BACK TO TABLE OF CONTENTS

SLOPE INSTABILITY SEISMIC SIGNATURES IN THE QUATERNARY SEDIMENTS OF THE ST-LAWRENCE ESTUARY (Qc. Canada).

Massé, M., McGill University, Montreal, Qc., Canada
Long, B.F., INRS Géoressources Quebec, Qc., Canada

ABSTRACT

Detailed seismic analyses of the St-Lawrence Quaternary sediments lead to a new sedimentation model and reveal several seismic evidences of slope instability, such as failure canyons, failure scars, major submarine landslides, active faults and gas horizons etc. Our analyses have indeed shown important accumulations of landslide deposits throughout the St-Lawrence Estuary, which can be up to 23km long and up to 175ms (130m) thick. These deposits were transported by different gravitational processes into the Laurentian Channel where they were laterally dispersed and formed important depocentres. These turbitique depocentres are seismically and morphologically very similar to submarine fans.

This paper represents one of the preliminary phases of the COSTA-Canada project and has for specific objective to constitute a preliminary inventory of all different slopes instability related seismic signatures for the St-Lawrence Estuary. This was done by describing the different failure structures and deposits, and relating them to different types of sediment transport processes.

RÉSUMÉ

Des analyses sismiques des sediments quaternaires de l’estuaire du St-Laurent ont permis l’etablissement d’un nouveau modele de sedimentation et l’identification des plusieurs evidences sismiques relie a l’instabilite des pentes (canyons d’effondrement, cicatrices de glissement, glissements sous-marins, failles actives et des horizons gaseux etc). Nos analyses ont d’ailleurs demontre d’importantes accumulations de depots glisses atteignant jusqu’a 23km de longueur et 175ms (130m) d’epaisseur. Ces depots ont ete transportes par differents processus gravitationels dans le Chenal Laurentien ou ils ont ete laterallement disperses et ont forme d’importants centres d’accumulation. Ces centres d’accumulation turbitiques ont une signature sismique et une morphologie similaire aux fans sous-marins.

Cet article s’inscrit dans le cadre du projet COSTA-Canada et a pour objectif de constituer un inventaire preliminaire des differentes signatures sismiques relies a des phenomenes d’instabilite des pentes. Pour ce faire nous avons procede a une description des differentes structures et depots de glissement et correle ces derniers avec differents types de transport gravitaires.

1. INTRODUCTION

Very few studies on the Quaternary sedimentation of the St-Lawrence River have been carried out. The first study was done by Nota and Loring in the St-Lawrence Estuary and the Gulf of St-Lawrence in 1961 (their results were published in 1964). D’Anglejan and Brisebois (1974 and 1978) studied the Quaternary sediments of the Upper Estuary, while Syvitski and Praeg (1989) and Praeg and al. (1992) collected and analysed high resolution seismic reflection profiles in the Middle and Lower estuaries and proposed a sedimentation model. Even though, all these authors agreed on the postglacial nature of the Quaternary sediments of the St-Lawrence, their isopach maps do not concord. According to Nota and Loring (1964) and D’Anglejan and Brisebois (1974) the Quaternary sediments do not exceed more less 30m. While, according to Syvitski and Praeg (1989) and Praeg and al. (1992), the maximum thickness vary from 50m to 300m and reach 400m at one location.

In 1991, a 114m long core was drilled near île aux Coudres, which lead to numerous studies (Sabeur, 1994; Occhietti and al., 1995; Clet and Occhietti, 1995). These studies all show that some Quaternary sediments are older than the last glacial period (Wisconsin). Todd and al. (1991) successfully correlated these core data to high-resolution seismic reflection profiles. In 1995, preliminary analysis of SOQUIP (*Société Québécoise d’Initiative Pétrolière*) low resolution seismic reflection profiles, which were collected in the 70’s and remained confidential until the 90’s, reveal that the sediment thickness in the St-Lawrence River can reach over 600 ms (more than 450 m) in more than one place (Long, pers. comm.). Finally, in 1999, during the MD-99 Cruise, two cores were drilled in the St-Lawrence Estuary, between the Saguenay Mouth and Rimouski, which were connected by a very high-resolution seismic reflection profile (Cagnat in prep.). The MD-99 preliminary results agree with those of Sabeur (1994), Occhietti and al. (1995) and Clet and Occhietti (1995).

Many authors have already pointed out these controversies and agreed on the importance to pursue the study of the Quaternary sedimentation of the St-Lawrence River. An overall project was therefore set up in order to determine the evolution of the Quaternary sediment in the St-Lawrence Estuary, between île aux Lièvres and

Rimouski (Masse, 2001). Detailed seismic analyses of the St-Lawrence Quaternary sediments lead to a new sedimentation model and reveal several seismic evidences of slope instability, such as failure canyons, turbidites, complex submarine channel system, failure scars, major submarine landslides, active faults and gas horizons etc. This paper which is based on that previous work represents one of the preliminary phases of the COSTA-Canada project which was set to assess the continental slope stability along the Canadian continental margin, estuaries and fjords with respect to natural processes and human activity (Locat, 2001). The specific objective of this paper is to constitute a preliminary inventory of all the different slope instability related seismic features for the St-Lawrence Estuary. This was done by: 1) describing the different failure structures, 2) describing the different failure deposits, and 3) relating these structures and deposits to different types of sediment transport processes.

2. METHODS

This study is based on: 1) the analysis of more than 700km of high resolution seismic reflection profiles, which were collected during three cruises (BS-97, ACH-97 and DR-98) (Figure 1), 2) the analysis of SOQUIP low resolution seismic reflection profiles (Figure 1), and 3) the Ile aux Coudres core and the preliminaries results of the MD-99 Mission. The seismic lines were shot with a sparker at 1 and 4Kj, which provided an average penetration depth of 1sec. (approximately 750m). The frequency content of the seismic data, centred on 400Hz, provided a resolution of 2.5m. SOQUIP seismic lines were shot at 8Kj, which provided an average penetration depth of 4sec. (approximately 3000m). The frequency content centred on 50Hz, which provided a resolution of 20m. Our lines were successfully correlated with the île aux Coudres core, SOQUIP seismic lines and the MD-99 preliminary results. Please note that all values in milliseconds (ms) were converted in metre (m) using the average sound speed in water (1500m/sec). Therefore, all values in metres are approximate.

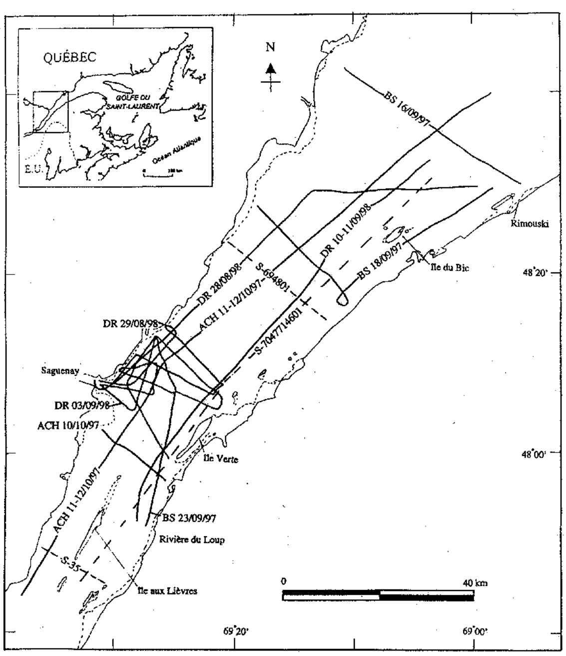

Figure 1: Seismic profiles used in this study.

3. SETTING

3.1 Submarine morphology

The St-Lawrence River bathymetric charts and the seismic profiles collected for this project both shows a very complex submarine morphology. The St-Lawrence Estuary is longitudinally divided by numerous series of rock axes. These rock axes, which are parallel or pseudo-parallel to the Estuary, are believed to correspond to the extension of the Appalachian Mountains in the St-Lawrence River (Masse, 2001). The Estuary is also divided by numerous perpendicular faults, which define a highly complex network of sedimentary sub-basins (Masse, 2001). According to these longitudinal rock axes and perpendicular faults the St-Lawrence Estuary was

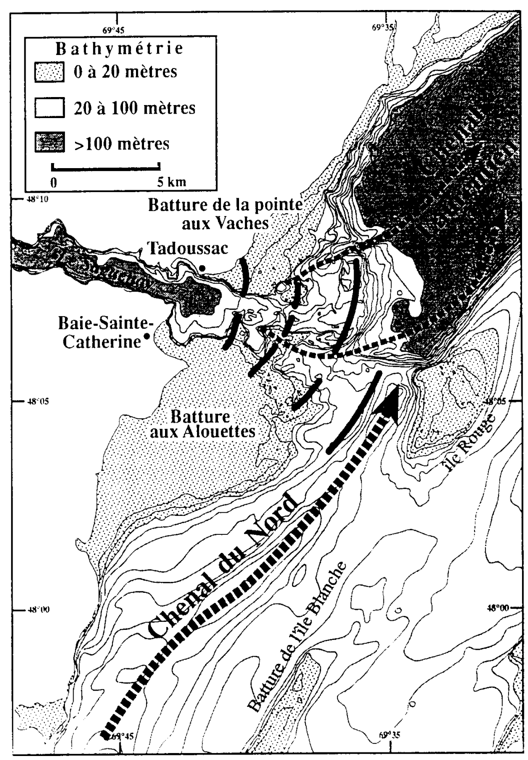

Figure 2: Saguenay Mouth submarine topography (Source : Dionne et Occhietti, 1996).

divided into five major sedimentary zones: 1) the North Channel, 2) the Saguenay Mouth, 3) the North Shore Continental Shelf, 4) the Laurentian Channel, and 5) the South Shore Continental Shelf. Most of the examples described and discussed throughout this paper come from the Saguenay Mouth and the Laurentian Channel sedimentary zones.

The submarine topography of the Saguenay Mouth sedimentary zone is marked by a series of very complex morphological elements (Figure 2). The main element being the bathymetric highs that are forming three transversal successive arcs which define three sub-basins. The two most external sub-basins are relatively shallow, from 25 to 35m deep, while the most internal sub-basin is much deeper, 50 to 135m deep (Dionne and Occhietti, 1996). The Saguenay Mouth is also characterised on each side by vast interdital flats (Battures des Alouettes and Battures aux Vaches). Finally, at about 15km from Tadoussac, and almost in the centre of the St-Lawrence Estuary, is the île Rouge sand banks zone.

The Laurentian Channel sedimentary zone's submarine topography, though also very complex, appears to be much simpler than the Saguenay Mouth sedimentary zone. The Laurentian Channel is a partially filled basin deeply incised into Grenvillian rock. The Laurentian Channel was the most important ice conduit of the Laurentian ice Sheet (Syvitski and Praeg, 1990; Piper and al., 1997). It extends over 1200 km and is located at depth over 300 to 400m, while is width vary from 60 to 80km (El-Sabh and Silverberg, 1990; Syvitski and al., 1990; Drapeau, 1992). The complex sub-marine morphological elements of both the Saguenay Mouth and the Laurentian Channel sedimentary zones largely influenced the St-Lawrence Estuary Quaternary sedimentation.

3.2 Quaternary sediments

The Quaternary sediment series of the St-Lawrence Estuary can reach over 600ms (more than 450m) in the Laurentian Channel (Figure 3). The study of the evolution of the Quaternary sediments, has shown two distinct sedimentary systems in the St-Lawrence Estuary: 1) a recent sedimentary system composed of one uncompleted sedimentary sequence and 2) an ancient sedimentary system composed of three independent, thought not complete, sedimentary sequences (Masse, 2001). These sedimentary sequences are 1) Sequence 1 postglacial sequence (probably late Wisconsinian and Holocene), 2) Sequence 2 first interglacial sequence (probably Sangamonian), 3) Sequence 3 second interglacial sequence (probably Yarmouthian), and 4) Sequence 4 third interglacial sequence (probably Aftonian) (Figure 3). These sequences were deposited during forced regression lowstands induced by glacial-isostatic rebound of the terrestrial crust after the retreat of the Laurentian Ice Sheet (Sequence 1) or during interglacial period (Sequences 2, 3 and 4). Even though this paper will consider all four sedimentary sequences, the postglacial sequence will be more specifically discussed. This sequence, which represents an almost complete sedimentary sequence is composed of four seismostratigraphic units: 1) Unit 1a – transgression systems tract, 2) Unit 1b – highstand systems tract, 3) Unit 1c – falling stage systems tract, and 4) Unit 1d – lowstand systems tract.

4. RESULTS

Detailed analysis of the seismic signature characteristics of each seismostratigraphic units and the underlying sedimentary sequences showed important evidences of slope instability such as failure canyons, turbidites, complex submarine channel system, failure scars, major submarine landslides, active faults and gas horizons.

4.1 Failure structures

Most failure structures examples come from the Saguenay Mouth sedimentary zone. There are, however, though not shown here, a few examples in the Laurentian Channel and other sedimentary zones of the St-Lawrence Estuary. The most important failure structures observed in the St-Lawrence estuary are failure scars, failure canyons, complex submarine channel system, and thick sedimentary lobes.

The failure scar illustrated in Figure 4, which is the biggest failure scar identified in the study area, has a height of 100m. This failure scar is located in the Saguenay Mouth sedimentary zone near the Head of the Laurentian Channel and most likely marks the position of

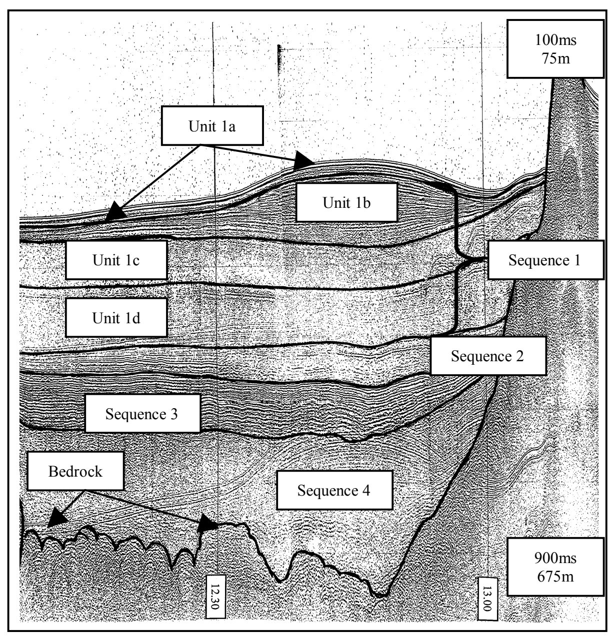

Figure 3 : Quaternary sedimentary sequences of the St-Lawrence Estuary.

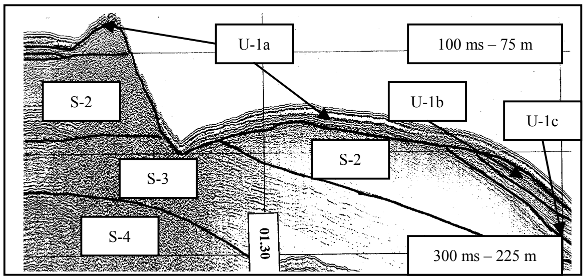

Figure 4: Example of a failure scar.

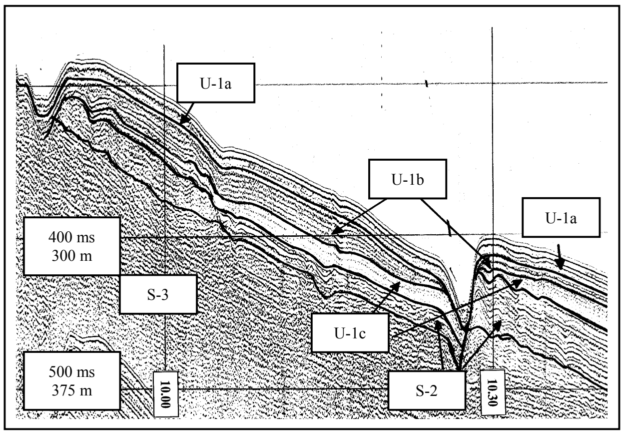

Figure 5: Examples of failure canyons.

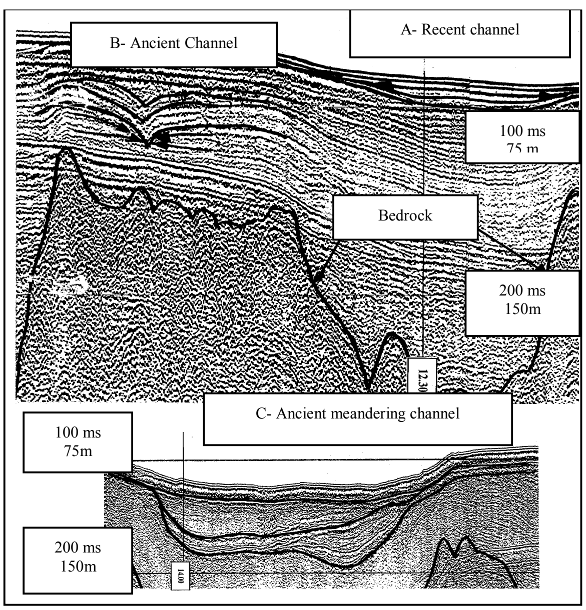

Figure 6: a) recent channel developing in unit 1a, b) ancient channel in sequences 2 and 3, c) ancient meandering channel in sequences 2 and 3.

the St-Lawrence shelf-edge paleo-delta. The failure canyons illustrated in Figure 5 are also located in the Saguenay Mouth sedimentary zone. These canyons, which may be of a few metres to tens of metres deep, have laterally grooved and eroded the seismostratigraphic Units 1a, 1b and 1c (1d being complete eroded in the Saguenay Mouth sedimentary zone) of the postglacial sequence and part of Sequences 2 and 3. Complex submarine channel networks, some of which are active, are present throughout the study area in both recent (Sequence 1) and ancient sedimentary systems (Sequences 2 to 4) (Figure 6). Some of these channel systems laterally extend over a few tens of metres. Two important sedimentary lobes, which can reach tens of kilometres long and almost a 75m thick are present in the Laurentian Channel and the North Channel sedimentary zones (Figure 7). These sedimentary lobes are seismically and morphologically very similar to deep-environment submarine fans and are made of turbidites deposits. We therefore refer to them as pseudo-submarine fans.

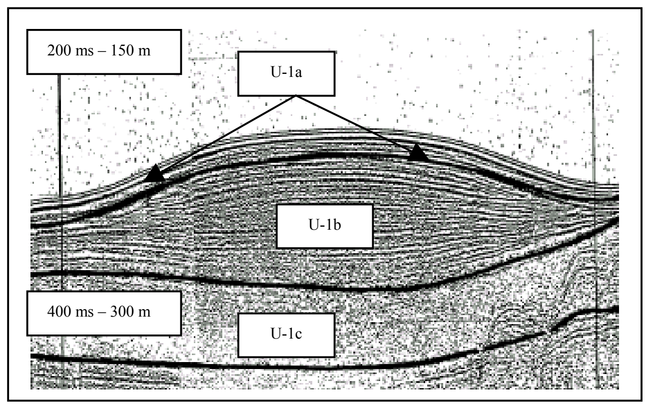

Figure 7 : Example of a sedimentary lobe.

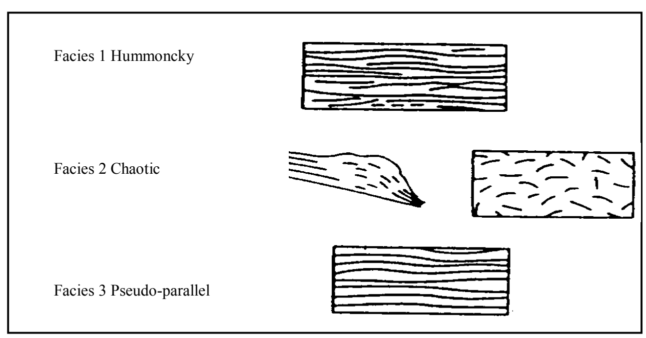

Figure 8: Seismic failure facies.

BACK TO TABLE OF CONTENTS

4.2 Failure deposits

Failure deposits, such as turbidites, are present throughout the study area and were observed in all four sedimentary sequences. They were identified with three main facies: 1) Facies 1 – hummocky facies, 2) Facies 2 – chaotic facies, and 3) Facies 3 – pseudo-parallel facies (Figure 8).

The hummocky facies is mostly associated with sedimentary lobes. These sedimentary lobes or pseudo-submarine fans are mostly present in Unit 1b of the postglacial sequence (Sequence 1) (Figure 7). Our analyses reveal that these sedimentary lobes can be up to tens of kilometres long and up to 75m thick and may also contain other facies such as chaotic facies. The chaotic facies are however mostly present at the foot of failure scars where there are important failure deposit accumulations without any define internal structure (Figure 9).

At the Head of the Laurentian Channel, sediments from Sequences 2 and 3 are characterised by a succession of hummocky facies and pseudo-parallel facies. This alternation of facies represents a superposition of thick failure sedimentary bodies and thin failure sedimentary horizons (Figure 10). The pseudo-parallel facies most likely represent either very low amplitude hummocky

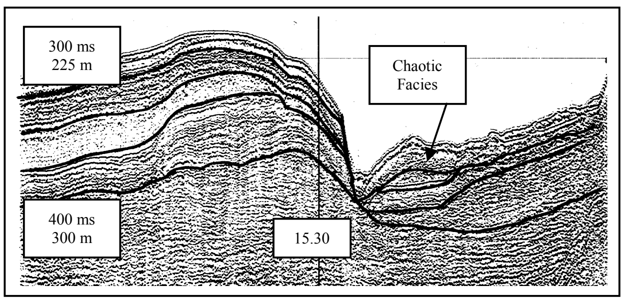

Figure 9: Example showing a failure scar and the associate chaotic facies.

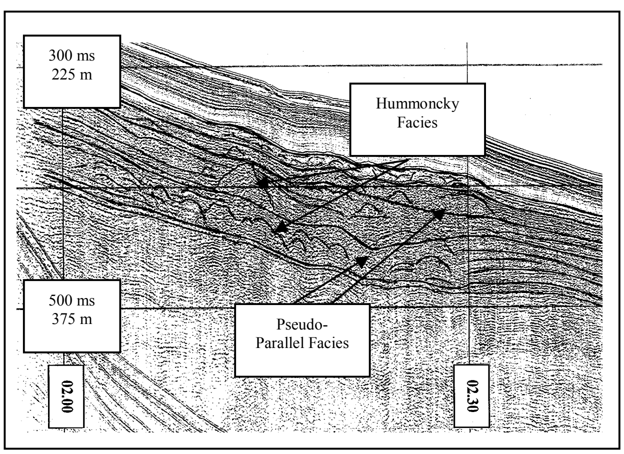

Figure 10: Example of a succession of hummoncky and pseudo-parallel facies.

facies or very low amplitude chaotic facies whose vertical amplitude would be under the resolution limit. In fact, the tomography axial analyses of the MD-99 cores show failure structures and failure deposits of only a few centimetres (Cagnat in prep.).

Finally, numerous submarine landslides of various amplitude were identified throughout the study area. At the limit between the Saguenay Mouth and the Laurentian Channel sedimentary zones, there is a major submarine landslide extending over more than 20km and affecting all four sedimentary sequences over a thickness of more than 175m (Figure 11). All three facies are present in these massive failure deposits.

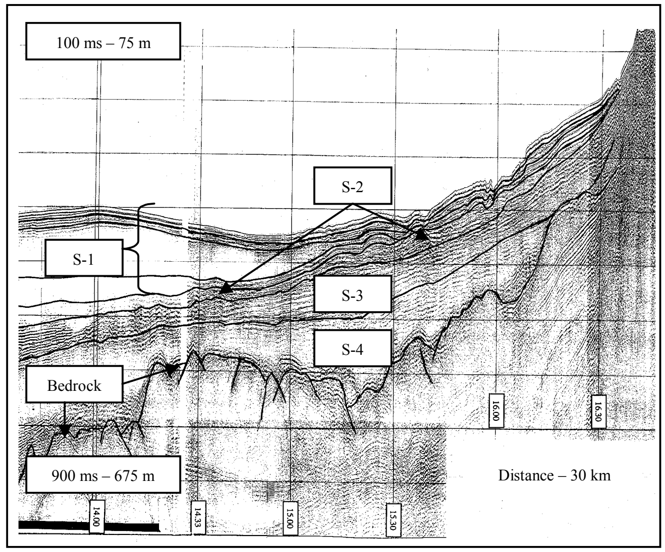

Figure 11: Example of a major failure landslide affecting all four sequences.

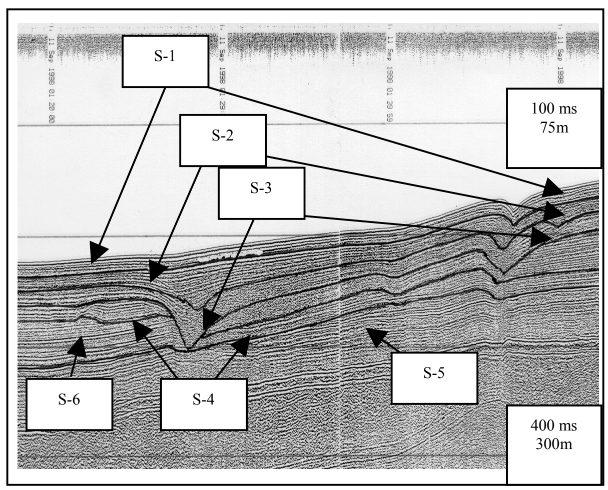

Figure 12 : Exemple of a submarine landslides probably triggered by a fault.

4.3 Faults and gas horizon

Numerous faults, some of which are still active, were identified in all sedimentary sequences throughout the study area. The submarine landslides shown on figure 12 were probably triggered by a fault. Gas horizons are however only present in the Laurentian Channel deepest water, where they can laterally extend over a few tens of meters (Figure 13). These gas horizons were identified on the MD-99 cores and seismic profile and would most likely represent gas hydrates (Long and Cagnat, 2000).

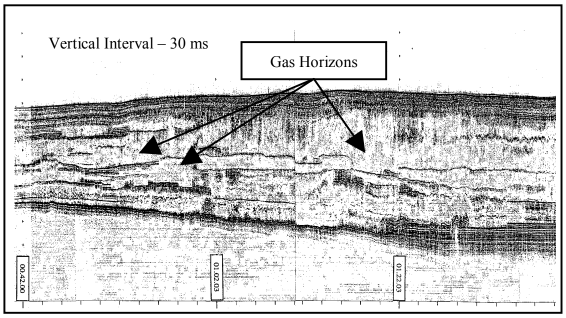

Figure 13 : Gas horizons in the Laurentian Channel.

5. DISCUSSION

5.1 Sediment sources

Further analysis of the distribution and thickness of each sedimentary sequences over the study area, along with the analysis of failure structures and failure deposits allowed us to determine the sediments sources for each sedimentary sequences. The sediments, of which the postglacial units are made of, mostly come from the St-Lawrence North Shore shelf-edge paleo-deltas. These sediments were firstly transported by gravity processes over the continental shelf and then downslope towards the Laurentian Channel south wall, where they laterally dispersed and formed important depocentres (sedimentary lobes) (Figure 7). The sediments of Sequences 2, 3 and 4 mostly came from the St-Lawrence shelf-edge paleo-delta and were transported downslope in the Laurentian Channel by a major submarine landslide, of which the breaking point is marked by the important failure scar shown in Figure 4.

5.1.1 Sedimentation Model

According to the sedimentary sequences distribution in the St-Lawrence Estuary, their seismic signatures, their particularities, and their thickness, the sediments can be grouped in two distinct deltaic systems: 1) a recent delta (Sequence 1) and 2) a series of ancient deltas (Sequences 2, 3 and 4).

5.1.1.1 Recent delta – Sequence 1

The sedimentation model proposed for the formation of the postglacial sedimentary sequence is divided in four evolution stages:

1) Stage 1 – distal deltaic very fine turbidites deposited during a marine transgression episode (Unit 1d)

2) Stage 2 – distal deltaic fine turbidites deposited during a high sea level episode (Unit 1c)

3) Stage 3 – proximal deltaic fine to coarse turbidites deposited during a falling sea level episode (Unit 1b)

4) Stage 4 – actual sedimentation low sea level episode (Unit 1a).

This model is concordant with the one proposed by Long et al. (1993) and Boespflug and al. (1994) at the île aux Coudres. Their analyses show the same succession of facies with at the base of the core very fine marine transgression deposits and highstand deposits that are overlain by an upward-coarsening succession that marks the different stages of the marine regression.

5.1.1.2 Ancient deltas – Sequences 2, 3 and 4

The formation of Sequences 2, 3 and 4 most likely followed the same evolution as the postglacial sequence. Perhaps, each of these older sequences probably followed the four stages of evolution earlier described. However, compaction and erosion of these sedimentary sequences during the glacial periods most likely explain why the four stages of evolution are either not identifiable (due to compaction) or not present (due to erosion). In many places the erosive nature of the contact surfaces (boundaries) proved that the Sequences 2, 3 and 4 were eroded in their upper part. The main difference between the recent delta and the ancient deltas dwell in the sediments sources. For each of the ancient deltas, the sediment supply mostly came from the St-Lawrence River which explains the important quantity of sediments in the Saguenay Mouth sedimentary zone and at the head of the Laurentian Channel where they formed the St-Lawrence shelf-edge paleo-delta which over hang the Laurentian Channel depression. The important failure scar at the head of the Laurentian Channel and the numerous and constant failure facies which characterised Sequences 2, 3 and 4 indicate that the sediments composing these sequences were transported by gravity towards the Laurentian Channel.

5.2 Sedimentary transport processes

The Quaternary sediments of the St-Lawrence Estuary were deposited by different gravity processes of which the three most important are: 1) debris flows deposits, 2) compression deposits, and 3) suspended load deposits. The succession of hummocky and pseudo-parallel facies is thought to represent one single event which took place first as bedload transport leading to compression deposits (hummocky facies) followed by a suspension movement, like a turbide cloud, which lead to suspended load deposits (pseudo-parallel facies). The chaotic facies represent debris flow deposits.

6. CONCLUSION

The St-Lawrence Estuary is made of four independent, though not complete, sedimentary sequences. The Quaternary sedimentary sequences can be divided in two main deltaic systems, a recent delta (Sequence 1) and ancient deltas (Sequences 2, 3 and 4). These two deltaic systems followed the same sedimentation evolution model. The main difference between these two systems lies in the sediment sources. Sediments of the recent deltaic system (Sequence 1) mostly come from the shelf-edge paleo-deltas of the North Shore of the St-Lawrence River, while the sediments of the ancient deltaic systems (Sequences 2, 3 and 4) mostly come from the St-Lawrence shelf-edge paleo-delta. In both cases, however, the same three main gravitational processes transported sediments: 1) debris flows deposits, 2) compression deposits, and 3) suspended load deposits.

This study has shown that Quaternary sediments of the St-Lawrence Estuary are mostly failure deposits and were mainly deposited by different gravitational processes. Slope instability evidences, such as failure structures, failure deposits, submarine landslides, active faults, and gas horizons are all present in both recent postglacial sediments and older interglacial sediments of the St-Lawrence Estuary. These phenomena occurred in the past, are occurring in the present and are very likely to occur in the future. Slope instability is a major natural hazard threatening economic activities and population along the Canadian coastline (1929 huge submarine landslide which generated a tsunami that killed 27 people in Newfoundland). As shown by this paper, the St-Lawrence constitutes a very good site for deltas and continental shelves stability/instability studies. The St-Lawrence Estuary being in the second most important seismic zone of Canada reinforces the need and the importance to further our studies.

7. ACKNOWLEDGEMENT

The authors would like to thank Dr. Bruce Hart of McGill University for proof reading and editing this paper.

8. REFERENCES

Boespflug, X., Long, BF, and Occhietti, S. 1995. *High Fequency Cyclicity Analysis from Scanner Density Measurements: Example of the Lower Sangamonien Formation of the St-Lawrence Estuary*. AAPG Conference, New Orleans.

Cagnat, E. *Étude sédimentologique de la série post-glaciaire-Holocène de l'estuaire moyen du St-Laurent: apport de la scanographie*. Memoir in preparation, INRS-Géorerssources

Clet, M. and Occhietti, S. 1995. *Palynologie des sédiments de la fin de l'optimum climatique de l'interglaciaire sangamonien, île aux Coudres, estuaire du St-Laurent, Québec*. Géographie Physique et Quaternaire, vol. 49, no.2, p.291-304

D'Anglejan, B.F. and Brisebois, M. 1974. *First Subbottom Acoustic Reflector and Thickness of Recent Sediments in the Upper Estuary of the St-Lawrence River*. Canadian Journal of Earth Sciences, 11, p.232-245

D'Anglejan, B.F. and Brisebois, M. 1978. *Recent sediments of the St-Lawrence Middle Estuary*. Journal of Sedimentary Petrology, vol.48, no.3, p.951-964

Drapeau, G. 1992. *Dynamique sédimentaire des littoraux de l'estuaire du St-Laurent*. Géographie Physique et Quaternaire, vol. 46, no. 2, p.233-242

Dionne, J-C. and Occhietti, S. 1996. *Aperçu du Quaternaire à l'Embouchure du Saguenay, Qc*. Géographie Physique et Quaternaire, vol. 50, no.1, p.5-34

El-Sabh, M.I. and Silverberg, N. 1990. *Oceanography of a large-scale Estuarine System: The St-Lawrence*. Coastal and Estuarine Studies, vol. 39, p.369

Locat, J. 2001. *Part II: COSTA-Canada: A Canadian Contribution to the Study of Continental Slope Stability*. Unpublished Report, p.1-15

Long, B.F, Boespflug, X., and Occhietti, S. 1995. *Cat-scan in Marine Stratigraphy: Quantitative Approach*. Marine Geology, 122, 2:281-301

Long, B.F. and Cagnat, E. 2000. Étude des hydrates de gaz de l'Estuaire moyen du St-Laurent par scanographie numérique. Internal Report, Ministère des Ressources Naturelles du Québec, Division du gaz et des hydrocarbures.

Massé, M. 2001. *L`Évolution des Dépôts Quaternaires de l'Estuaire du St-Laurent*. Unpublished Memoir, University of Quebec in Rimouski, p.128

Nota, D.J.G. and Loring, D.H. 1964. *Recent depositional conditions in the St-Lawrence River and Gulf – reconnaissance survey*. Marine Geology, 2, p.198-235

Occhietti, S., Long, B., Clet, M., Boespflug, X. and Sabeur, N. 1995. *Séquence de la transition Illinoien-Sangamonien : Forage IAC-91 de l'île aux Coudres, estuaire moyen du St-Laurent, Québec*. Canadian Journal of Earth Sciences, 32, p.1950-1964

Piper, D.J.W., Moran, K., Andrews, J. and Hesse, R. 1997. *High resolution transects of Laurentide Ice Sheet outlets (LISO): ice-sheet forcing of high-latitude climate and sedimentation systems*. Ocean Drilling Program Proposal no. 455

Praeg, D., D'Anglejan, B. and Syvitski, J.P.M. 1992. *Seismostratigraphy of the Middle St-Lawrence Estuary: A Late Quaternary Glacial Marine to Estuarine Depositional/Erosional Record*. Géographie Physique et Quaternaire, vol. 46, no. 2, p. 133-150

Sabeur, N. 1994. *Étude sédimentologique de la série Sangamonien de l'estuaire du St-Laurent*. Unpublish Memoir. University of Quebec in Rimouski, p.176

Syvitski, J.P.M. and Praeg, D.B. 1989. *Quaternary Sedimentation in the St-Lawrence Estuary and Adjoining Areas, Eastern Canada: An Overview Based on High Resolution Seismo-Stratigraphy*. Géographie Physique et Quaternaire, vol. 43, no.3, p.291-310

Syvitski, J.P.M and al., 1990. *Global Climatic Change as Measured through a Continuous Late Wisconsinan Quaternary record with Special Emphasis on the Holocene: a CCDP proposal for drilling in the Saguenay Fjord and the St-Lawrence Estuary*.

Todd, B.J., Occhietti, S. and Burns, R.A. 1991. *Seismic reflection mapping of bedrock topography and Quaternary seismo-stratigraphy of the middle St-Lawrence Estuary, île aux Coudres, Québec*. Current Research, Part D, Geological Survey of Canada, paper 91-1D, p.53-59