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New evidence of slope instability in the Outardes Bay delta area, Quebec, Canada

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Abstract The Outardes Bay delta constitutes one of the best sites to study the formation of failure deposits in a modern lowstand environment. These deposits are located in a pseudo-shelf-edge position along the northern part of the Laurentian Channel in the St. Lawrence Estuary. The site has been investigated over the past 20 years with a Raytheon model RTT1000 boomer (3.5 kHz, 400 J) on the shelf, and most recently with a Simrad model EM 1000 multibeam sonar (95 kHz) on the slope to provide high-resolution seismic and bathymetric data. The seismic data show wavy, chaotic and contorted reflectors which are typical in marine environments characterised by instability features. The multibeam sonar data have revealed many slope instability features such as creep folds, channel incisions, debris flows, and rotational slide scars. Thus, these interpreted features are in direct relationship with the seismic interpretation of the data collected upslope. These geomorphological and geophysical signatures express both past and present sedimentological processes. Some of the mass movement signatures observed in the surveyed area are believed to be related with the great M_S~7 Charlevoix earthquake in 1663.

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Introduction

Some Canadian Holocene deltas formed after a relative sea-level fall of 100 m and are thus good examples of modern lowstand deltas. Many of these have been studied extensively over the past decade, e.g. the Rupert Bay, Fraser, Natashquan, Moisie and Outardes deltas (Hart and Long 1990a, 1990b, 1996; Michaud 1990; Hart et al. 1992, 1998; Christian et al. 1997;). Sea-level fluctuations, sediment supply, basin morphology, and hydrodynamic parameters such as tides and currents (Sala and Long 1989) control the progradation. These modern lowstand system environments show geomorphologic evidence of slope instability, such as creep folds, collapse depressions, bottom water scarp systems, shallow rotational slides, channel erosion caused by mass wasting, submarine channel systems, turbidity currents, aprons, fans, and distal debris flow deposits, mainly caused by the progradation of these systems (Hart et al. 1992; Hart and Long 1996). Elsewhere, slope instability has generated submarine landslides which are responsible for tsunamis and damage to infrastructure, such as the rupture of submarine telecommunication cables (Hampton et al. 1996).

The Outardes Bay delta is one of the best sites to study failure deposits in a modern lowstand environment. This system also represents a good analogue for continental margin settings at water depths averaging 300 m. These relatively shallow depths permit the enhancement of geological features which cannot be observed with the same resolution on continental slopes (McAdoo et al. 2000).

The Outardes Bay delta is located on the North Shore of the St. Lawrence River, Quebec, Canada, approximately 20 km west of Baie Comeau (Fig. 1). The Outardes River drains an area of 18,780 km^2 and is bordered on both sides by the large Betsiamites and Manicouagan Rivers (Hart 1987). These three rivers have been dammed for hydroelectric purposes. The average discharge of the Outardes River is 555 $m^3 s^{-1}$ and the tidal range is 2 to 3 m (Hart and Long 1996). Dam construction during the mid-1970s on the Outardes River has considerably reduced bedload transport. Since then, suspension load constitutes most of the sedimentary discharge (~300,000 m^3 $year^{-1}$). Mechanical erosion of the beach cliffs (clay) caused by wave action has led to a retreat of the shoreline of ~0.5 m $year^{-1}$ in the Ragueneau area (Allard 1982). Thus, wave action has more influence on the sedimentary budget than the river discharge itself.

The study area is part of a deltaic prism which contains the Betsiamites and Outardes river deltas. The Outardes Bay delta has formed after a drop in the relative sea level of approximately 140 m since the last glaciation (Wisconsinan) 10,000 ka ago. A palaeo-shelf break developed 12 km north of the present river mouth during the late glacial highstand on Precambrian bedrock. According to Dubois (1979) and Michaud (1990), the relative sea level of the higher portion of the St. Lawrence Estuary has been stable since 2.00 ka B.P. Cagnat (2003) has calculated a sedimentation rate of ~1.5 mm $year^{-1}$ for the last 2,290 ka B.P. based on ^{14}C dates obtained on shells sampled from a long core taken off Rimouski (MD992220; MD: denotes the Marion-Dufresne core number). The MD992220 core is located at 48°38′24″N,68°37′48″W in the Laurentian Channel at 320 m water depth, ~30 km SW of the study site. Glacio-isostatic rebound was particularly rapid during the first millennium following glacial retreat. Since 5.50–6.00 ka B.P., the glacio-isostatic rebound is on average ~3 mm $year^{-1}$ (Dubois 1980). The Outardes Bay delta is located in the Lower St. Lawrence Seismic Zone (LSLSZ). The LSLSZ is not known historically for seismic events of high magnitude (GSC 2001). In fact, only two events have reached a seismic magnitude (M_S) exceeding 5 (GSC 2001). Most of the earthquakes in the LSLSZ occur along or between the mapped Iapetan faults (or St. Lawrence palaeo-rift faults), beneath the Logan line and the Appalachians (GSC 2001). The Logan line consists of a thrust fault which follows the demarcation between slightly deformed autochthonous rocks which formed the continental shelf of the Iapetus ocean (Late Proterozoic), and the allochthonous rocks which were thrusted on to the shelf (Saint-Julien 1977).

The Outardes Bay delta is a forced regression delta lying in a pseudo-shelf-edge position along the northern part of the Laurentian Channel in the St. Lawrence Estuary. The Laurentian Channel is a glacially excavated trough approximately 300 m deep. This study is based on seismic data collected by Long (1981) interpreted in Hart and Long (1996), and multibeam data collected by Urgeles et al. (2001). The purpose of the study is to present new evidence of slope instability in the Outardes Bay delta area, apparent on multibeam

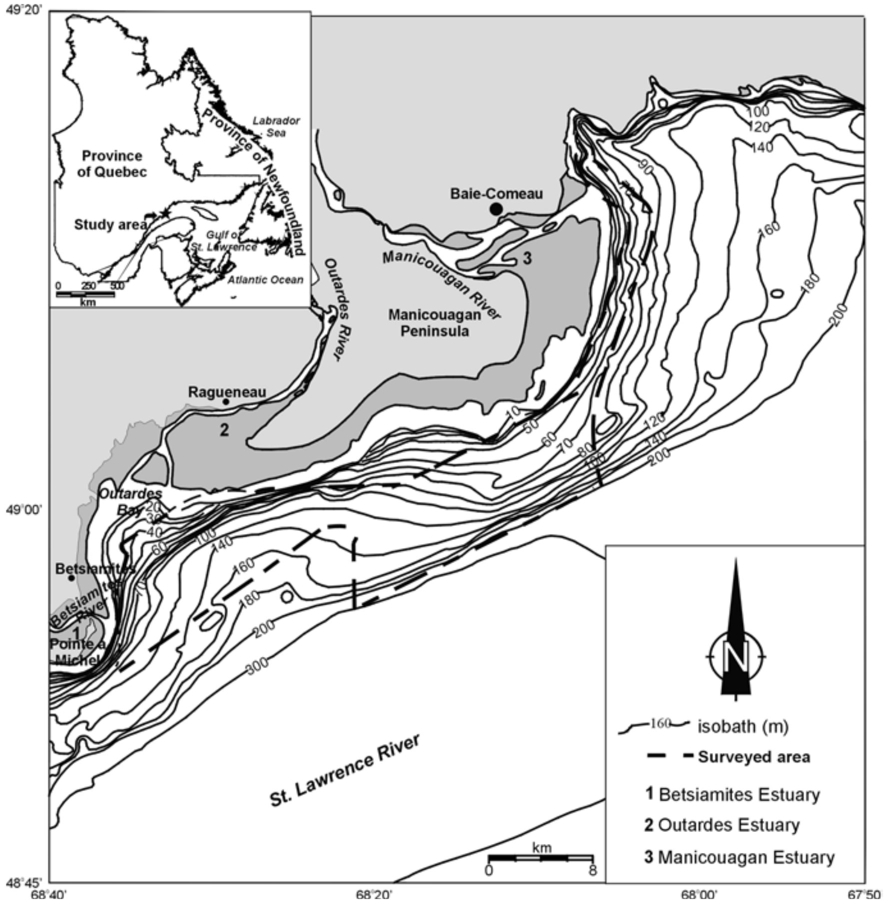

Fig. 1 Location of the study area showing regional bathymetry and locations mentioned in text

coverage, and to establish relationships between this coverage and the seismic profiles published by Hart and Long (1996).

Earlier data sets

An earlier seismic survey was carried out with a single-channel Raytheon RTT1000 sub-bottom profiler (3.5 kHz, 400 J) in 1981 over an area of 220 km^2 at 5- to 120-m water depths (Long 1981; Hart and Long 1996; Fig. 2). The seismic data sets revealed several slope failure features such as wavy, incoherent, truncated, incised and chaotic reflectors on sub-bottom profiles averaging 10 m below the seafloor (Fig. 2). The seismic character of line A–A′ consists of oblique, discontinuous and incised reflectors. Because of the steep slope gradient, the B–B′ sub-bottom profile exhibits steep oblique reflectors. Wavy and contorted reflectors are also present in this segment. A 1-m-thick seismic facies showing wavy reflectors overlies the stratified strata slide deposits. The C–C′section intersects the D–D′ segment at D′. The C–C′ section shows a bedrock signature represented by undulating, chaotic, and steep oblique reflectors. The bedrock is 3 m below the seafloor near point C, and 7.5 m below the seafloor at the slope break. The failure deposits are 4.5 m thick and they are capped by 1.5 m of new submarine lobe sediments. The D–D′ profile shows wavy, disturbed, and oblique reflectors. The undulating reflectors represent the draping of 12-m-thick sediments over bedrock. A lobe which reaches a maximum thickness of 7.5 m can also be seen on this profile.

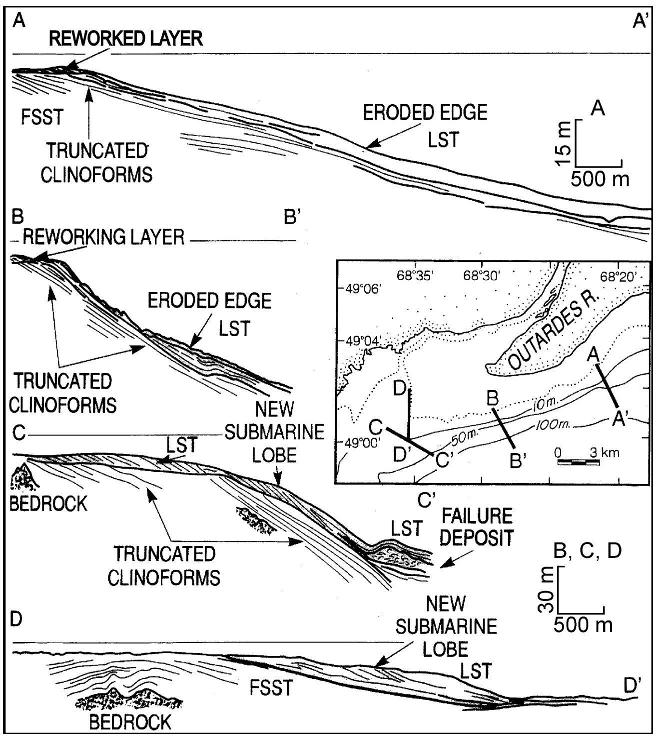

Fig. 2 Line drawings of seismic profiles from the Outardes Delta (adapted after Hart and Long 1996). *FSST* Falling stage system track and *LST* lowstand system track

On the A–A′ line, the oblique reflectors at the top of the seafloor slope indicate truncated clinoforms. The discontinuous strong reflectors are reworked layers. The undulating seafloor slope reflector character is interpreted in this paper as an erosional signature and is probably caused by sea bottom currents. The small incisions at the top and bottom of the strong discontinuous reflector may represent channel incision. Thus, beside the incisions, the A–A′ line reflectors express stratigraphic features which are similar to those recorded along the B–B′ line, i.e. eroded strata, reworked layers, and truncated clinoforms. On the B–B′ section, the strong and discontinuous reflector which can be observed near point B corresponds to a reworked layer. Contorted reflectors show that slumping has occurred on most of the slope. At the base of the slope, a series (~3 m thick) of slide blocks of stratified strata is suggested by the gently undulating reflectors. The wavy reflectors correspond to erosion features induced by bottom current circulation. On the C–C′ profile, the weaker oblique reflectors are interpreted as truncated clinoforms. The chaotic reflectors at the base of the lobe slope are typical of failure deposits. The undulating seafloor on the top of these deposits has been identified as compression dunes on the Fraser Delta foreslope (e.g. Christian et al. 1997), although this interpretation has been questioned by Mosher and Thomson (2002). On the D–D′ profile, the strong oblique reflector which can be traced laterally over 2,500 m has been interpreted as the prograding surface (10° dip) of a new submarine lobe (Hart and Long 1996). The weaker oblique reflectors within the new submarine lobe correspond to the progradation fronts of the system, and the disturbed reflector near the upslope break of the progradation surface represents slumped strata. The strong reflector identified on the D–D′ line, and interpreted as a progradation surface, can also be followed on the C–C′ profile.

From their seismic facies interpretation, Hart and Long (1996) proposed the following palaeogeographic reconstruction. During the last forced regression, the main fluvial channel of the Outardes River eroded deltaic and prodeltaic sediments of the highstand system tract (HST) and of the falling stage system tract (FSST). During this period, the forced-regression delta plain was incised. For this reason, the raised delta plain of the modern coastline is characterised by an incised channel system and numerous low terraces. The present active delta feeds a submarine fan which is over 50 m thick in water deeper than 300 m (Syvitski and Praeg 1989).

Material and methods

High-resolution bathymetric mapping of the Outardes Bay delta seabed was carried out by means of a SIMRAD EM 1000 multibeam echosounder installed on board the CSS FG Creed, a Canadian Hydrographic

Service vessel. The vessel is a catamaran designed to reduce wave motion and resistance of the ship's forward motion, which makes it a very stable platform for high-speed surveys (Urgeles et al. 2001). A stabiliser system controls the pitch and roll of the vessel and allows adjustment of the heel and trim of the catamaran in real-time. During the cruise, positioning was by a differential positioning system. The EM 1000 operates at 95-kHz frequency with 60 beams spaced at 2.5° for a total coverage of 150° or 7.5 times the water depth (Hughes-Clarke et al. 1996). The multibeam echosounder has permitted determination of the geomorphology of the seafloor and the sedimentary transport axis.

The data were collected during the 3 to 5 September 2000 cruise. The data sets were processed onboard, using University of New-Brunswick Ocean Mapping Group software (OMG) to correct artifacts and errors introduced during data collection. During post-processing, tidal correction was merged into the survey data files (Urgeles et al. 2001). The grid resolution of the maps is 5×5 m per cell.

Results

Bathymetric data

In this sector, the principal geomorphologic structures are creep folds, submarine landslide scars, and debris flows. The pseudo-shelf is cut by man-made channels and sinuous to meandering natural channels. The man-made channels consist of two straight troughs which were created when electric cables were retrieved at the end of the 1950s (Fig. 3). These electrical cables were installed in the mid-1950s to test a potential electrical transport route to serve the south shore population of the St. Lawrence River (Hydro-Quebec, personal communication 2001).

Five zones (zones 1 to 5 in Fig. 3) were investigated in more detail because of the high concentration of failure signatures.

In Fig. 4a, the first zone presents a three-dimensional projection of submarine landslide features approximately 3.6 km NE of the Betsiamites Estuary. This zone is located at 20- to 120-m water depths and reveals geomorphologic evidence of creep folds, braided channels, and a sinuous channel. The field of creep folds can be observed in an area extending 2 km^2 in a NE direction. The wavelength (λ) of the folds is 90 m. The field of creep folds is formed on a 1.5° slope. The braided channel incision extends 3.3 km in a north-easterly direction. The main channel is 90 m wide. The most distal part of the channel (from the Betsiamites Estuary) is filled with sediments. The sinuous channel is 300 m wide at most, and corresponds to a relict feature which can be followed for 1.8 km along an ESE/WNW axis on a 1° slope.

The second zone is influenced by both the Betsiamites (SW of zone 2) and the Outardes (NEE of zone 2) estuaries (Fig. 4b). This zone contains two areas dipping almost perpendicularly to each other, one dipping to the north-east (1°) and the other to the south (1°). In the northern part of this zone, several failure scars can be seen. These scars are on average 150 to 250 m wide,

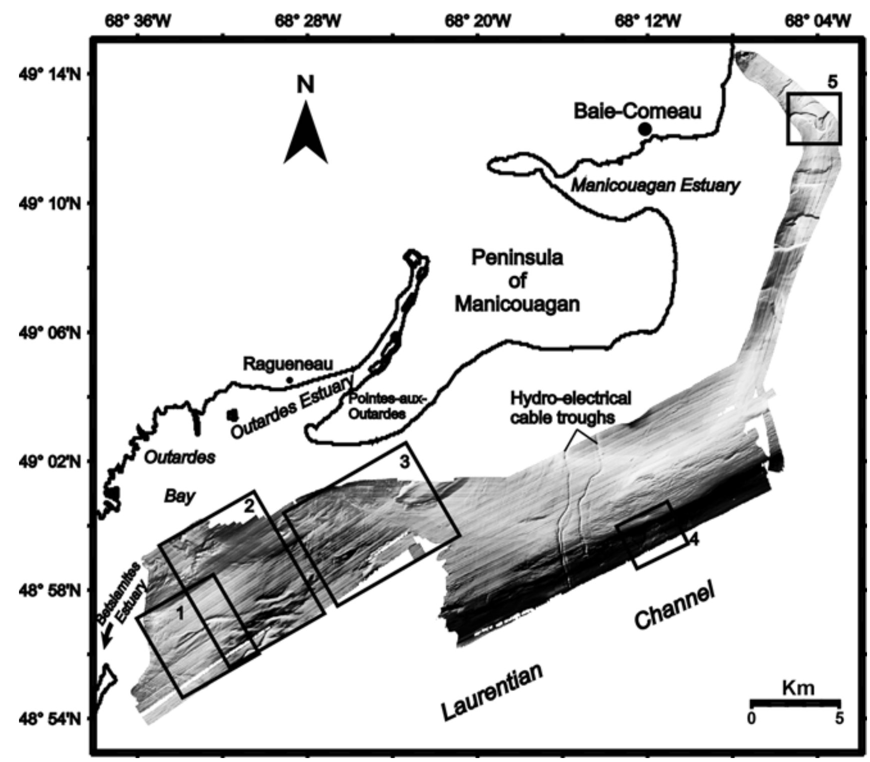

Fig. 3 Shaded surface render of the surveyed area (*shaded relief*). *Zones 1* to *5* denote areas of detailed analysis

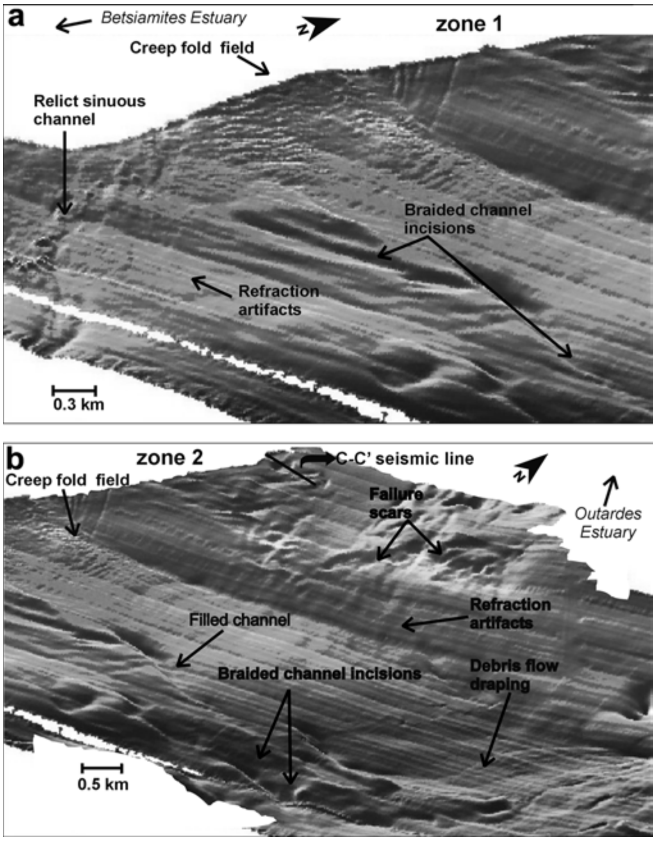

Fig. 4 a Three-dimensional projection of the multibeam coverage in zone 1 showing a sector in the Betsiamites Estuary area. **b** Three-dimensional projection of different submarine landslide features in zone 2. **a** and **b** View from N110°, 20° elevation and sun illumination from N235°

occurring sparsely at water depths of 20 to 80 m. In this area, the incised braided channel system (Fig. 4) runs through the deepest part in a SW–NE trend. Similarly, to the proximal part of this system in the Betsiamites Estuary (zone 1), the channels appear partially filled along long axes. A debris flow drapes a 0.8-km-wide sector and seems to bypass and fill the distal part of the braided channel system.

The third zone, located 4.8 km south of the present Outardes Estuary at 80- to 160-m water depths (Fig. 5a), covers an area of approximately 20 km^2 and shows different types of slope instability features: a rotational slide, a channel incision, and a debris slide. The rotational slide is almost 3 km long and 0.7 km wide. The head scar left by the slide is 15 m high. The volume of material displaced by the event represents a few 10^6 m^3.

The channel incision is sinuous and lies on the steeper part of the slope (9°). This v-shaped geomorphic element is 1.2 km long and 0.2 km wide. The channel ends on a thick ridge at its most southern point.

The maximum length of the debris lobe slide corresponds to a distance of 320 m. The debris slide has a main scarp of 760 m long by 40 m high. The volume of the slide is estimated to about 10^6 m^3. Two transverse ridges can also be observed on Fig. 5a. The left ridge can be seen only in part. The right one is ~1.5 km long and 0.24 km wide. The two ridges are located at the base of the slope (170-m water depth). In the top right-hand corner of this zone, numerous minor slide scars are found on the upper and steeper part of the slope.

The fourth zone, located along the north wall of the Laurentian Channel in the deepest part of the surveyed area (Fig. 5), shows a major rotational slide on a 5° slope. The slide is 3 km long and 2 km wide at its toe. The main scarp is 80 m high, and the volume of the slide is evaluated at several 10^6 m^3. This major slide is characterised on both sides by the presence of minor lateral slides. Minor slides are also present on the NE side of the slope. Geomorphological evidence of another major slide can be seen on the SW side of the rotational slide described above.

The fifth zone corresponds to the shallower part of the study area (Fig. 6). Figure 6 is a shaded surface render and shows an active meandering channel, ~3 km long by 0.6 km wide in the E–W axis. The depositional zones cover 180,000 and 144,000 m^2 at the top and bottom of zone 5 respectively. Another depositional zone, external to the main channel and interpreted as levee deposits, represents an area of ~200,000 m^2. A relict, SW–NE-oriented braided channel system can also be observed in zone 5 and is partly filled by sediments. Some wave-induced bedforms can be seen in an area of 2.2 km^2. The bedforms are oriented in a NW direction and have wavelength of about 240 m.

Refraction artifacts

Refraction artifacts (see Figs. 4, 5, 66) are present in most (if not all) of the multibeam-processed data because of sound velocity variations in the water column (Hughes-Clarke 2000a). Such variations are due to water-column structural changes which are a function of the local oceanographic variability (e.g. tidal fronts, upwelling, changes in the wave mixing, solar heating), in both space and time (Hughes-Clarke 2000b). In this study, the sound velocity profile was measured every day to calibrate the multibeam sonar data (Urgeles et al. 2001; Furlong, personal communication 2001). This may have caused a poor estimation of the water column profile and then contributed to the generation of artifacts because of the delay between sound velocity acquisition and the application of the appropriate correction factor onboard. The sound velocity fluctuations in the water causes the distortion of the outer beam ray paths. The refraction artifacts can be observed as parallel tracks which look like small-scale ridges along the ship's track (Figs. 4, 5, 6). Two types of artifacts were encountered during the post-processing: (1) point-like bathymetric lows and (2) small-scale parallel ridges. The first was easily removed with the SwatEd-refraction editor tool created by the OMG. By contrast, it was difficult to completely remove the second type because of the more subtle signal. These artifactual features are

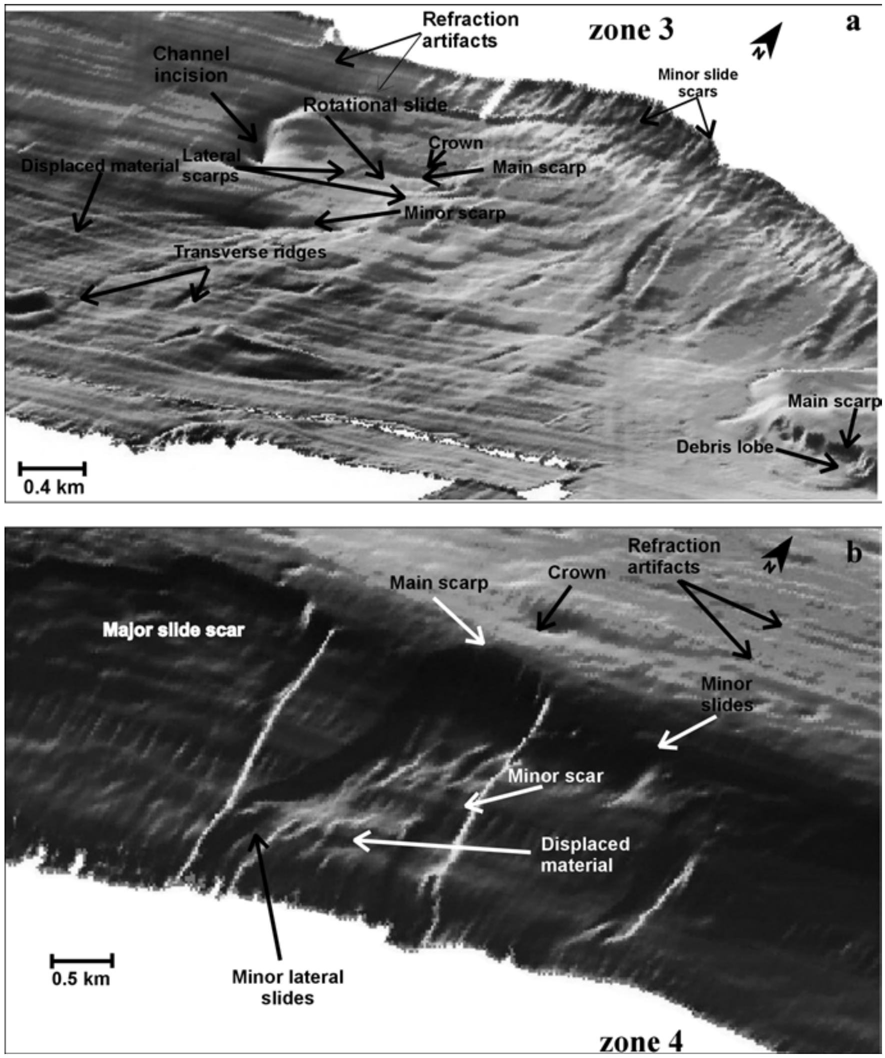

Fig. 5 a Three-dimensional projection of the multibeam coverage in zone 3 showing three types of slope instability features. **b** Three-dimensional projection of zone 4 showing a detailed description of a rotational slide. **a** and **b** View from N110°, 20° elevation and sun illumination from N235°

mostly related to the outer beam patterns. This problem was partly solved during post-acquisition processing by using the SwathEd ‘‘refraction editor’’. The ‘‘refraction editor’’ allows an empirical estimate of systematic biases due to imperfect measurement of the water column (as a function of time). In the present case, these artifacts have not been considered as a problem for the geomorphologic interpretation of submarine landslide signature, because of their small dimensions and their constant presence.

Discussion

The field of creep folds and the channel incision suggest that the sedimentary discharge of the Betsiamites River plays a major role in the formation of the slope (Fig. 4a, b). In addition, we cannot ignore the impact of the Outardes River sedimentary discharge on the geomorphic signature in this sector. Partial lateral filling processes of the braided channel incision probably result from minor submarine slides induced by the sedimentary discharge from the Outardes Estuary. The apparently constant vertical filling of the entire sinuous channel suggests that it is relict. The two channel-incision patterns were formed by different mass wasting events and by fluvial supply coming from the palaeo-Betsiamites River. The creep fold field was induced by creeping activity induced by sediment input.

Multibeam imagery (Fig. 4a, b) also reveals the effects of the two slopes on the sedimentation and geomorphic record of the second zone. The seabed morphology indicates that influence of the Betsiamites Estuary no longer predominates in the area but that the sedimentological conditions are now dominated rather by the Outardes estuarine system. This interpretation is corroborated by the partial filling of channels which may have been triggered by the steepness of the south-dipping slope. The large dimensions of the braided channel system clearly indicate that this system was once drained by important sediment supply. The failure scars suggest that several minor submarine landslides took place on this slope. These submarine landslides were caused by the instability generated by the steepness of the slope in conjunction with the high sediment supply from the Outardes Estuary.

In Fig. 5a, the rotational slide and the debris slide present fresh scars with no evidence of sediment draping. The instability factors responsible for this slide may have been controlled by the Outardes Estuary discharge, erosion upslope, and the angle of the slope. The short runoff distance of the debris slide lobe and the seafloor physiography of the debris slide sector indicate that gravity was not the main cause of this slide. Earthquakes should be considered as main triggering mechanism for this debris slide.

Also in Fig. 5a, the predominant v-shape of the channel incision supports the theory of an erosional canyon induced by the wasting of displaced material coming from the upper part of the slope. The thick ridge located in the southward segment of the channel may represent the deposition zone of the channel-drained material. The fact that this channel did not show fresh scars when the data were collected reveals that it has not been active for some time.

Two hypotheses can be proposed to explain the presence of the transverse ridges contained in zone 3 (Fig. 5a). (1) The two ridges can be linked to the braided channel system shown in zones 1 and 2 and may represent the distal part of the Betsiamites Estuary system. (2) The two ridges may correspond to compression "megabulges" formed in the front of displaced material fans which were built up by recent Outardes Estuary sedimentary input. The overview of the study area (Fig. 3) seems to support the first hypothesis but the lack of multibeam imagery data in this portion of the study area does not permit a clear conclusion. The minor upper slope slide scars show active processes occurring in this sector. The important number of scars and their small sizes suggest high-frequency processes. The steep slope of this area prevents the accumulation of major sediment volumes. The Outardes Estuary must play a significant role on the sedimentary evolution of this sector.

The meandering channel of Fig. 6 and the Manicouagan Estuary have a similar W–E orientation. This is evidence that the active character of the meandering channel appears closely linked to the Manicouagan Estuary dynamics. This channel drains sedimentary discharge generated by upper system submarine slope failures. When the channel cannot contain the volume of the flow, it presumably overflows and forms levee deposits. The relict braided channel may therefore indicate the hydrodynamic evolution of this part of the study area. The formation of the bedforms is related to modern bottom currents coming from the south-east (Crémer et al. 2001).

Based on the multibeam data published in this paper, the steep slope of the pseudo-shelf edge is thought to induce frequent submarine landslides because of the fresh character of the slide scars, and also because of the number and dimensions of these scars. Masse (2001) shows as well that many submarine landslides occurred along the north wall of the Laurentian Channel ~30 km upstream from the study area. Three mechanisms can be proposed to explain the presence of instability elements in zone 4: (1) the steep slope gradient, (2) gas expansion, and (3) earthquakes. In the case of gas expansion, Cagnat (2003) has documented two important degassing phases related to the presence of gases in a core (MD992220) between depths of 17.5 and 21.5 m beneath the subsurface. Thus, even though core site MD992220 is located ~30 km SW of the study area, it is difficult to dismiss the possibility that gases may contribute to instability on the Outardes Bay delta's slope.

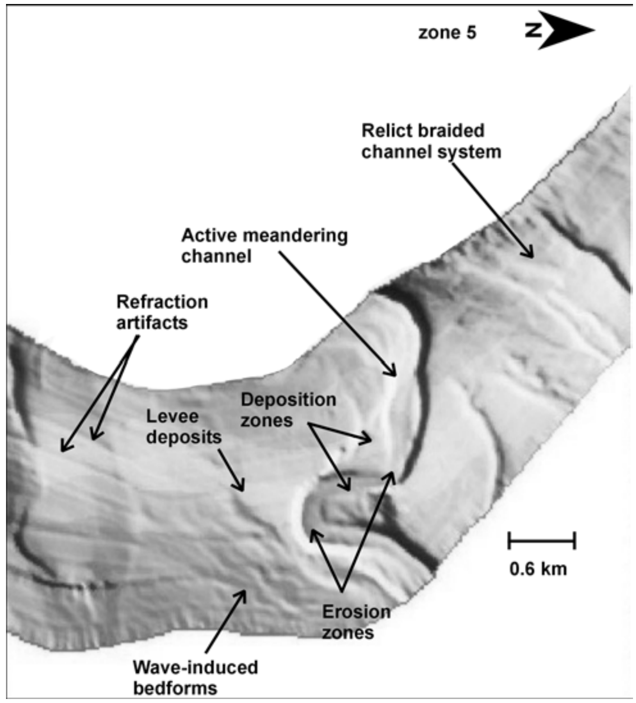

Fig. 6 Shaded surface render of the multibeam coverage in zone 5 showing a detailed image of an active meandering channel

Evolution of the deltaic system

Many truncated clinoforms show a basinward progradation of the deltaic system during the Holocene forced regression (Hart and Long 1996). The steepness of the clinoforms (~25–30°) reveals significant fluvial sediment input. The Manicouagan Peninsula is interpreted as Holocene prodeltaic deposits generated in part by the Outardes system (Hart 1987). The fluctuation of this system reveals processes which have played a strong role in the evolution of the style of sedimentation. Waves remobilised the sediment around the Manicouagan Peninsula. Bedform orientation appears to be governed by bottom currents (SE) (Fig. 6). The major sea-level drop which occurred during the past 10 ka has generated fluvial channel incisions in the deltaic and prodeltaic deposits and a direct sediment supply to the slope. The different subsurface morphologies indicate that erosion mechanisms were active in the Outardes Bay delta. These mechanisms are believed to be partly related to submarine landslides because of the observed seismic signature of failure deposits (Fig. 2, B–B′ profile). Other mechanisms such as wave and tide currents and storm waves can also explain the reworking of sediments.

Modern system dynamics

The steepness of the prograding slope and the sedimentary discharge of the system have led to the generation of submarine landslide features in the shallow parts of the delta front. An understanding of sedimentation rates is problematic in this sector. Cagnat (2003) has demonstrated that, in this sector, St. Lawrence River sedimentation rates have been relatively low for the last ~2 ka B.P. Also, in the mid-1970s, the Outardes River discharge was regulated by three dams. Since then, the sedimentary budget of this river consists mostly of suspension load. Thus, both the St. Lawrence River and the Outardes River sedimentation rates cannot be cited as the main causes for the triggering of recent submarine mass movements in the study area. However, besides these fluvially derived sedimentation rates, the shoreline cliffs, composed mainly of marine clays, act as the principal source for sediment input to the pseudo-shelf located ~10 km north of the study area (Cataliotti-Valdina and Long 1983). After being eroded, the cliff material is redistributed in the Outardes Bay delta sector by the Outardes River discharge. The amount of eroded material which is redistributed in the upper slope section constitutes an additional load to that part of the system. Thus, the resedimentation of the eroded material on the top of the delta's foresets can represent an aggravating factor which can explain, in part, the occurrence of instability elements in this part of the delta slope.

Glacio-isostatic rebound has increased slope instability in this area. Dubois (1980) has demonstrated that this rebound is still important in the study sector (~3 mm year^{-1}). Elsewhere, the isostatic rebound in south-western Norway ranges approximately from 3.2 to 5.85 mm year^{-1} (Bakkelid 1986). Bøe et al. (2000) have shown that some sediment failures in south-western Norway were probably triggered by seismic reactivation of a local fault by postglacial, regional isostatic rebound. Evidently, glacio-isostatic rebound can destabilise non-cohesive material on a slope. Thus, the re-equilibration of the crust in the Outardes Bay delta area could be a possible cause of many slope instability features in this sector.

It seems unlikely, however, that the low magnitude but high activity of the LSLSZ can be linked to a reactivation of the Logan line due to a re-equilibration of the crust after the withdrawal of the ice-sheet (Lamontagne, personal communication 2001). According to Lamontagne (1999), the Logan line is not active, and earthquake epicentres in the LSLSZ originate well below the Logan line, i.e. in the Canadian shield. In addition, there is no high-resolution structural map of the study area (Tremblay et al. 2003). The only structural interpretations available for this sector have been published in Stanford and Grant (1990). These interpretations are based on a extrapolation of a wide-meshed seismic grid which is well below the resolution of the present study. So, it is hard to rely on this geological map to pinpoint the Logan line as a reason to explain instability evidence observed in the Outardes Bay delta area. Therefore, in this area, the glacio-isostatic rebound probably constitutes a homogeneous crustal uplift independent of regional faulting. A relation can be established between the erosion of the shoreline cliffs by wave action and glacio-isostatic rebound. Effectively, the height of the glacio-isostatic rebound per year is equal to the height of the "new" exposed cliff which is available for erosion and thus, for re-sedimentation on the delta. This situation can correspond to the "shingle turbidite" described by Vail et al. (1991), and explained as being a "healing phase" of the slope by Posamentier and Allen (1993). The "healing phase" translates the re-equilibrium of the slope. This phase will last until the state of equilibrium of the system is reinstated. The cliff's eroded material thus constitutes an additional "stress" applied on the slope.

The geomorphologic evidence of instability in the deeper part of the system, especially along the pseudo-shelf-break, may have been caused by storm wave action and probably seismic activity if gas content is important. According to Hampton et al. (1996) and to the Geological Survey of Canada (GSC 2001), it is unlikely that earthquakes, as a single triggering factor, can be implicated in recent submarine landslides in this region. In fact, to induce a submarine landslide, M_S~6 earthquakes are necessary (Hampton et al. 1996). However, it is very likely that earthquakes, in conjunction with other factors (e.g. high gas content), can trigger submarine landslides. In the LSLSZ, no event of $M_S > 5.1$ has been recorded in the past century (GSC 2001). On the other hand, it is hard to overlook the effects of the great 1663 Charlevoix earthquake (M_S~7) in the study area (GSC 2001). The strong ground motions induced by this earthquake were felt in Boston (USA) (~800 km from the epicentre) where houses were shaken so badly that tops of several stone chimneys were broken (GSC 2001). Therefore, some observed instability features may be linked to this event, especially the zone 4 major rotational slide (Fig. 5). Thus, it is not impossible that the 1663 earthquake, in conjunction with other factors, for example, gas, could have triggered mass movements in the study area. The presence of gas has been documented in the degassing phases observed by Cagnat (2003) in core MD992220. The presence of gas has been identified in previous studies (Hampton et al. 1996; Christian et al. 1997) as a factor which can lead to slope instability. The gas weakens static shear strength of the material. Thus, the normally stable deposit can fail on nearly flat surfaces driven by small gravitational forces produced, for example, by floods and high river sediment discharge or by cyclic loading generated by earthquakes (Hampton et al. 1996).

The maximal magnitude recurrence curve for the Charlevoix-Kamouraska seismic zone (maximum seismic magnitude = 7.5) shows that for an earthquake of $M_S = 7$, the recurrence is ~800 years. The last time an M_S~7 occurred in the Charlevoix-Kamouraska seismic zone was in 1663 (Adams et al. 1999). Thus, it can be inferred that the M_S~7 1663 Charlevoix earthquake was the last seismic event capable of initiating large seafloor failures, as shown as in Fig. 5a,, b. If Cagnat's (2003) average sedimentation rate is taken as sediment accumulation at the site of study between 1663 and 2000 (which is the year of the multibeam data acquisition), then the thickness of the sedimented layer would be ~50 cm. So, it can be assumed that the principal morphologic elements of the bigger slides (e.g. scarps and resedimented failed masses in Fig. 5a, b) would be preserved after the draping of ~50 cm of "normal" sedimentation.

The multibeam imagery shows submarine channels which may have been pathways to drain mass wasting material down the slope. The main submarine channel features are located near Pointe-à-Michel in the Bestiamites Estuary area. These features represent an ancient, submarine braided channel system which was fed by slope failure material coming from the palaeo-Betsiamites Delta. The draping and filling of these channels show that the Outardes River delta is the most recent dominating system in this sector. In the Manicouagan Estuary zone, the channels seem to have migrated northwards. The active meandering drainage pattern suggests that channel incision occurred on a gently dipping slope. The southern segments of the channel exhibit sediment filling and thus demonstrate that they were inactive when the data were collected. The lack of data in this sector limits the interpretation of the dynamic processes which control the evolution of this part of the system. It can be hypothesised that those channels may have fed (for the inactive ones) or are feeding (for the active one) fan(s) eastwards in deep marine settings, as is the case for the Outardes system (Syvitski and Praeg 1989). The quasi-absence of bedforms and the omni-presence of submarine landslide signatures in the study area clearly indicate that the sedimentation mechanisms are linked to mass wasting events.

The interpreted features based on the multibeam data for the slope and on the seismic data for the pseudo-shelf show that these two parts of the system are controlled by the same sedimentation mechanisms and, thus, dominated by mass wasting events. Seismic and multibeam data have shown evidence of instability. Although the seismic and the multibeam data mostly cover two distinct areas of the system, ~800 m of the seaward portion of the C–C′ seismic line (Fig. 2) is overlapped by some multibeam data (Fig. 4b). This section shows, at the base of the lobe slope, chaotic reflectors overlain by a strong undulating reflector, typical of failure deposits. On the multibeam imagery (Fig. 4b), the portion of the surveyed area corresponding to the section of the same seismic line shows a hummocky seafloor which represents a succession of failure deposits (Hampton et al. 1996).

Conclusion

The present paper has highlighted past and modern sedimentation processes related to submarine landslides in the Outardes Bay delta sector. Seismic data show, in part, the prograding evolution of the delta in relation to relative sea-level fluctuations. Seismic lines have also contributed in underscoring the strong erosional activity imposed on the system. Bathymetric data have shown geomorphologic elements generated by active hydrodynamic processes in this area. Because of the steep regional slope, these geomorphologic constituents are constantly susceptible to reworking by mass wasting events. The three-dimensional view permitted a better appreciation of the two different slope vectors over the field of study. Even more, this view has helped to see that the Outardes system dominates the Betsiamites system.

Different factors can be cited as causes for the observed submarine landslide features: (1) sediment input due to cliff erosion by wave action, (2) high slope gradients, (3) gas, (4) earthquakes, (5) glacio-isostatic rebound and (6) storm events. Earthquakes are not believed to be a contributing factor for recent (i.e. during the past century) mass wasting generation in the field of study because of their insufficient magnitude to trigger landslides. However, the great M_S~7 1663 Charlevoix earthquake is very likely responsible, in conjunction with other factors, for some of the mass movement signatures observed in the surveyed area.

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