GEOMORPHOLOGICAL AND GEOPHYSICAL EVIDENCE OF HOLOCENE SEAFLOOR INSTABILITY ON THE SOUTHERN SLOPE OF THE LOWER ST. LAWRENCE ESTUARY, QUÉBEC.

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RÉSUMÉ

Des données récemment acquises pour la cartographie du fond marin, combinées à d'autres données acquises dans les années 80, montrent des évidences d'instabilité du fond marin le long de la rive sud de l'estuaire maritime du Saint-Laurent, au Québec. Les jeux de données incluent de la bathymétrie multifaisceaux, des échantillons du fond marin, et des profils de sismique-réflexion à très haute résolution. Parmi les phénomènes d'instabilité identifiés, on retrouve des étalements latéraux, possiblement de la liquéfaction, des décrochements rotationnels, des coulées de débris, et des glissements sous-marins de blocs de sédiments intacts. On estime que ces événements ont eu lieu depuis 7000 ans. Plusieurs facteurs peuvent contribuer à la formation des instabilités observées, incluant la sismicité, les taux de sédimentation élevés, la présence en sous-surface de gaz et autres fluides, et les changements de niveau marin relatif.

ABSTRACT

Recently collected seafloor mapping data combined with data collected in the 1980s reveal several instability features on the seabed along the southern slope of the Lower St. Lawrence Estuary, Québec. The datasets consist of multibeam bathymetry, seafloor samples, and very high resolution seismic reflection profiles. Instability features include lateral spreading, possible liquefaction, rotational slumps, debris flows, and blocky submarine landslides. Age estimates range from 7 ka to recent for failure events. A number of factors may contribute to the observed instability including seismicity, high sedimentation rates, sub-surface gas and fluids, and changing relative sea-level.

1. INTRODUCTION

The St. Lawrence Estuary is the outlet of the Great Lakes-St. Lawrence Basin, one of the world's largest freshwater basins comprising about 25% of the Earth's freshwater reserves and supporting a population of approximately 45 million people (Environment Canada 2006). The estuary was a key conduit for Late Wisconsinan ice advance (Syvitski and Praeg 1989) and ablation (Parent and Occhietti 1999; Occhietti *et al.* 2001). Its mega-scale morphology can be attributed to recent glacial excavation and erosive processes, as well as much older regional tectonic elements (Tremblay *et al.* 2003).

The Lower St. Lawrence Estuary (LSLE) is 230 km long and extends from Tadoussac in the southwest to Pointe-des-Monts in the northeast (Duchesne *et al.* in press) (Figure 1). Previous studies of the surficial sediments of the Lower St. Lawrence Estuary have focused on geophysical interpretation of the Quaternary succession (Syvitski and Praeg 1989; Massé 2001) as well as investigations of seabed stability on the north slope of the estuary and Saguenay River mouth (Duchesne *et al.* 2003; Cauchon-Voyer 2007; Massé and Long 2001).

Generally, the south slope of the LSLE is considered more stable than the north slope because regional gradients are less and large deltas that are loci of seabed instability in the north are not present on the south slope. The purpose of this paper is to present new evidence of seafloor instability in three areas along the southern slope of the LSLE, between Trois-Pistoles and Matane, Québec.

2. METHODS

This study is based on multibeam bathymetry, high-resolution seismic reflection data, and piston/gravity cores. The multibeam bathymetry data were collected in partnership with the Canadian Hydrographic Service during several surveys onboard the CCGS F.G. Creed in 2005-2006 (Campbell *et al.* 2007). The multibeam system was a Simrad EM1002, a 98 kHz multibeam system that consists of 111 beams, 2° x 2° beam angle, and has an operational range of 10-800 m. Preliminary processing of the data was conducted onboard the vessel, with final post-processing completed by the Canadian Hydrographic Service

A high-resolution geophysical and groundtruth survey was conducted during October- November 2006 onboard CCGS Matthew (Campbell 2007). The high-resolution seismic reflection system consisted of the Huntec DTS (deep-towed system). This system is towed up to 100 m below the sea

In : J. Locat, D. Perret, D. Turmel, D. Demers et S. Leroueil, (2008).
Comptes rendus de la 4e Conférence canadienne sur les géorisques: des causes à la gestion.
Proceedings of the 4th Canadian Conference on Geohazards : From Causes to Management. Presse de l'Université Laval, Québec, 594 p.

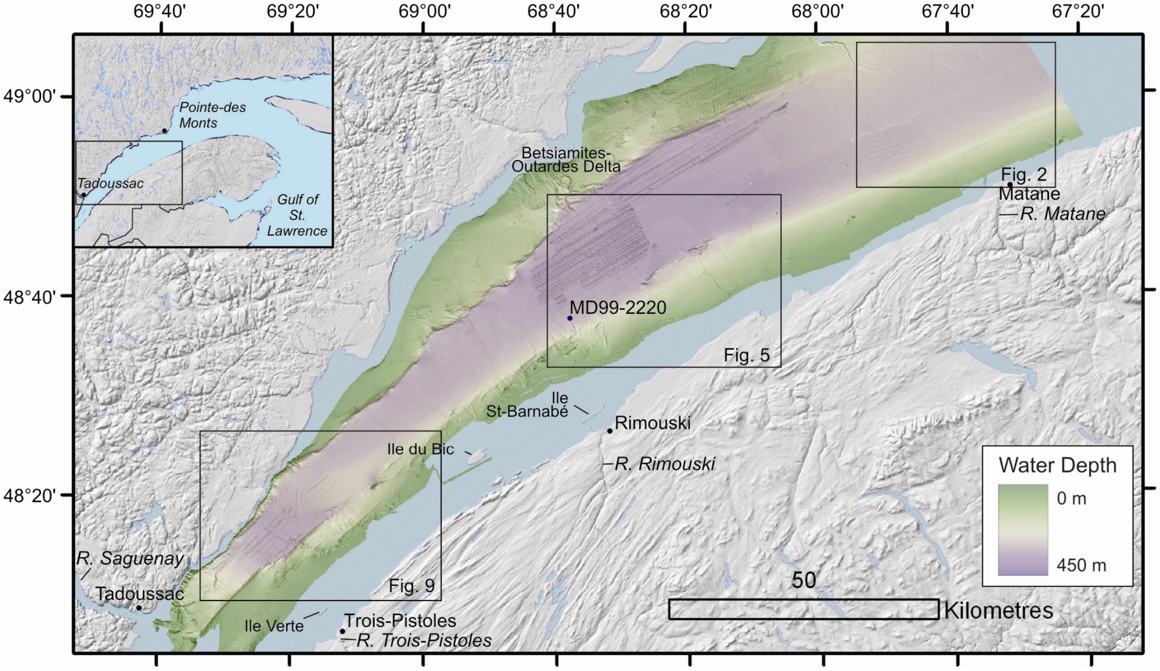

Figure 1. Map showing study area, locations mentioned in text, and location of core MD99-2220.

surface to remove noise. The system used a boomer sound source mounted on the towfish and the acoustic reflections were recorded by an internal hydrophone onboard the towfish and a 3 m hydrophone streamer towed behind the fish. The system gives a maximum vertical resolution of 0.20 m. Other groundtruth data collected during the mission included 2 m gravity cores, seafloor photographs, and VanVeen grab samples.

The data described above are supplemented by similar geophysical and groundtruth data colleted by the Geological Survey of Canada during the 1980s and 1990s, as well as two long piston cores (MD99-2220 and MD99-2221; Cagnat 2003 and St-Onge *et al.* 2003) which provide age control for much of the area.

3. GEOLOGICAL AND GEOMORPHOLOGIC SETTING

The axis of the Laurentian Channel trends parallel to the faulted contact between Appalachian and St. Lawrence Platform bedrock to the south and Grenvilian basement to the north. This contact forms the Laurentian Channel trough which varies from a half graben to graben structure, bounded by normal faults to the north and south (Tremblay *et al.* 2003). Thick deposits of Quaternary sediments partially fill the Laurentian Channel trough. The thickest deposits occur downstream from where the Saguenay River enters the estuary. Here, the deposits reach a thickness in excess of 400 m (Syvitski and Praeg 1989; Duchesne *et al.* in press). A seismo-stratigraphic framework was developed by Syvitski and Praeg (1989) and has been further refined by subsequent work (Massé 2001; Duchesne *et al.* in press). Interpretations of this seismo-stratigraphy have varied from a Last Glacial Maximum to present sequence, to several phases of glacial advance and retreat over a number of glacial cycles. The regional seismo-stratigraphic units discussed in this paper are described in Table 1.

The regional seafloor geomorphology of the LSLE is inherited from the underlying bedrock and tectonic elements, which in places were modified by glaciogenic

Table 1. Regional seismi-stratigraphic units discussed in text.

Seismic Unit	**Geological and Acoustic Character**	**Estimated age**	**Reference**
1	Lowermost unit; unconformably overlies bedrock; acoustically transparent with high amplitude upper boundary.	Unknown, possibly sampled in June 2007 (sample COR0703-029PC), awaiting results.	Syvitski and Praeg 1989; Duchesne *et al.* In Press, Cauchon-Voyer 2007
2	Conformably overlies unit 1; series of continuous, high amplitude reflections.	Unknown, sampled in June 2007 (sample COR0703-029PC), awaiting results.	Syvitski and Praeg 1989; Duchesne *et al.* In Press, Cauchon-Voyer 2007
3	Conformably overlies unit 2; thins downstream; where sampled consists of homogeneous glaciomarine clay; acoustically transparent.	~ 7.6 ka and older (MD99-2220)	Syvitski and Praeg 1989; Duchesne *et al.* In Press, Cauchon-Voyer 2007; St-Onge *et al.* 2003)
4	Conformably overlies unit 3 ; constant thickness; laminated paraglacial silty clay ; continuous parallel to sub-parallel reflections.	~7.6 ka- 6.7 ka	Syvitski and Praeg 1989; Duchesne *et al.* In Press, Cauchon-Voyer, 2007; St-Onge *et al.* 2003)
5	Conformably overlies unit 4; constant thickness; acoustically transparent.	~6.7 ka to present	Syvitski and Praeg 1989; Duchesne *et al.* In Press, Cauchon-Voyer 2007; St-Onge *et al.* 2003)

processes. The floor of the Laurentian Channel occupies a graben, while the north and south banks correspond to either the adjacent horsts or updip portions of half grabens (Tremblay *et al.* 2003). The LSLE is up to 440 m deep in the main part of the channel. The north slope is steep, with most gradients exceeding 4°, and predominantly comprises a single slope plane. In contrast, the south slope is much more gradual, between 1° and 3°, and in places is interrupted by locally steep flanks. These steeper areas are associated with streamlined bedrock highs that trend parallel to the channel axis, some of which are sub-aerially exposed (e.g., Ile du Bic, Ile Verte, Ile St-Barnabé)(Figure 1).

3.1 Previous Work on Seafloor Stability in the Area

Previous work on seafloor stability in the LSLE has been focused in the Betsiamites-Outardes Delta regions on the north slope (Cauchon-Voyer 2007; Duchesne *et al.* 2003) and at the head of Laurentian Channel, near the mouth of the Saguenay River (Massé and Long 2001).

Cauchon-Voyer (2007) conducted a detailed study of the Betsiamites area and recognized several phases of submarine landsliding based on very high resolution seismic reflection correlation and coring. Landslides were dated at 9 ka, 7.25 ka (largest event), AD 1663 (associated with the M~7 Charlevoix earthquake) and AD 1860-1870 (possibly associated with M~6 and M~6.5 earthquakes).

Duchesne *et al.* (2003) described in detail the geomorphology of several instability features in the Outardes Delta region where submarine slide scars are preserved on the modern seabed and imaged with multibeam bathymetry. They inferred that the most recent failures are possibly associated with the 1663 Charlevoix earthquake. Massé and Long (2001) illustrated several examples of large scale submarine landslides present in their seismic unit 1B (approximately seismic unit 4 in this paper) imaged on high resolution sparker data and industry multichannel seismic reflection data.

4. RESULTS

For organizational purposes, the areas of seafloor instability will be examined based on geographic extent; Area 1- north of Matane, Area 2- north of Rimouski , Area 3- north of Trois-Pistoles (Figure 1).

4.1 Area 1- Offshore Matane

Regionally, the Laurentian Channel slope off Matane has the lowest gradient in the study area. Multibeam bathymetry surveys in 2006 revealed a fissure on the seabed in the area in approximately 200 m water depth (Figure 2). The main fissure is 4 km long, 180 m wide and 15 m deep with en echelon fractures present at the western portion of the fissure (Figure 3). Approximately 800 m downslope, the seabed is hummocky (Figure 3). Pockmarks (gas escape craters) are common on the seafloor in this area (Figures 2 and 3).

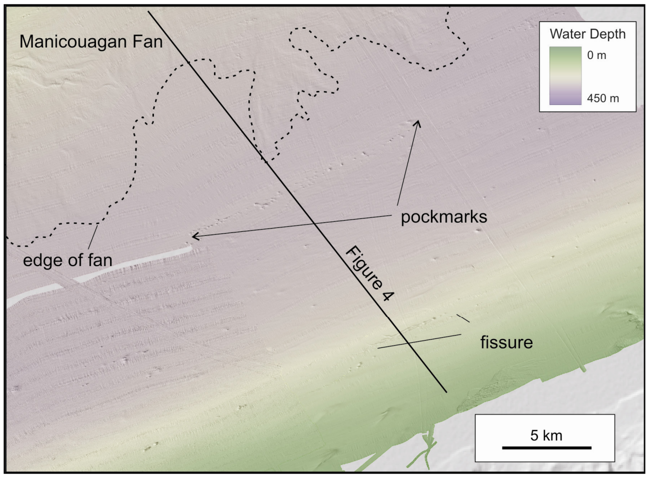

Figure 2. Seafloor surface render of Area 1-offshore Matane.

High resolution seismic reflection data show an area of acoustic wipeout below the fissure (Figure 4B). Downslope from the fissure, seismic reflections are continuous with the exception of the upper 10 m which is incoherent and undulates. This interval is correlated to seismic units 4 and 5. Further downslope from the fissure, the seismic character becomes hummocky. The disturbed interval is conformably overlain by ~ 2m of acoustically stratified sediment. The base of the acoustically stratified unit can be correlated with MD99-2220 and has an age of ~ 500 a.

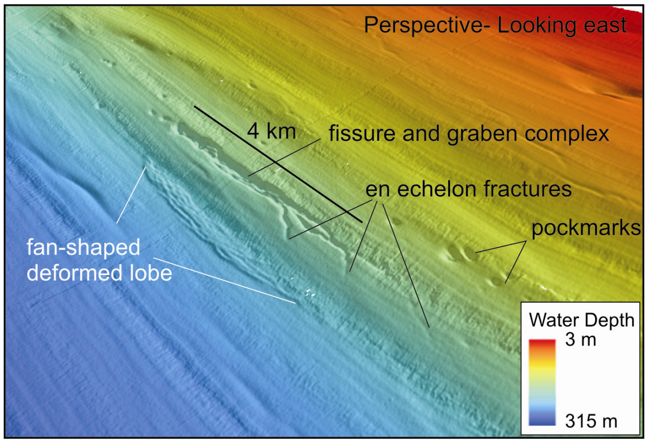

Figure 3. Perspective view of seafloor morphology in Area 1 illustrating a large instability feature and pockmarks.

Deeper in the section, seismic units 1-3 are imaged, as well as a seismic unit interpreted here and by others as bedrock (Syvitski and Praeg 1989; Tremblay *et al.* 2003; Duchesne *et al.* in press). The position of the fissure corresponds to an increase in gradient in the sub-surface geology (Figure 4). A similar configuration is observed in several other places where a subsurface change in bedrock gradient corresponds to a pockmark at the seabed, or a thinning of the overlying seismic units.

4.2 Area 2- Offshore Rimouski

The regional gradient of the slope off Rimouski is steeper than Matane, with more common streamlined bedrock outcrops at the seabed (Figures 5 and 6). The seafloor has an irregular topography, similar to the butte and channel morphology described by Cauchon-Voyer (2007) for the Betsiamites area, but more subtle (Figure 5). There is a terrace that occurs at 30 m water depth over the entire area which to the east changes to a downslope trending lineation (Figures 5 and 7). Other parallel lineations are present (Figure 5). Up-dip, the lineation coincides with the edge of a buried escarpment (Figure 7) and down-dip the lineation demarcates the edge of a lobe on the channel floor.

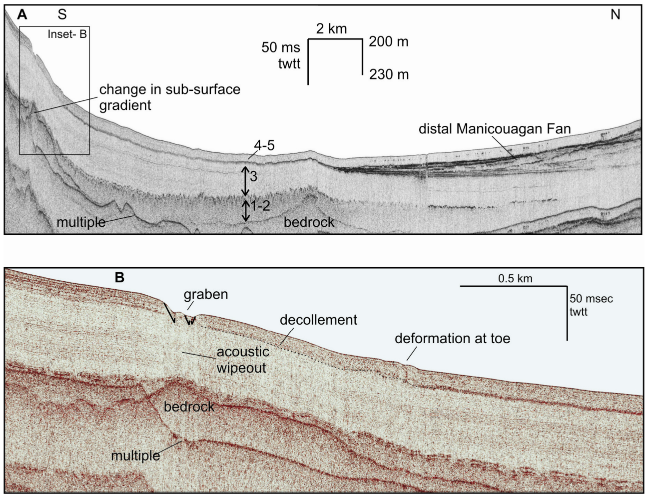

Figure 4. A) Regional Huntec DTS seismic reflection profile (envelope data) off Matane. B) Enlarged portion of Figure 4A showing in detail the seismic reflection character of the instability feature.

Syvitski and Praeg (1989) illustrated an example of a seafloor slump in Area 2 (Figure 8, their Figure 8b). As in the case of the fissure in Area 1, the headwall of the failure coincides with a change in subsurface gradient and a bedrock high. High resolution seismic reflection data from Area 2 show a widespread zone of incoherent and transparent reflections near the contact between seismic units 3 and 4 (Figure 7).

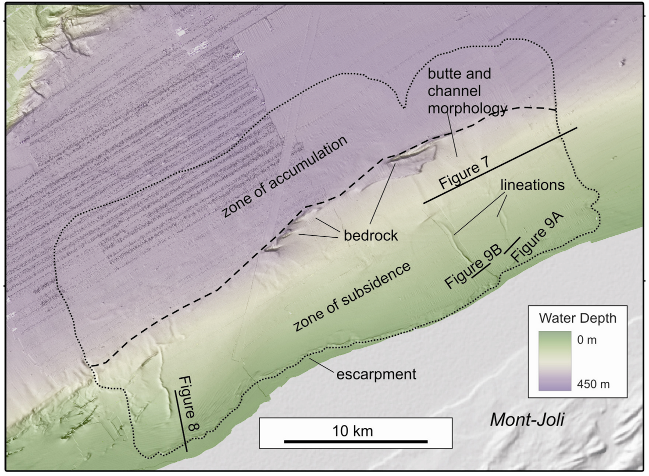

Figure 5. Seafloor surface render of Area 2- offshore Rimouski.

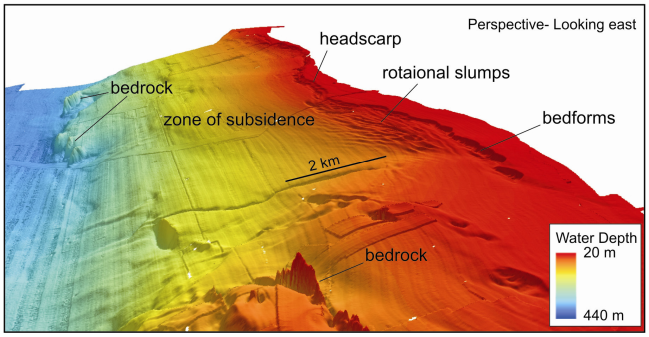

Figure 6. Perspective view of seafloor morphology in Area 2 illustrating a large area of seafloor disturbance.

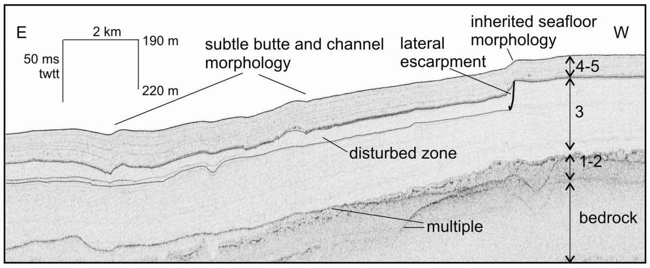

Figure 7. Huntec DTS seismic reflection profile (envelope data) in Area 2 illustrating the relationship of subsurface disturbed zones to seafloor morphology.

This seismic character is commonly associated with mass transport deposits (Mosher *et al.* 2004). In places, the base of the incoherent unit changes stratigraphic levels and these changes correlate with the butte and channel topography at the seafloor. Similarly, the downslope lineations correspond to elevation changes in the incoherent interval, with the eastern most lineation marking the edge of the incoherent zone (Figures 7 and 9).

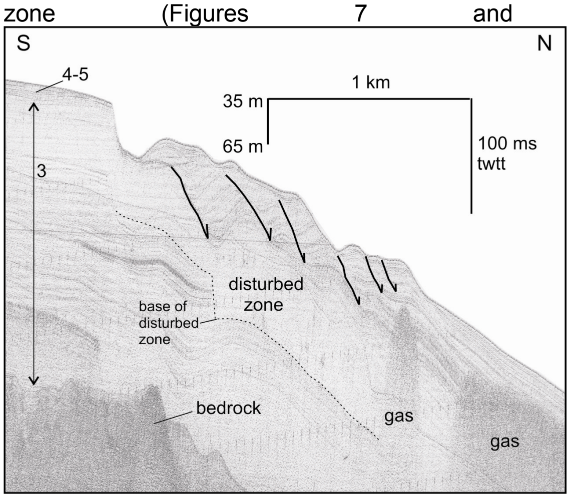

Figure 8. Huntec DTS seismic reflection profile showing near-surface slumps and a buried disturbed interval. Modified from Syvitski and Praeg (1989).

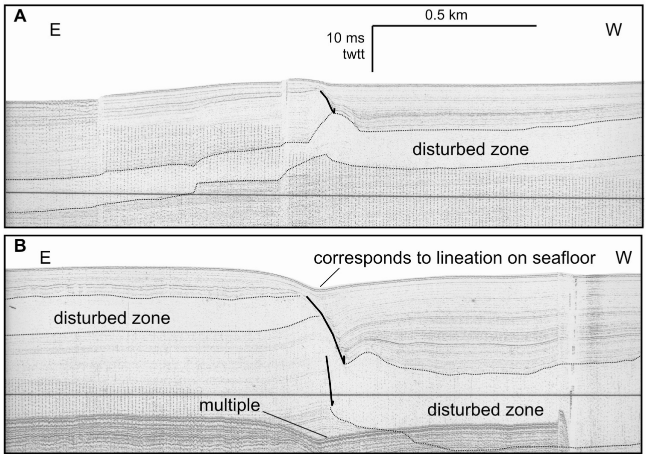

Figure 9. A) and B) Huntec DTS seismic reflection profiles illustrating a shallow disturbed zone in Area 2.

4.3 Area 3- Offshore Trois-Pistoles

The seafloor off Trois-Pistoles has a higher gradient than the area off Matane and, as in Area 2, streamlined bedrock outcrops are present (Figures 10 and 11). A terrace similar to that off Rimouski is present, but varies in water depth between 30 and 50 m and in places it has a height up to 75 m. An extensive submarine landslide is imaged on the seafloor in multibeam bathymetry (Figures 10 and 11).

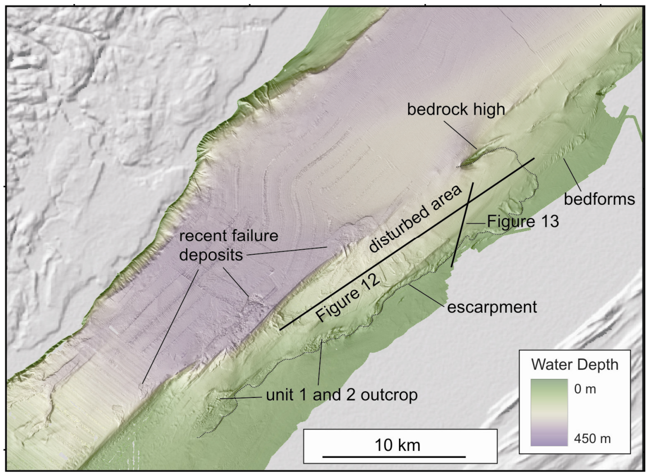

Figure 10. Seafloor surface render of Area 3- offshore Trois-Pistoles.

High resolution seismic reflection data show that thick accumulations of unit 4 and 5 occur in Area 3 (Figure 12) and reveal a complex history of erosion and deposition. There is a widespread acoustically transparent interval at the boundary between units 3 and 4 that appears to have an erosive base in seismic reflection data. Extensional and detachment features are visible in the subsurface (Figure 13). Irregular seabed and truncated reflections at the seabed indicate a recent period of erosion (Figure 12). On the channel floor, failure deposits are draped with a 1-2 m thick veneer of stratified sediment.

5. DISCUSSION

5.1 Evidence of seafloor instability

Our data show abundant evidence of seafloor instability along the southern slope of the LSLE. Seafloor surface renders of multibeam bathymetry data from Area 1 show many of the classic geomorphological features associated with lateral spreading and slumping (Doyle and Rogers 2005). These include a graben complex at the headwall, a fan shaped lobe downslope, and deformation and compression at the toe of the feature (Figures 3 and 4B). En echelon, curvilinear normal faults have developed away from the main fissure. Seismic reflection data reveal a probable decollement surface at the boundary between seismic units 3 and 4 (Figure 4B). A gravity core recovered from the toe of the slump contains tilted sandy mud beds at 60 cm down core. The composite age model developed by St-Onge *et al.* (2003) gives an age of ~500 a.

The geomorphology in Area 2, offshore Rimouski, shows evidence for lateral spreading and slumping on a larger scale than Area 1. Here, the up-dip zone displays subsidence or withdrawal over a large area and detachment at the headwall escarpment. Downslope deposition is apparent on the Laurentian Channel floor (Figure 5). On the channel floor, the slump deposits are stratigraphically below the 7.25 ka deposits of Cauchon-Voyer (2007). The morphology of the headwall escarpment may have been modified by tidal currents, as noted by Syvitski and Praeg (1989). A zone of rotational slumps is present in the southwest corner of Area 2 that are stratigraphically above the main disturbed zone for the area (Figures 6 and 8). Downslope trending lineations within the disturbed zone correspond to stratigraphic shifts in the disturbed intervals and are not channels (Figures 7 and 9).

In Area 3, the seabed has been more severely affected by submarine landsliding than in Areas 1 and 2. A 75 m high

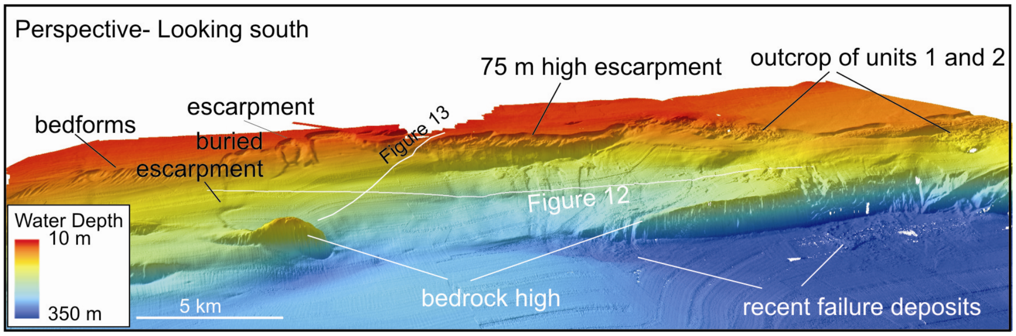

Figure 11. Perspective view of Area 3 illustrating several features discussed in the text.

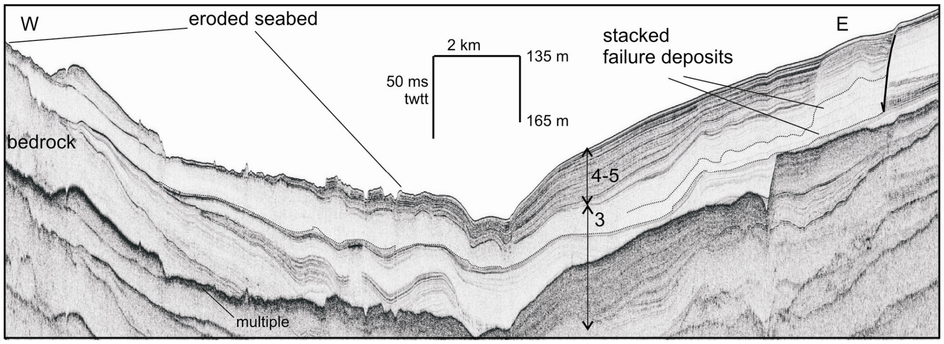

Figure 12. Huntec DTS seismic reflection profile (envelope data) illustrating evidence of recent and past seafloor instability.

escarpment exposes outcrops of seismic units 1, 2 and bedrock (Figure 10). Large blocky failure deposits are visible on the seabed surface renders (Figures 10 and 11). On the channel floor, the shallowest failure deposits are draped by ~ 2m of sediment, approximately 1000 ybp using the age model (St-Onge *et al.*, 2003). Similar to Area 2, much of the subtle seafloor morphology is related to subsurface instability features (Figure 12). The deeper widespread failed zone appears to be contemporaneous to the disturbed zone in Area 2.

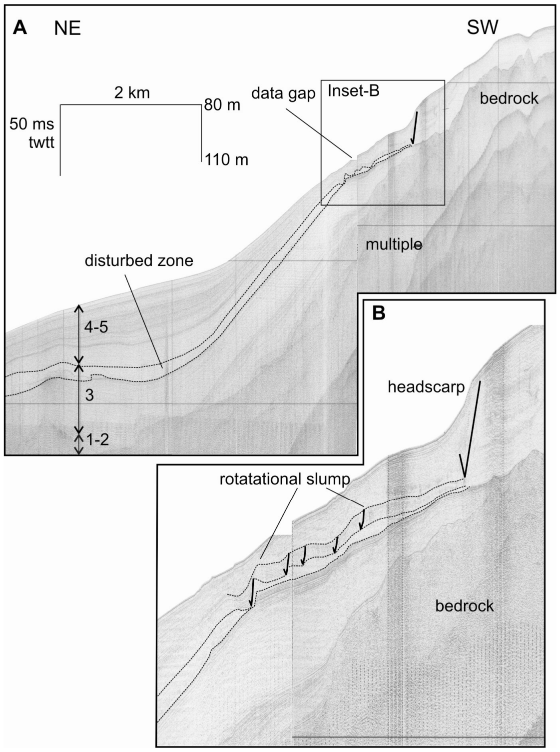

Figure 13. A) Huntec DTS seismic reflection profile showing a widespread buried/disturbed zone. B) Enlarged portion of Figure 13A showing the large headscarp and some shallow rotational slumps.

There are a number of similarities between the three areas examined in this study. In all areas, seabed failure is confined to Seismic units 4 and 5, and in particular is associated with the boundary between Seismic units 3 and 4 (Figures 4, 7, 12, and 13). Also, in all cases, the position of headscarps or headwall detachment appears to be governed by the nderlying bedrock, with headwalls coinciding with an increase gradient in underlying bedrock (Figures 4, 8 and 13). Finally, the three areas studied lie basinward of rivers, namely Rivière Matane, Rivière Rimouski, and Rivière Trois-Pistoles (Figure 1).

5.2 Contributing factors to seafloor instability in the LSLE

A number of factors could contribute to the observed seafloor instability in the study area. These are:

a) cyclical loading due to earthquakes and oceanic effects (tides and waves)
b) underconsolidated sediments associated with high sedimentation rates
c) excess pore pressures in the sediment due to high sedimentation rates and loading
d) effects of subsurface fluids on pore pressure and seafloor morphology
e) changes in pore pressure regimes due to sea-level variations
f) locally steep slopes controlled by subsurface bedrock
g) locally steep slopes resulting from erosion by tidal currents

Large intraplate earthquakes occur in Eastern Canada (Wu 1998). The LSLE is in close proximity to the lower St. Lawrence Seismic Zone and the Charlevoix Seismic Zone, the most seismically active region of Eastern Canada (Lamontagne *et al.* 2003). Significant earthquakes in the region include the 1663 Charlevoix earthquake (estimated M 7.0), the 1925 Charlevoix-Kamouraska earthquake (M 6.2) and the 1988 Saguenay earthquake (M 5.9) (earthquakes.nrcan.gc.ca). Previous authors have attributed much of the landsliding observed on the north slope to earthquakes (Cauchon-Voyer 2007; Duchesne *et al.* 2003).

High sedimentation rates can cause underconsolidation in the sediment column and result in excess pore pressure (Sultan *et al.* 2004). Latest Pleistocene/early Holocene sedimentation rates in the St. Lawrence Estuary were high. Radiocarbon dating of cores MD99-2220 and 2221 show that sedimentation rates approached 2.7 m/ka between 8500 and 7000 cal YBP (St-Onge *et al.* 2003) and coincide with the deposition of seismic unit 3. Sedimentation rates were on the order of 1.5 m/ka during deposition of seismic unit 4. These rates compare to other glaciomarine settings off eastern Canada such as St. Pierre Slope (Piper and

MacDonald 2001) and northern Labrador Shelf (Hall *et al.* 1999).

Evidence of subsurface gas has been recognized in the LSLE in geophysical records (Figure 8) (Syvitski and Praeg 1989; Duchesne *et al.* in press; Pinet *et al.* in press), as fluid escape features on the seabed (Figure 2) (Cauchon-Voyer 2007) and as gas expansion in cores (Campbell 2007). Subsurface fluid and escape features have been associated elsewhere with sediment instability (Piper *et al.* 1999; Lastras *et al.* 2004). Subsurface gas may affect slope stability by increasing pore pressures as fluids migrate towards the seafloor. Pockmarks change the local seafloor morphology and create locally steep slopes which may be initiation points for seafloor retrogression or interrupt down slope support of the shallow sediments.

The Holocene sea-level history of the LSLE is complex with a double sequence of transgression and regression (Dionne 2001). A Holocene lowstand of about 10 m below modern sea-level occurred around 7 ka, during the period of the deposition of seismic unit 4. The timing of this lowstand coincides with such depositional features as the largest failure recognized by Cauchon-Voyer (2007) and the development of the deepwater fan off Manicouagan (Figure 4A). In other studies, lowered sea-level has been associated with times of gas hydrate dissociation which may lead to seabed failure (Mienart *et al.* 2005). Gas hydrate indicators have not been recognized in the study area.

In all the areas examined in this study, the headwalls or detachment points are associated with changes in subsurface topography, where the bedrock becomes steeper. Syvitski and Praeg (1989) show examples of where they have interpreted seafloor erosion by tidal currents as flow is deflected around bathymetric highs. In fact, the headscarps in Areas 2 and 3 appear modified by seafloor currents and bedforms are visible (Figures 6 and 11). A number of bedrock highs that have seafloor expression show evidence of moating, which is attributed to current erosion.

It is unlikely that a single factor can be attributed to the observed instability features in the area. Submarine landslides, lateral spreading and debris flows are normal process in the evolution of a prograding margin; however as natural hazards they can lead to the damage or destruction of seafloor infrastructure and the triggering of tsunamis. A number of locations within the study area may be preconditioned for failure. For example, a location that has experienced high sedimentation rates, has locally steep slopes, and is in close proximity to earthquake epicenters would be more likely to fail than a location with little or no sediment accumulation and on a gentle slope.

In a future report, the proposed trigger mechanisms will be compared over the entire LSLE in order to evaluate the seabed stability for the region. For a first attempt, much of the information is available and simply needs to be integrated. For example, the seismic stratigraphy has been mapped on all available data which allows identification of the thickest Holocene deposits and where steep bedrock occurs. Modern seabed gradients can be calculated quickly in a GIS to identify areas of steep slopes. The distribution of subsurface fluid indicators has been mapped. Data exists on the location of known historical earthquakes. Other data are available on the geotechnical and physical properties of sediments from core samples.

6. CONCLUSIONS

Holocene seafloor instability features have been identified along the southern slope of the Lower St. Lawrence Estuary. These features range from lateral spreading and liquefaction to rotational slumps, debris flows and blocky submarine landslides. The ages of these events range from 7 ka to recent. A number of factors may contribute to the observed instability. Future work should be focused on examining the spatial and temporal relationships of the contributing factors and more detailed examination of the physical and geotechnical properties of seismic units 1-5.

7. ACKNOWLEDGEMENTS

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