GÉORISQUES IV GEOHAZARDS

# MORPHOLOGICAL AND STRATIGRAPHIC ANALYSIS OF THE COLOMBIER LANDSLIDE AREA, QUÉBEC

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RÉSUMÉ
Une cicatrice de glissement de terrain subaérien de 6.5 $km^2$ est identifiée dans les sédiments quaternaires situés à l'ouest du complexe deltaïque de la rivière Betsiamites, près de la municipalité de Colombier, sur la Côte-Nord de l'estuaire du St-Laurent au Québec. Une analyse morphologique et stratigraphique du secteur du glissement de Colombier, intégrant des données morphologiques, des résultats d'essais au piézocone et des interprétations d'une campagne de sismique réflexion, a été entreprise afin de définir les caractéristiques de glissements de terrain. Trois zones générales avec différentes caractéristiques géomorphologiques ont été définies dans la cicatrice de glissement: la zone Ouest avec un terrain en pente sud-ouest régulier, la zone Est avec une succession des crêtes allongées et de dépressions et finalement la zone d'accumulation de débris qui semble être le prolongement des débris dans l'Estuaire. La stratigraphie du secteur se compose de dépôts aux caractéristiques variables latéralement, résultant d'épisode de glissements de terrain et de la progradation deltaïque lors de la dernière phase régressive du niveau marin relatif. Quatre unités sismostratigraphiques et un réflecteur avec un fort contraste d'impédance acoustique, interprété comme la roche en place, ont été identifiés sur la section de sismique réflexion obtenue sur la plage. Trois de ces unités sismostratigraphiques corrèlent potentiellement avec 3 couches de sol identifiés par les essais au piezocone.

ABSTRACT
A 6.5 $km^2$ subaerial landslide scar is identified in the Quaternary sediments located west of the Betsiamites River deltaic system at Colombier, on the north shore of the St. Lawrence estuary in Québec. A morphological and stratigraphic analysis of the Colombier landslide area, integrating morphological data, piezocone data and results from a seismic reflection survey, has been initiated in order to define the characteristics of the slope failure events. Three general zones with different geomorphological characteristics within the subaerial landslide scar were defined: the West zone with a regular southwest sloping terrain, the East zone with succession of elongated ridges and depressions and finally the accumulation zone of the landslide which likely appears to be an extension of the landslide debris in the Estuary. The stratigraphy of the area consists of deposits with laterally variable characteristics resulting from landslide events and deltaic progradation during the last relative sea-level regressive phase. Five seismic units and a reflector with a strong acoustic impendence contrast, interpreted as the bedrock, were identified on a seismic section obtained on the beach. Three of these seismostratigraphic units potentially correlate to 3 soil layers identified in the piezocone soundings.

## 1. INTRODUCTION

Numerous landslides have occurred in Eastern Canada in the sediments deposited following the retreat of the Laurentide Ice Sheet. These deposits are mostly located in the coastal areas around the St. Lawrence River valley (Fig. 1), where most of the population is gathered. Landslides constitute a risk for the population as well as for man-made infrastructures and the Colombier landslide is a striking example of the destructive potential of such events. The 6.5 $km^2$ Colombier subaerial landslide scar is located in the Quaternary sediments 3 km west of the Betsiamites River on the North Shore region of the province of Quebec. Highway 138, which is the main road and lifeline on the North Shore of Quebec, runs directly across the landslide scar (Fig. 2). This subaerial landslide scar is likely to be the second largest known to have occurred in the province of Quebec, after the 1663 St-Jean Vianney landslide (Lasalle and Chagnon, 1968). Understanding the triggering factors for mass movements in this coastal environment is necessary for landslide risk assessment on the Quebec North Shore in the area in order to identify similar environments along the St. Lawrence Estuary.

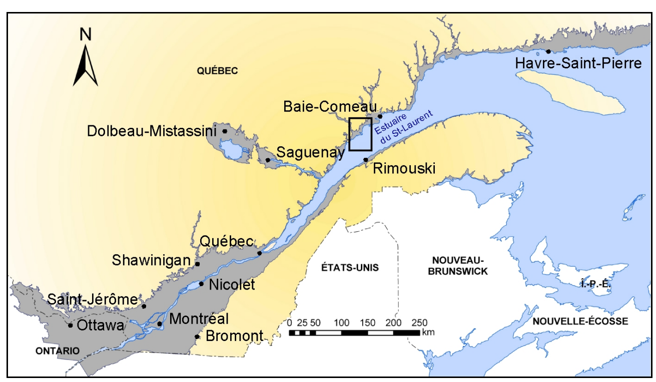


Figure 1. Localisation of the study area and limit of the marine submersion associated with the last deglaciation. Modified from Gadd, 1974.

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The Colombier landslide was first described by Bernatchez (2003) who provided a general description of the landslide scar geomorphology and stratigraphy. He observed that the scar may have resulted from at least two different failure events and proposed that part of this landslide was triggered by the major earthquake (M~7) that occurred in the province of Québec on February 5th 1663 (Smith, 1962). In addition to this landslide, other subaerial mass movements have been previously identified in the vicinity of the study area (*e.g.,* Chute-aux-Outardes, Allard, 1984).

The aim of this paper is to present ongoing work carried out in the Colombier landslide area in order to define the characteristics of the slope failure events. We first present new data revealing the morphology of the landslide scar area. Secondly, we suggest an interpretation from a seismic reflection survey integrated with piezocone soundings results to propose a preliminary description of the stratigraphy of the area. Finally, we make a few concluding remarks on this ongoing research.

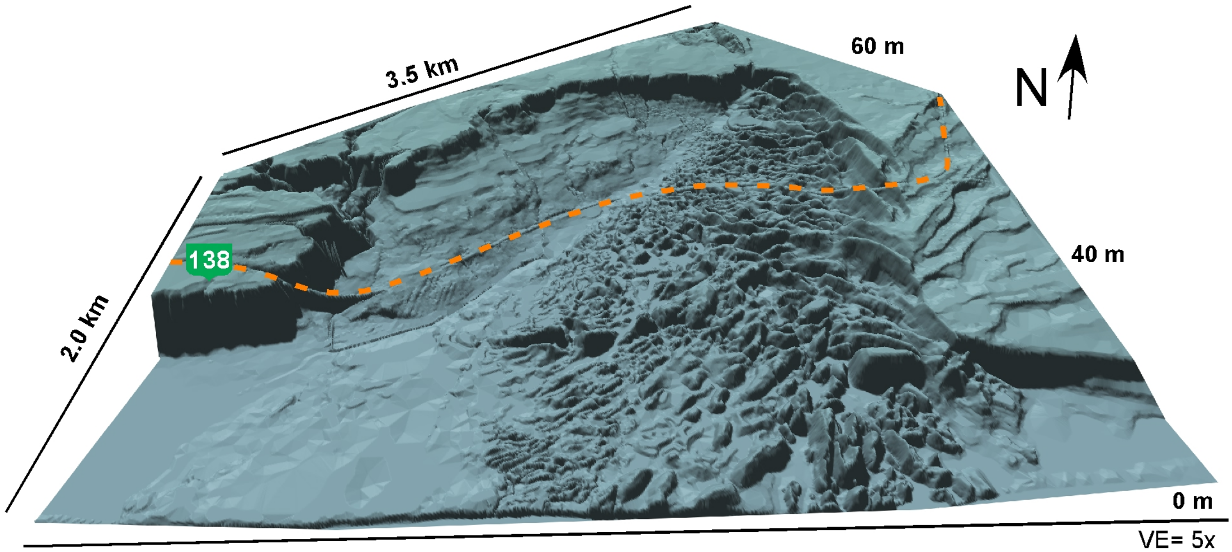


Figure 2. Shaded digital elevation model of the Colombier landslide scar area with indication of the position of Highway 138, which is the lifeline of the Quebec North Shore. The elevation ranges from the shoreline to 60 m. VE= 5x

## 2. REGIONAL SETTING

The Colombier area is located on the North Shore of the Lower St. Lawrence Estuary at about 400 km northeast of Québec City (Fig. 1). This area was submerged by the Goldthwait Sea (Dredge, 1983) and subsequently influenced by large deltaic complexes linked to the northward retreat of the Laurentide Ice Sheet during the Late Wisconsinan. Sea level reached a maximum at about 150 m above sea level in the vicinity of the study area and lowered to the present sea level at around 7.5 ka BP in $^{14}$C years (~8 ka cal BP) (Bernatchez, 2003). Today, the Colombier area is a large coastal plain interrupted by several terrace levels and truncated by the Betsiamites River. The coastline in the area has a N-S and a W-E orientation, east and west of Betsiamites River, respectively. The Betsiamites River flows into the St. Lawrence Estuary with a W-E direction. The tides in Baie-Comeau, the reference station for the area, are semidiurnal with average amplitude of 3.8 m. The largest tides are in the order of 4.3 m (Canadian Tide and Current Tables). The study area is located between the Lower St. Lawrence Seismic Zone (LSZ) and the Charlevoix Seismic Zone (CSZ) (Adams and Atkinson, 2003).

Bernatchez (2003) described the Holocene coastal stratigraphy of the Betsiamites and Manicouagan-Outardes deltaic complexes. He described the Holocene coastal stratigraphy of the Betsiamites River area as a sequence of emerged glacio-marine, prodeltaic, deltaic, fluvial and littoral deposits. Syvitski and Praeg (1989) provided a regional seismostratigraphic framework for the late Quaternary sedimentation offshore in the St. Lawrence Estuary. Cauchon-Voyer *et al.* (2008) integrated both analyses to describe the sequence of deposits found in the submarine portion of the Betsiamites River deltaic complex.

Offshore, the regional seafloor morphology of the Estuary can be divided into three physiographic regions: a sub-horizontal shelf, a slope and the Laurentian Channel. The shelf has an average width of 10 km and a maximum slope of 2°, with water depths ranging from the shoreline to about 150 m. The shelf break occurs between 150 and 200 m water depth, creating a slope with maximum height of 200 m. The Laurentian Channel is a long sub-horizontal topographic depression in the seafloor of the Estuary and has a maximum water depth of 375 m and a width of 45 km in the study area. Cauchon-Voyer *et al.*, (2008) have described the submarine geomorphology of the area between the Betsiamites River and Rimouski and have identified several landslide scars and accumulation of debris. They have proposed a chronology for 4 mass movement events in the submarine area that lies in immediate proximity to the Colombier landslide (Fig. 3). These 4 failures are dated as older than 9280 cal BP, 7250 cal BP, AD 1663, and AD 1860 or AD 1870.

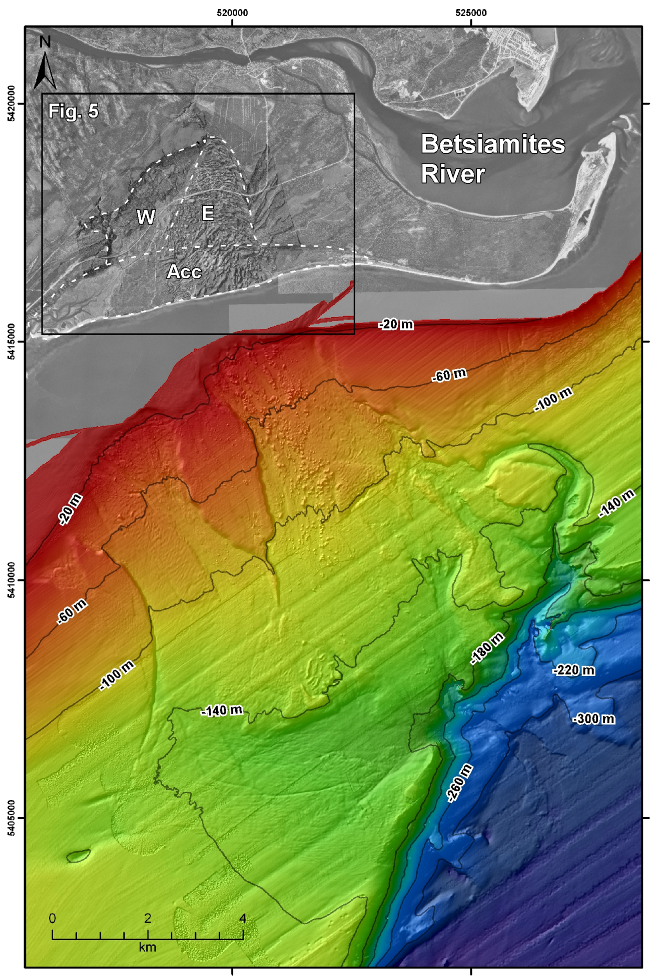


Figure 3. Bathymetric coverage of the study area, ranging from 5 to 325 m water depth. Bathymetric contour lines are at 40 m interval starting at 20 m depth. On shore, W, E and Acc indicate the position of the three zones within the landslide scar and insert refers to Figure 5.

## 3. DATA AND METHODS

The description of the landslide follows a morphological analysis, aerial photo interpretation and geometrical measurements carried out on the digital elevation model (DEM) (Fig. 2). The DEM was computed at a 1 m resolution from hypsometric lines at 1 m contour interval obtained from photogrammetry on 1:15000 aerial photos taken in 1996 (Q96312_008-011 and Q96311_195-198).

In order to obtain a 2D image of the stratigraphy of the disturbed area on the beach, a continuous seismic reflection profile was produced over a total length of 5.2 km. Seismic reflection data were acquired using an array of 24 geophones (40 Hz) at 5 m spacings. The configuration for the survey is a repetition of 12 shots increasing at 5 m steps, the first shot being fired at 2.5 m away from the first geophone (Fig. 4). The source was a “Buffalo gun” firing 12-gauge blank charges in holes about 50 cm below the ground surface (Pullan and MacAulay, 1987). The data were acquired with a Geometrics Strata Visor seismograph.

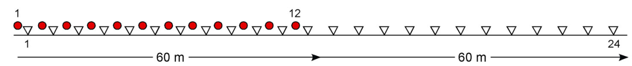


Figure 4. Diagram of the configuration of the geophone (triangles) and the 12 shot locations (circles).

The seismic data were processed with the software WinSeis Turbo. Normal moveout corrections were applied to correct for changes in distance between the source and each receivers. Stacking velocities were determined during the processing and the constant speed of 1575 m/s was used to linearly convert two-way travel time to approximate depths for the section presented in this paper. Band pass filtering (150, 200, 500, 600 Hz) was also applied to the presented section. Interpretation of the data was performed with the Kingdom Suite software package.

Sixteen piezocone tests were performed in the area of the scar (Fig. 5) between September and October 2006. They were carried out with a 15T apparatus with a 15 $cm^2$ base area. To obtain a better definition of the stratigraphy, the penetration rate was of 60 cm/min and the pore pressure ($u_{base}$) and tip resistance ($q_T$) were recorded at 10 mm intervals.

## 4. LANDSLIDE MORPHOLOGIES

The Colombier landslide is located within a large coastal plain of about 7.5 km wide by 25 km long interrupted by several terrace levels. They were established during the last submergence of the coastal area, which started around 11,000 BP in $^{14}C$ years (Bernatchez, 2003). The highest, but intermittent, terrace in the vicinity of the landslide scar is located at about 70 m of elevation (Fig. 5). A second terrace is located at 60 m of elevation and corresponds also to the highest point of the Colombier landslide scar. Large bedrock (Grenvillian province) outcrops are visible above the highest terrace, at elevation ranging between 80 and 140 m. Bedrock outcrops are also present at a distance of 200 m from the main scarp and on the beach, west of the landslide scar (Fig. 5). Flat peat bugs are found west of the landslide scar at elevation ranging between 60 and 80 metres. Many well-defined paleo-beach ridges are visible on the surface of the 30 and 15 m terraces east of the scar.

The landslide scar has a horseshoe shape with a maximum width of 3200 m and length of 2400 m. The elevation of the main scar decreases from 60 m to 40 m and has an average height of 30 m. We defined three general zones with different geomorphological characteristics within the landslide scar and we will refer to them as the West (W), the East (E) and the accumulation zones (Acc) (Fig. 3).

The West zone extends over 2.8 km$^2$ and is characterized by a regular southeast sloping terrain (Fig. 2). The main scarp height range between 10 and 30 m and its slope angle varies between 15° and 25°. The western flank was eroded by small creeks (Fig. 5), which drain the northwest terrain above of the landslide. The slope of the terrain has an average slope of 2.5° with minor relief variation.

The main morphological characteristic of the East zone is a succession of elongated ridges and depressions (Fig. 2). Two main orientations of ridges can be observed. The first group has a W-E orientation (270°N), which is parallel to the direction of the landslide (red on Fig. 5). They have average height, width and length of 10 m, 40 m and 200 m, respectively. The second group has an ESE-WNW orientation (300°N) (purple on Fig. 5). These ridges are slightly larger than the W-E ridge and have an average length of 275 m and maximal heights and widths of 25 and 60 m. They appear to be a continuity of the western flank. Both groups of ridges are likely constituted of stratified sandy materiel, which is similar to the material found in the upper 60 m terrace and rest on remoulded clayed sediments (Bernatchez, 2003). Many small and elongated lakes are found between the ridges. These lakes are depressions filled with standing water. In contrast with the West zone, no organized drainage system was identified in the East zone.

The accumulation zone of the landslide is defined as the subaerial area where the displaced material has accumulated. This zone includes the salt water mashes on either side of the landslide scar, a levelled and forested area with average elevation of 5 m and the sandy beach. Ridges are also observed (green ridges on Fig. 5) in this zone and have a different orientation than in the East zone. They are mostly disorganized but have a general NE-SW (215°N) trend. This zone appears to be an extension of the landslide debris in the Estuary, *i.e.,* the debris were deposited on the seafloor. The northern limit of this zone is the estimated position of the marine terrace prior to the landslide.

Offshore (Fig. 3), the general morphology of the shelf can be summarized as a large landslide scar characterized by two topographic depressions separated by a butte with steep flanks and a flat top. The flanks of the scar have an average height of 15 m and the butte is constituted of intact deposits (Cauchon-Voyer *et al.*, 2008). A rough estimate for the volume of this 40 km$^2$ submarine scar on the shelf is ~600 x 10$^6$ m$^3$. The landslide scar is overlain by landslide blocks, with sizes of up to 20 x 60 x 150 m. These blocks extend up to 8 km downslope from the shoreline. It was proposed by Cauchon-Voyer *et al.* (2008) that the scar and the overlaying debris result from two different failure events; the large landslide scar was dated at 7250 cal BP and the debris deposited in the pre-existing depressions were dated at AD 1663.

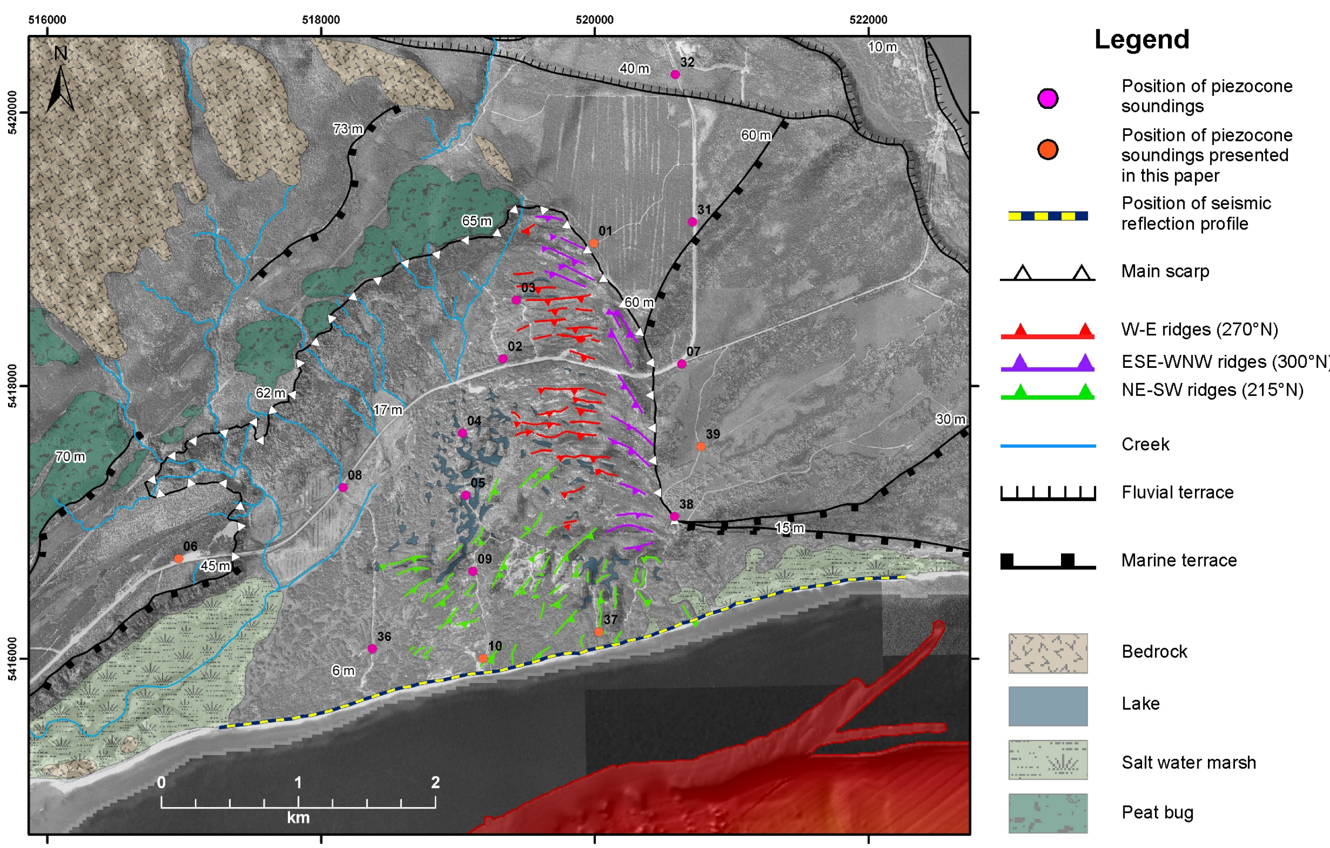

Figure 5. Geomorphological interpretation of the Colombier landslide. The black numbers refer to the piezocone soundings. The black and white elevation values represent the elevation at the point exactly below the label.

## 5. STRATIGRAPHIC ANALYSIS

As a second step in understanding the failure events that have shaped this landslide scar, it is necessary to describe the stratigraphic sequence of original deposits. In this section, we present results from piezocone soundings integrated with seismic reflection interpretation along the coastline to propose a description of the original stratigraphy of the area.

### *Original stratigraphy*

Sixteen piezocone tests were carried out in the vicinity of the landslide scar and provide a basis for a general description of the stratigraphy of the area. The complex stratigraphy resulting from the deltaic sedimentation in the Betsiamites River area is reflected in the piezocone sounding results. The piezocone profiles present laterally variable characteristics resulting from landslide events and also by the highly variable depositional pattern known to develop in prograding deltaic complexes (Hart and Long, 1996).

Seven piezocone soundings were performed outside the landslide area, 6 on the eastern flank and 1 in the western flank on the landslide (Fig. 5). Piezocone C46001 (Fig. 6) was performed 50 m away from the main scarp on the marine terrace at 60 m of elevation. The profile consists of 29 m of material with very high tip resistance ranging between 30000 and 40000 kPa and almost null pore-water pressure (~5 kPa), which indicates that it is a sandy deposit.

Piezocone profiles 32, 31, 07, 39 and 38 show similar high tip resistance and very low pore-water pressure for the upper soil layer, which thickness ranges between 15 and 30 m for these 5 profiles. On profile C46039 (Fig. 6) performed at 37.7 m above sea-level (asl), this sandy layer is 27 m thick. At 10 m of elevation in this profile, there is a change in soil properties, which results in decreasing values of tip resistance ranging between 5000 and 20000 kPa. This layer is interpreted as a stratified silt and sand deposit. At an elevation of 0 m, there is a 3 metres thick layer of soil with regular trends of tip resistance and pore water pressure. Under this layer, the deposit is composed of stratified layers of soil, likely silt and sand.

On the western flank, the profile C46006 is 60 m long (Fig. 6), which is the maximal possible length for these piezocone soundings. The test was performed at an elevation of 47.6 m asl. For the upper 6 metres, which is composed of sand, the tip resistance average 8000 kPa with a peak up to 30000 kPa. At 5 m depth (42.7 m asl), a change in material results in a decrease in tip resistance and an increase in pore water pressure. The tip resistance values are highly variable, ranging between 1500 to 5000 kPa, which likely results from alternating layers of silty and sandy material. At an elevation of 26 m, the tip resistance and the pore water pressure profiles have regular trends, which is characteristic of uniform material. The interval between the elevation of 18 m and -15 m below sea level, shows variable characteristics, which imply that the material is also stratified.

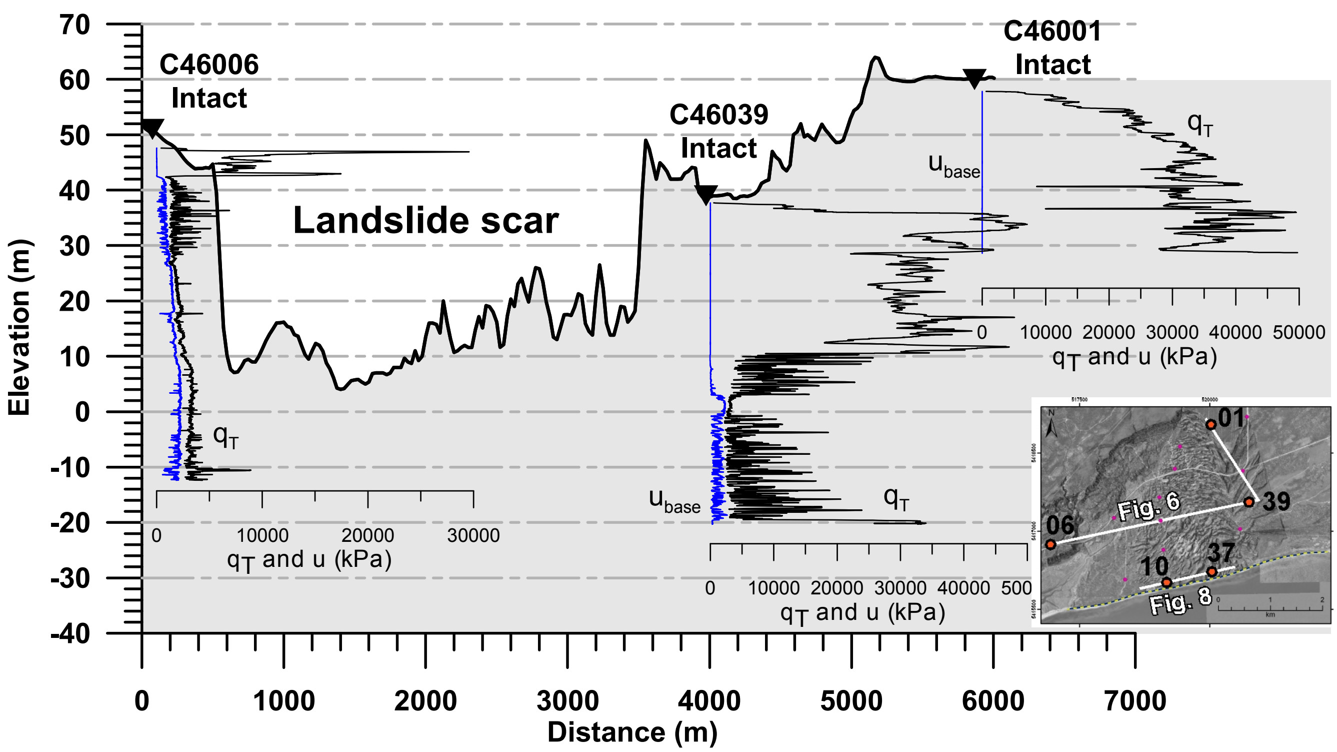


Figure 6. Piezocone soundings in the intact deposits outside the landslide scar. Black line with grey filling corresponds to the topographic profile. Insert indicates the position of the topographic profiles and piezocone soundings shown in Figs. 6 and 8.

The stratigraphy around the landslide head scarp can be simplified to an upper layer of sandy material, which thickness increases from 6 to about 30 metres from west to east respectively. The lower sections of the presented piezocone soundings (Fig. 6) indicate that there are highly stratified deposits changing with depth into a more uniform soil with less stratification. The failure plane of the landslide events likely occurred within the stratified soil layer.

*Stratigraphy along the coastline*

The seismic reflection data allows the definition of a preliminary seismostratigraphic sequence along the coastline. The reflections have central frequencies in the range of 300 Hz, which is typical for marine sediments (Hunter *et al.*, 2000). The interpretation of this sequence will be validated with upcoming boreholes and piezocone soundings planned for summer 2008. Four seismic units and a reflector with a strong acoustic impendence contrast, interpreted as the bedrock, were identified on the seismic section. These 4 units were defined according to the amplitude and geometry of the inner reflections and to the attributes of the upper transition of each body. Preliminary stratigraphic interpretation is derived from the work carried out offshore by Syvitski and Praeg (1989), which was later integrated by Cauchon-Voyer *et al.* (2008) for the submarine segment of the Colombier and Betsiamites River area.

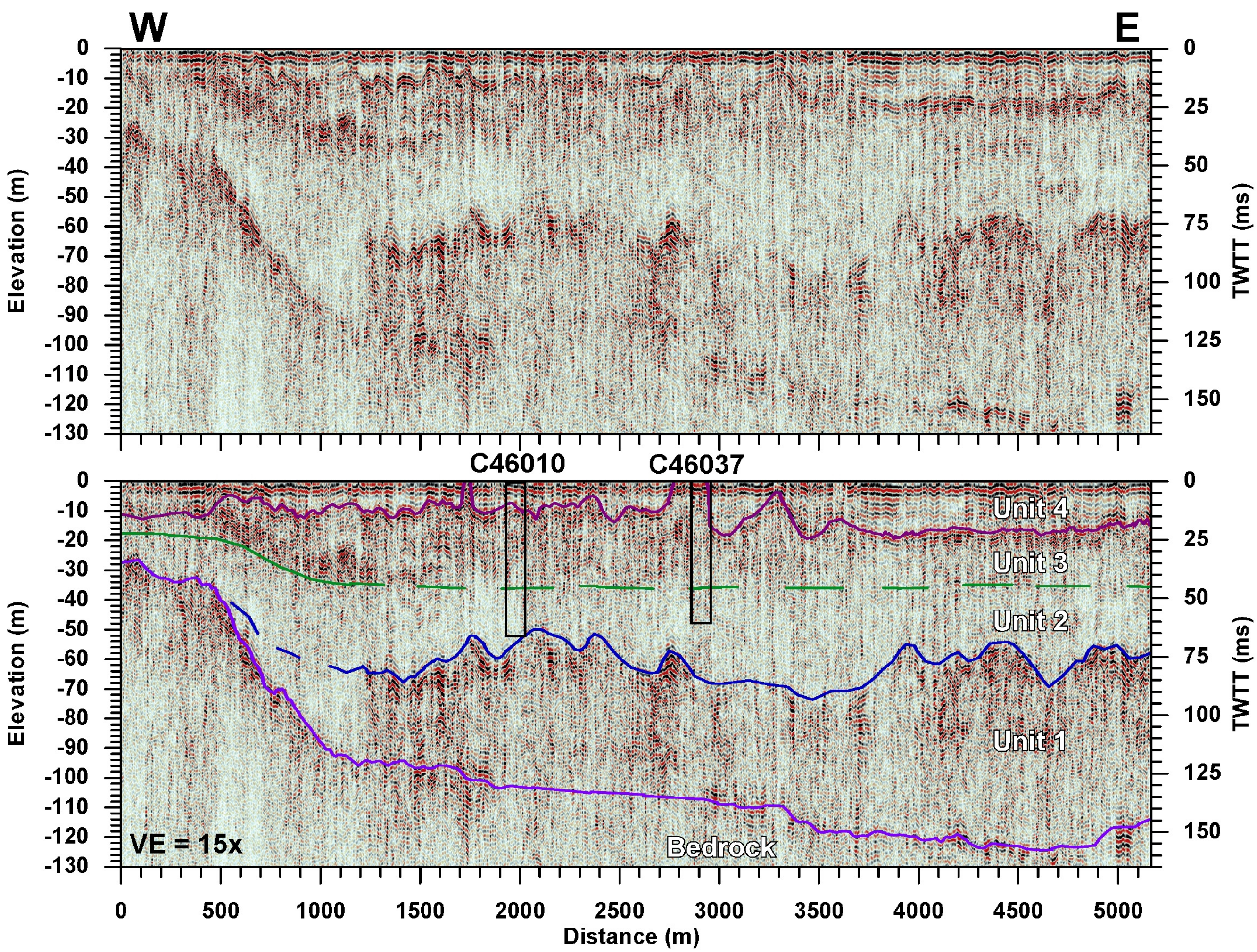


Figure 7. 5.2 km-long continuous seismic reflection profile. Right scale is in milliseconds two way travel time (TWTT) and left scale is approximate depth in metres (elevation), linearly converted using a constant speed of 1575 m/s. The black rectangles indicate the positions and depths reached by the two piezocone soundings carried out close to the shoreline.

The sediment-bedrock interface is characterized by relatively continuous high amplitude reflections, where little energy penetrates below this boundary. The depth to the bedrock increases from 125 m to 30 m (Fig. 7). This interpretation is coherent with the fact that a bedrock outcrop is visible on the beach at about 600 m from the western end of the seismic line.

Unit 1 is a highly variable acoustic body with strong internal reflections. The upper boundary of this body is irregular and its thickness ranges between a few metres to 60 m. In light of our current work, it is difficult to propose a definite interpretation for this body, but we can suggest that the lower part of this body may be constituted of till and ice-proximal sediments (Syvitski and Praeg, 1989). Upcoming work will help precise the geological interpretation for this unit.

Unit 2 is a very low amplitude body and presents only few weak reflections. The upper transition of this unit is weak and often absent, *i.e.,* the contact in acoustic impedance is too weak to obtain coherent reflections. Its thickness ranges between 10 to 30 m. This facies could correlate to the Goldthwait Sea sediments (Syvitski and Praeg, 1989).

Unit 3 is a stronger amplitude body with strong internal reflections and an irregular upper boundary. This facies could correspond to the highly stratified paraglacial deposits identified in the Estuary (Syvitski and Praeg, 1989). However, the irregular relief of the upper boundary of this body, which often reaches the surface of the section, indicates that the upper part of this seismic body may correspond to the landslide debris. This could imply that the debris were deposited on the stratified sediments and that the impedance contact between both bodies is too weak to obtain a clear boundary. This hypothesis must be validated with core data.

Unit 4 has dense closely packed sub-horizontal reflectors conformable with Unit 4. The amplitude of this unit varies between low and high. This unit could represent landslide debris reworked by littoral processes (*e.g.,* tides, wave action and longshore drift).

Two piezocone soundings, C46010 and C46037, were performed in the accumulation zone of landslide debris, at about 100 metres from the position of the seismic reflection profile on the beach (Fig. 7). The beach is an eroded surface reworked by littoral processes with an erosion terrace of about 5 to 10 metres high. Both profiles were performed above this terrace level, at 9.4 m asl for C46010 and 12.9 asl for C46037 (Fig. 8). Both soundings were 60 m long and penetrate below the layer of debris.

For piezocone C46010, there is a 12 metres thick layer of sand with tip resistance increasing up to 15000 kPa. The layer between 3 to 7 m bsl has variable characteristics, likely resulting from stratifications and landslide disturbance. At 12 m bsl, there is a 15 cm thick layer with tip resistance increasing from 2000 to 10000 kPa. Below this layer, the tip resistance and pore-water pressure profiles have regular trends, with few peaks likely resulting from soil stratifications. The higher values of tip resistance obtained at 48 m bsl could potentially correlate to seismostratigraphic Unit 1, which has strong internal reflections.

Sounding C46037 (Fig. 8) has three main layers. The first layer has tip resistance increasing to 25000 kPa, the second layer with general regular trends of tip resistance and pore-water pressure with few peaks, and the third layer which is mostly uniform. The second and third layer could correlate to seismostratigraphic Unit 3 and Unit 2, respectively.

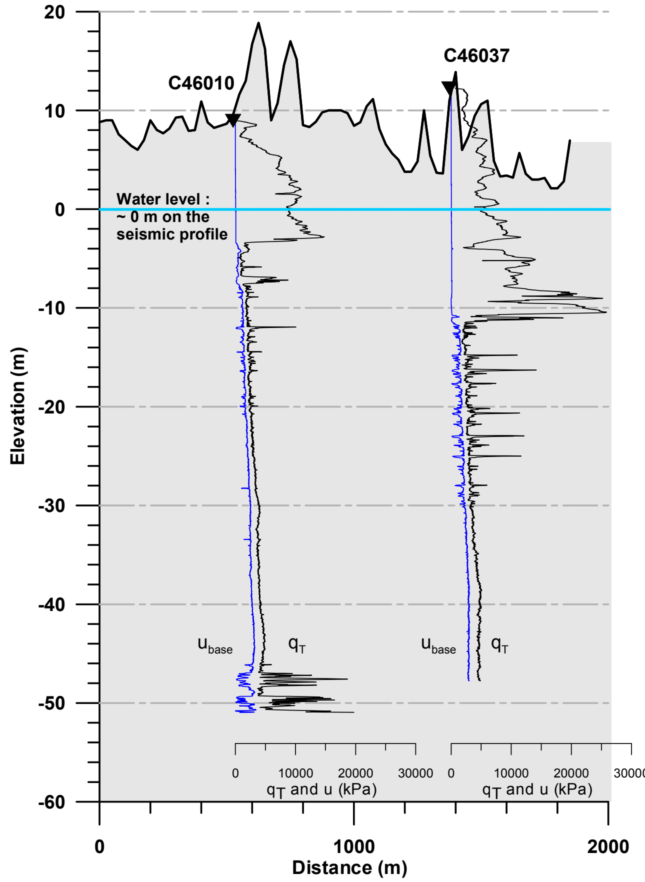


Figure 8. Piezocone soundings in the accumulation zone of landslide debris, at about 100 metres from the position of the seismic reflection profile on the beach. See Figure 6 for position of the profile.

## 6. CONCLUDING REMARKS

This analysis of the Colombier landslide area was initiated in order to define the morphological and geomorphological characteristics of the slope failure events. This important analysis will provide a geological framework for a future slope stability analysis. The observations and results derived from this ongoing work allow us to make a few general concluding remarks:

- The stratigraphy of the site of the landslide varies from west to east and may have influenced the morphology of the landslide.
- The irregular bedrock morphology in the area may have had a significant control on the extent of the landslide scar.
- Considering the effect of such a landslide on the North Shore of Quebec if it was to occur today, there is a need to pursue our research in the area and identify similar environments along the St. Lawrence Estuary.

## 7. ACKNOWLEDGEMENTS

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