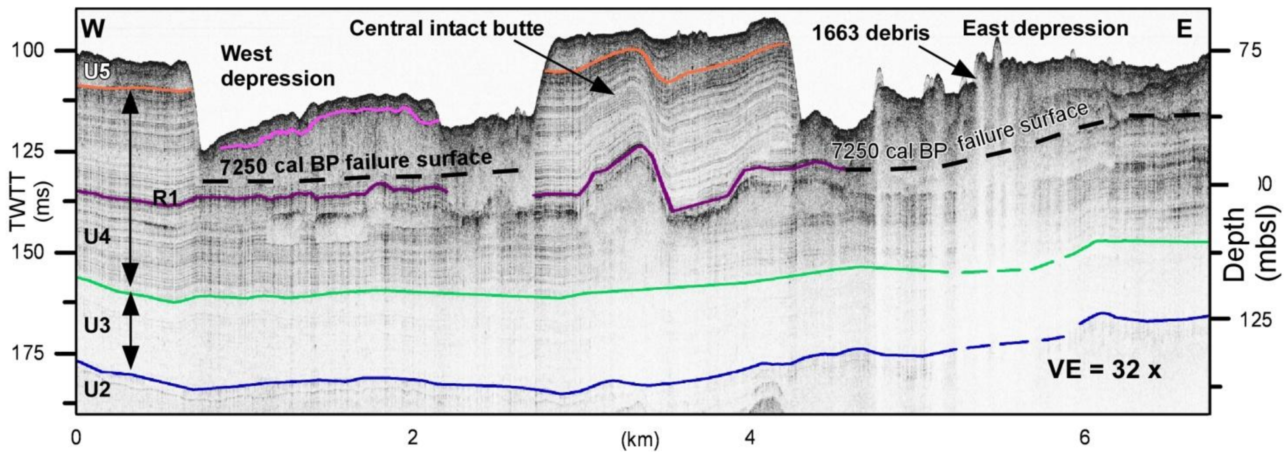


Figure 4. Seismic profile across the butte showing the various stratigraphic units and the accumulation of debris in both depressions and on the butte (see Fig. 2 for the location of the seismic line). Units U2 to U4 are also described on the geotechnical profiles in Figs. 5 and 8.

The current post-slide sediments covering the failure surface are mostly composed of the Colombier slide debris as we will see later. This indicates that the Betsiamites slide debris were largely remolded by the sliding mechanism and flowed away from the scar onto the existing seafloor of the deeper part of the Estuary. The debris coming from the Betsiamites slide formed the large depositional lobe observed at an average water depth of 350 m and covering an area of about 104 $km^2$ (Fig. 3a). It has a maximum width of 15 km and an average thickness of 9.4 m, thus has an estimated volume of ~1 $km^3$. Seismic profiling and samples recovered from the lobe area indicate the presence of a few cm-thick turbidite layer associated with the 1663 Colombier landslide event on top of hemipelagic sediments covering the 7250 cal BP debris. The debris originating from the Betsiamites slide are underlain by part of stratigraphic Unit 5 and their deposition was dated by mapping seismic reflections from the top of the debris accumulation to the location of core MD99-2220 ~15 km away in the Laurentian Channel where a chronostratigraphy is available (St-Onge et al., 2003). Duchesne et al (2003) and Cauchin-Voyer et al. (2008) reported smaller submarine slides signatures few kilometers to the East but they are not dated yet. Following the Betsiamites slide, there appears to be no mass movement events with a similar magnitude until 1663, so that in the area, hemipelagic sedimentation and shoreline erosion, transport and sedimentation were taking place during that period.

3.2 The 1663 Colombier slide

Various morphological indications suggest that several failure phases occurred at different times in the Betsiamites River area (subaerial domain). The integration of the results indicates that the final morphology of the large Colombier subaerial scar was the result of a complex slide initiated by the 1663 earthquake. The various elements related to this slide are presented in Figures 3 to 9.The morphological analysis will show that the final morphology of the 1663 Colombier slide event resulted from four related failure phases which all probably occurred one after the other over a short period of time (hours or days).

The interpreted subaerial topography prior to the 1663 Colombier slide event is shown in Figure 6 and characterized by two main terraces, at elevation of 60 and 40 m (Cauchon-Voyer et al. 2011). The elevations of the terraces are interpreted taking into account the orientation of the remaining terraces on both sides of the landslide scar and of the raised beach observed outside the scar. The ground surface on the upper terrace is almost flat with slope angle between 0.5 and 2°.

Prior to the 1663 failures, the back escarpment of the Betsiamites slide event was located at water depth of -10 m (Fig. 6). Part of this escarpment is still preserved immediately east of the Colombier landslide scar and has a slope angle of 8° and an average height of 25 m (pointed by an arrow in Fig. 7).

It is interesting to note that from this morphological reconstruction, borehole 46010 would have been offshore if it had been drilled prior to the slide, indicating the shoreline moved seaward as a result of the slide. At this borehole site, the failure surface has been identified with the piezocone to be at an elevation of -8.0m (Figure 5).

The sequence of events leading to the four failure phases, shown in Figure 7, is presented hereafter and the reader is referred to the Cauchon-Voyer et al. (2011) for more details.

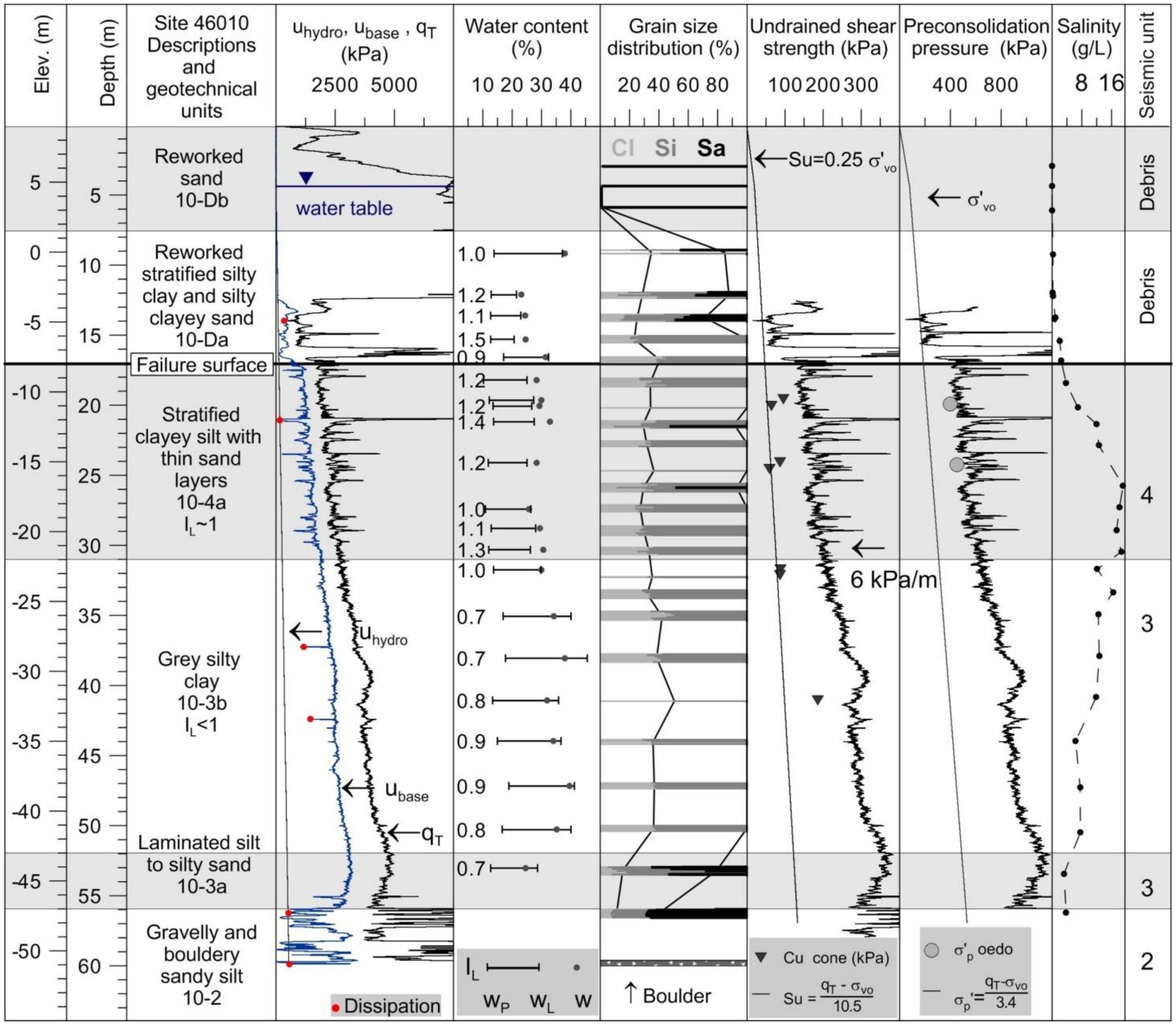

Figure 5. Geotechnical properties of borehole 46010.

*Phase 1*

Phase 1 occurred first underwater and mobilized part of the beach to an approximate location between the actual shoreline and the 40 m terrace (Fig. 6). Prior to this submarine failure, the 8º and 20 m high upper escarpment of the 7250 cal BP Betsiamites landslide scar probably followed the -10 m contour line. Presumably, the 1663 earthquake liquefied a sandy layer emerging in the submarine headwall at a water depth of -40 m. This planar failure probably reached above the current shoreline up to at least the location of the coastal soundings 36, 10 and 37 (Fig. 2). On those shoreline CPTU soundings, the subaerial landslide debris deposits are interpreted at elevations ranging between -13.5 and -6 m. Large blocks of deformed and rotated sediment beds are also observable on the beach at low tide. The space below the current shoreline must have been made available for debris spread prior to the subaerial failure, hence supporting the hypothesis of a submarine failure occurring first. More than 145 million $m^3$ of material were mobilized over an approximate area of 9.3 $km^2$, which implies an average thickness of 15.6 m for the submarine landslide body.

It is difficult, on the basis of available data, to define the exact lateral extension of the 1663 Colombier submarine failure (Phase 1). The back escarpment of the 7250 cal BP Betsiamites event in the East depression was partly destroyed by this submarine failure, which provides an approximate southern boundary. However, the absence of an escarpment on the bathymetric map in the West depression could suggest that: (1) the Colombier submarine failure also occurred on the crest of the Betsiamites submarine scar in the West depression and eroded this escarpment; or (2) the debris of the Colombier subaerial failures simply covers the back escarpment of the Betsiamites submarine scar. The rotated and deformed blocks along the shoreline extend at least to the proposed boundary of the submarine failure (Phase 1). As a result, the volume estimation of 145 $hm^3$ for the submarine slide involves some uncertainties.

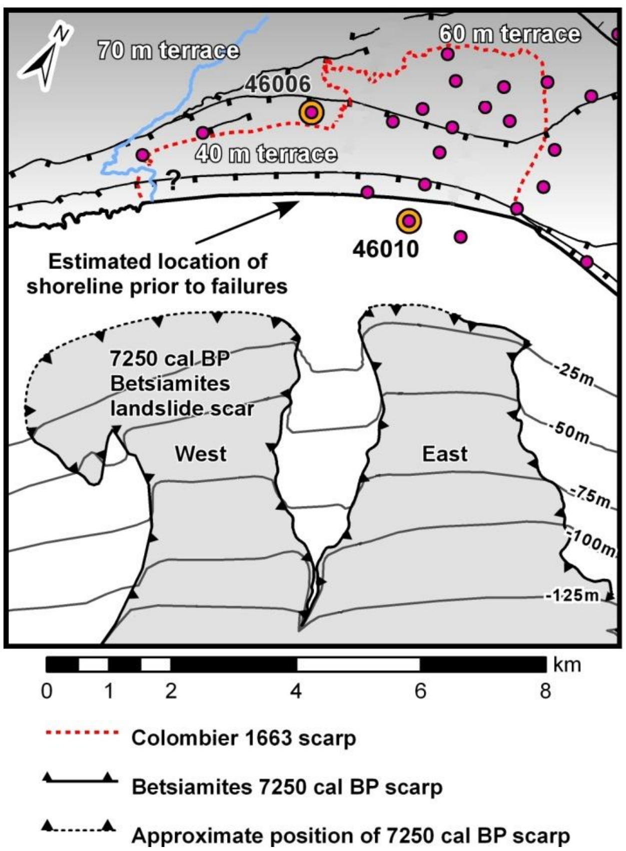


Figure 6. Interpreted topography prior to the 1663 Colombier slide event (see Figs. 2 and 3 for symbols definition).

It is important to take into consideration that the failure developed in a clayey silt unit (geotechnical 10-4a, in Figure 5) within which many thin silt and sand layers are observed and that it may have played an important role in the failure development. Dan et al. (2009 ) demonstrated, with an example from the Algerian margin, that thin sand and silt beds were the main cause of sediment deformation and liquefaction during earthquakes and this could have occurred from the Colombier submarine failure. Similar observations were obtained in the laboratory by Konrad and Dubeau (2003). This phenomenon can also be emphasized by the fact that the water becomes trapped between impermeable sublayers of clayey material. Kokusho (1999) demonstrated that this behaviour can occur under seismic loading and lead to a soil mass that may glide above a water film. This mechanism may have played an important role in the generation of the submarine failure (Phase 1). Similarly, Levesque et al. (2006) showed in the Saguenay Fjord that many earthquake triggered failures occurred along bedding planes and led to the nearly complete removal of material above the rupture surface.

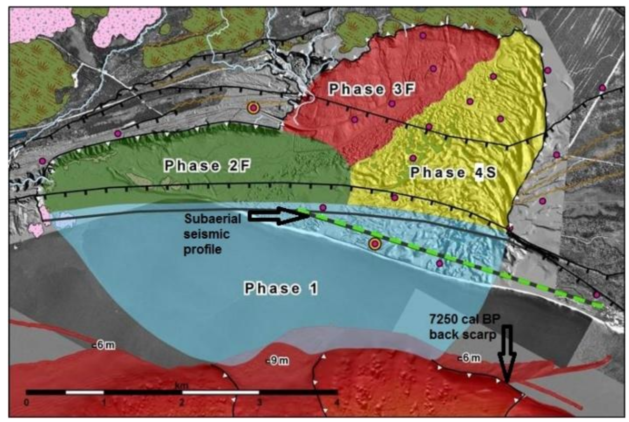


Figure 7. Landslide extent and failure phases of 1663 Colombier slide event. The Colombier slide event involved four successive failure phases: one submarine and three subaerial (see Figs. 2 and 3 for symbols definition).

*Phase 2F*

Shortly after the submarine failure (Phase 1), it is interpreted that a large subaerial flowslide (Phase 2F, F for flowslide) developed in the West zone. The 40 m marine terrace is truncated by the western flank (Fig. 7) of the flowslide. This truncation provides the main evidence to interpret that this area was eroded by a flowslide. The bedrock outcrops on the shoreline and is also found at about -10 m at site 46006 (Fig. 2). The presence of bedrock implies that the rupture surface could not be much lower than sea-level. The height of the back escarpment of the landslide is about 45 m. The liquidity index of the soil in the upper portion of the slope (6-L4a and 6-L3c in Fig. 8) is above 1.2, which likely facilitated development of a flowslide (e.g., Leroueil et al. 1996). If it is assumed that the rupture surface developed only on land and stopped at the shoreline and that the rupture surface was at sea-level. The estimated volume for this phase of the subaerial landslide is about 130 million $m^3$. The retrogression distance from the interpreted shoreline ranges between 800 and 1200 m. This section of the subaerial scar has an area of 3.4 $km^2$ and an average width of 3.1 km. Landslide debris appear totally evacuated from the subaerial scar and flowed into the estuary which is consistent with the fact that it was a flowslide. On the marine seismic profile, the layer of debris related to this event is interpreted to be less than 10 m thick, thus less than 22% of the initial slope height (Fig. 4).

*Phase 3F*

After Phase 2F, a second flowslide (Phase 3F) developed in the Central zone. Flowslide 2F acted in fact as an initial failure leaving an unstable backscarp in which flowslide 3F developed. The estimated area for flowslide 3F is 2.5 $km^2$ and the maximum retrogressive distance was likely between 2600 and 3000 m.

The volume of displaced material in this area of the subaerial scar is 75 million $m^3$. The debris of flowslide 3F moved westward into the open space created by flowslide 2F and into the scars of the submarine failures of 1663 (Phase 1) and 7250 cal BP. Only a 3-4 m thick layer of debris remains in the Central area of the subaerial scar, confirming that this phase is indeed a flowslide. Four CPTUs were carried out in the upper west Central area. Refusal was met at depths between 14.6 and 22.8 m, which is generally shallower than the soundings carried out in the East zone, suggesting that the bedrock is not as deep in this area.

Few uncertainties remain with regard to the exact position of the rupture surface. It appears that the rupture surface of flowslide 3F was actually above the shoreline and did not follow the same level as the rupture surface of the submarine failure (Phase 1) or the West flowslide 2F. The rupture surface of the central flowslide 3F is interpreted to be at an elevation of 7.3 m on CPTU 08, which was carried out at an elevation of 11.1 m. The location of the rupture surface indicates that the 8 m high escarpment left in the western portion of the central scar (pointed by a black arrow in Fig. 9) could be in fact the lower part the headwall of the west flowslide 2F and where, subsequently, the rupture surface of Phase 3F came into light. The transition of $I_L$ >1 and $I_L$ <1.2 occurs at about 18 m at borehole site 46006 (Fig. 8), 400 m west of the escarpment of Phase 3F with a rupture surface located at 7.3 m at the position of CPTU 08. The surface between this transition at borehole 06 and the rupture surface at site 08 makes an angle of 0.4°. This surface which corresponds to a significant change in liquidity index could potentially correspond to the plane of retrogression of the failure for Phase 3F.

Four main conditions must be met to develop a flowslide in fine grained material (Tavenas 1984; Leroueil et al. 1996; Leroueil 2001). First, there must be an initial slope failure leaving an unstable backscarp in the slope. For example, this first failure can be initiated by an external trigger such as earthquakes or erosion. Then, (2) the material of the slope must have the ability to be remolded. A $I_L$ > 1.2 and $cu_r$ < 1 kPa is required to allow the remoulded material to flow (Leroueil 2001). This depends, in part, on (3) the height of the slope ($H$) as it controls the potential energy available for remoulding. It also depends on the mechanical and physical characteristics of the material such as its plasticity and undrained shear strength. For an $I_p$ ~10, the soil characteristics act as predisposition factor for failure given by a stability number $\gamma H/cu$ > 4 (Leroueil 2001). Finally (4), the topography must be favourable to allow the failed mass to flow outside the landslide scar.

The morphology of the scar area indicates that the rupture surface of the west flowslide 2F is interpreted to be more or less at sea-level in material with $S_u$ of about 200 kPa (geotechnical unit 6-3a on Fig. 8). Stability analyses demonstrated that seismic forces are apparently required to bring the slope to failure (Cauchon-Voyer, 2011). This failure could either have resulted from the initial earthquake or a following aftershock. In fact, historical accounts reveal that the 1663 earthquake had few aftershocks in the following hours and days, and could potentially have liquefied a thin layer of sandy material in the laminated clayey silt unit (unit 6-3a in Fig. 8). This analysis also suggests that for Phase 3F, it is possible that the submarine failure did not necessary played a direct role as it may have done for failure 2F.

According to the geometry of the rupture surfaces, flowslide 3F probably developed quickly as a result of flowslide 2F. In fact, a remnant escarpment was identified within the scar (pointed by a black arrow in Fig. 9). Flowslide 2F hence acted as first failure for flowslide 3F. In addition, for a stability number of 4, with a bulk density ($\gamma$) of 19 kN/$m^3$ and average shear strength ($S_u$) of 150 kPa, as it is the case for the slope prior to flowslide 3F, the minimal height that would remould the clay is 31.5 m. For flowslide 3F, the height of the slope above the rupture surface is about 35 m and implies that the slope met the elevation potential energy requirement. In addition, the material involved in failure 3F (6-4a and 6-3c in Fig. 8) has a liquidity index greater than 1.2, implying that it gets easily remoulded and has the ability to flow outside the landslide scar into the estuary. Both geotechnical units on borehole 46006 between 42 and 18 m (6-4a and 6-3c) have a $I_L$ > 1.2 and $cu_r$ < 1 kPa (Fig. 8).

The rupture surface of flowslide 3F was identified at an elevation of 8 m on CPTU 08. If this elevation is compared to the elevation of changes in index properties at the location of borehole 46006 (Fig. 8), it is possible to suggest that change in $I_L$ controlled the development of the rupture surface. The Phase 3F rupture surface hence could have propagated over a low angle of 0.4°in sensitive clayey sediments (6-4a and 6-3c) and left intact the soils below having a higher resistance and a lower sensitivity (units 6-3b and 6-3a). Since the deposits above the rupture surface are highly sensitive ($I_L$ > 1.2) they easily flowed out of the scar once remoulded. After a first failure, the new exposed back scarp was unstable, failed, and then liquefied to lead to further retrogressive failures. The final halt was apparently controlled by the stratigraphy when the rupture surface reached the coarser sediments draping the bedrock. Finally, in this case, the topography was favourable for the evacuation of the liquefied clay. The space at the toe of the slope was already cleared by the first submarine failure (Phase 1) and the debris could disperse without constraint in the Estuary.

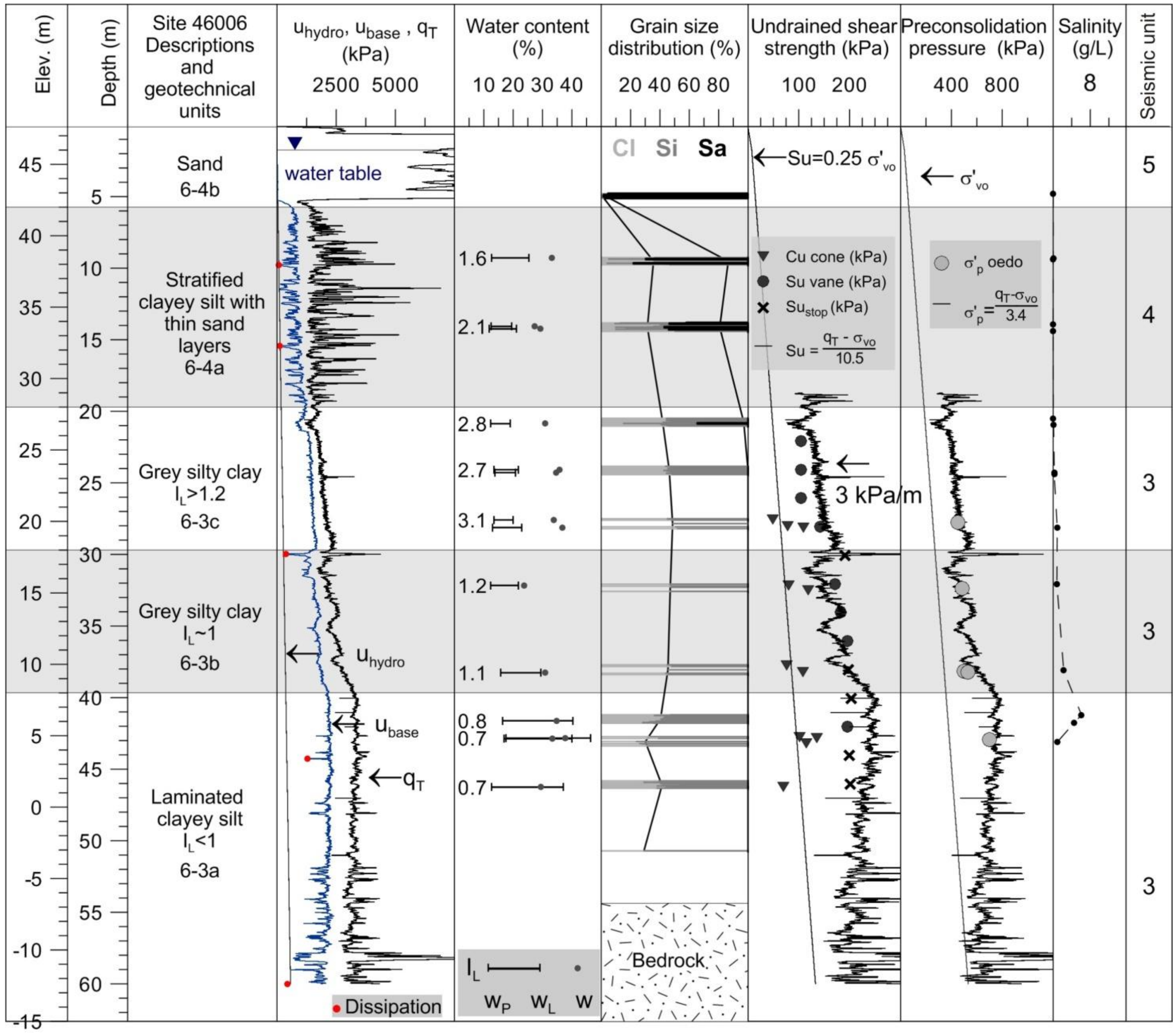


Figure 8. Geotechnical properties of borehole 46006.

*Phase 4S*

As a result of the destabilization of the shoreline by the 1663 Colombier submarine failure (Phase 1) and associated flowslides 2F and 3F, Phase 4S (S for spread) occurred. Flowslide 3F and the lateral spread of Phase 4S probably occurred more or less simultaneously but the remoulded material of the flowslide 3F must have evacuated the scar more rapidly and pushed towards the East the sandy and stiffer blocks of spread 4S (green and yellow ridges on Fig. 9). The boundary between the Phase 4S and 3F is approximate and based on the morphology of the debris remaining in the scar. The debris remaining in the scar of the lateral spread 4S are characterized by a repetitive pattern of ridges (horst) and troughs (graben) mostly oriented perpendicular to the direction of movement, which is typical of lateral spreads (Cruden and Varnes 1996).

Few blocks of clayey material moved underwater toward the central butte and in the West depression of the 7250 cal BP Betsiamites landslide scar, but most of the blocks are found in the East depression. It is thought that these clayey soils were initially between the rupture surface and the sandy layer (U4-sand, 6-L4b in Fig. 8) above and were extruded under the weight of the sand layer. The maximum distance between the location of the interpreted location of the back scarp left by the submarine slide (Phase 1) and the back escarpment of the spread (Phase 4S) is 2600 m. The approximate width of the landslide body of Phase 4S is about 1300 m. CPTU 118 is the only sounding directly in the center of the lateral spread and shows the rupture surface to be at least at an elevation of -13 m. In fact, since the area has a complex lithostratigraphy and there is no core validation, it is difficult to define exactly the position of the rupture surface on CPTU 118. The area of the lateral spread 4S is about 3.7 $km^2$ and mobilized an estimated slide volume of 180 million $m^3$.

The rapid extrusion of the material involved in Phase 4F must imply that the first submarine failure (Phase 1), which occurred as a result of the 1663 earthquake, unloaded rapidly the toe of the subaerial slope. If it is assumed that the submarine failure stopped close to the location of the previous shoreline, an undrained back-analysis indicated that the newly exposed subaerial slope in the eastern portion of the scar (25°) is unstable with a factor of safety of 0.95 (Cauchon-Voyer, 2011). As for the submarine failure, it is important to realize that the failure developed in a unit of stratified sediments and could have behaved as ''weak'' layers during an earthquake (Locat et al. 2014). Sensitive clay spread: Extremely rapid lateral spreading of a series of coherent clay blocks, floating on a layer of remoulded sensitive clay (Locat et al. 2011; Hungr et al. 2013). In addition, according to Cruden and Varnes (1996), spread may result also from the liquefaction or flow (or extrusion) of softer material overlain by a stiffer layer. The movement is translational and leads to a general subsidence of the overlying mass into the softer underlying material. In the case of the Colombier spread (Phase 4S), the upper sandy layer prior to failure was dense. Therefore, after failure, the large blocks of coarser material rapidly sanked into the remolded layer of silty clay layer, forming grabens and generating a massive and rapid extrusion of material into the estuary. In fact, a thickness of more than 40 m of soil is missing in the upper portion of the landslide scar and more than 30 m in the lower portion of the slope. In the upper portion of the scar, CPTU 02 was carried out at an elevation of 18.8 m, and the elevation of the terrain prior to failure was estimated at 60 m, which demonstrates the powerful extrusion of material that prevailed since 40 m of soil is missing. In fact, it was established that most of the debris remaining in the scar are sandy material (Cauchon-Voyer et al. 2011) as demonstrated by thickness up to 40 m. It is also possible that, in addition to the initial failure in the clayey layers (layers 3 and 4 in Fig. 8), the overlying sandy layer acted as a weight (e.g. piston) helping the clayey material to get remolded and facilitated even more the extrusion of material from the slope into the Estuary in the space opened by the submarine slide (Phase 1).

The significant velocity of the material extruded onto the sea floor at Phase 4F is illustrated by the large debris deposits found in the eastern depression left by the Betsiamites slide. Some more or less intact blocks from Phase 4F sled as far as 6 km over the central butte on a slope of about 1° (Fig. 9b). The sandy block are also visible on seismic line in the East depression (Fig. 4).

## 4 CONCLUDING REMARKS

The prediction of landslide activity along the coast of the St. Lawrence Estuary and the evaluation of the potential for submarine failures to reach the current shoreline is significant and should be integrated in geohazard mapping and coastal planning. This reconstruction of the sequence of landslide events shows that the Betsiamites slide did prepare the ground for the 1663 Colombier slide by providing a steep submarine escarpment quite close to the shoreline. The Colombier slide had to be initiated underwater in order to provide a free space for the debris of phase 3 and 4 to evacuate on the seafloor. It is therefore clear that the 1663 submarine failure had to retrogress upslope and in order to destabilize the subaerial shoreline, which subsequently caused a large multi-component subaerial landslide (Phase 2 to 4).

In this case, the stability of the slope prior to 1663 failure events was reduced by the presence of the 7250 cal BP Betsiamites submarine scars that acted as a predisposition factor by changing the general geometry of the slope. Mapping of previous shallow submarine scars should hence be integrated in subaerial landslide analysis along a coastline.

Considering the volume of the sediment involves in these slide, future work will look into their tsunamigenic potential and potential traces left in the nearby coastal areas on both sides of the St. Lawrence Estuary.

In summary, this investigation of the coastal instabilities in the Betsiamites River delta area enabled the identification of a landslide complex of 74 $km^2$ in the subaerial and submarine domains. The Betsiamites submarine landslide event dated at 7250 cal BP, mobilized a volume of 1.3 $km^3$ over an area of 54 $km^2$. The Colombier landslide was initiated by the 1663 earthquake, which involved 4 successive failure phases: one submarine and three subaerial. The total volume of material mobilized in 1663 is 530 million $m^3$ over 20 $km^2$, which is among the largest documented subaerial landslides in Canada.

## ACKNOWLEDGEMENTS

The authors wish to thank the Ministère des Transports du Québec (MTQ), NSERC and FQRNT for their financial support. We thank the MTQ for the permission to use their topographic and LIDAR surveys, borehole, and piezocone soundings data of the Colombier - Betsiamites area, and in particular to D. Robitaille and P. Locat for their involvement in the project. We recognize the contribution of Patrick Lajeunesse and all scientists and crew members on board the Coriolis II, F.G. Creed, and Guillemot vessels. The Canadian Hydrographic Service and GSC-Quebec are also acknowledged for their contribution to bathymetric data acquisition.

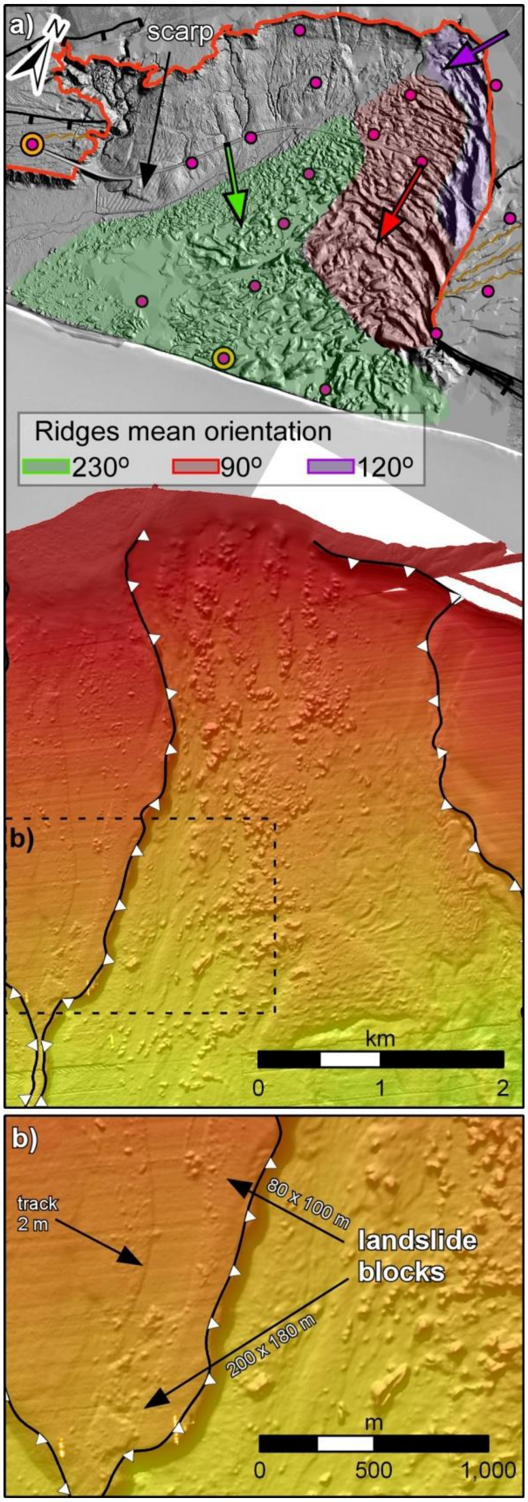

Figure 9. Morphology of the debris within the subaerial and submarine landslide scars. a) Arrows indicate the direction of the movements of the subaerial ridges, which are assumed perpendicular to the orientation of the ridges. b) .Subaerial blocks dispersed underwater. On the central butte, the blocks produced an erosion glide track about 1-2 m deep. (see Fig. 2 for symbols definition).

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