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Marine geology of the St. Lawrence Estuary

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Abstract. The St. Lawrence Estuary, Eastern Canada, contains a very thick (>450 m) Quaternary sedimentary sequence. The results from recently conducted geophysical surveys in conjunction with piston coring indicate that these sediments were deposited under very high sedimentation rates, sometimes as high as ~30 m/ka during the last deglaciation. Results also reveal evidence of large submarine landslides during the Holocene, changes in sedimentation rates and the significant role of submarine canyons and channels to transfer sediments from the coast to the deeper marine environment. Finally, this paper highlights the presence of more than 1900 pockmarks on the seafloor of the St. Lawrence Estuary and discusses their possible origins: active hydrocarbon seeps in the Laurentian Channel and biogenic gas seepage on the northwestern shoulder of the Laurentian Channel.

1. Introduction
During the last few years, a significant and fruitful collaboration between several universities, the Geological Survey of Canada and the Canadian Hydrographic Service allowed the acquisition of > 8000 km² of multibeam bathymetric data, ~14 000 km of seismic profiles and 700 m of sediment cores from the St. Lawrence Estuary, Eastern Canada (Fig. 1). This new high-resolution database allowed novel observations and discoveries that build upon the pioneer marine geology research conducted by the Geological Survey of Canada in the St. Lawrence Estuary and adjacent Gulf of St. Lawrence in the 1980’s and 1990’s (e.g., [1-4]). In this paper, we will review some of these recent findings and discuss their implications for stratigraphy, sedimentation, natural hazards and pockmark
genesis in the St. Lawrence Estuary. The oceanography and Quaternary geology of the St. Lawrence Estuary and Saguenay Fjord are summarized in this volume in a companion paper [5].

![Figure 1. Location of the Lower St. Lawrence Estuary, Eastern Canada. Also illustrated are the multibeam bathymetry (in background), the localities and cores mentioned in the text, the Laurentian Channel, the seismic line presented in Fig. 2 and the location of the Les Escoumins (LET) and Forestville troughs (FT; see text for details and Fig. 5).](image)

2. Stratigraphy of the Quaternary deposits in the St. Lawrence Estuary

High-resolution seismic reflection surveys conducted in the Lower St. Lawrence Estuary allowed the identification of eight seismic units, with a total sediment thickness of more than 450 m in certain areas [6]. Seismic units 1 to 5 are recognized throughout most of the estuary and are illustrated in Figure 2. Units 1 and 2 have a highly variable thickness and fill most of two major bedrock depressions that exist in the Lower St. Lawrence Estuary. Unit 3 is observed over the entire Lower St. Lawrence Estuary basin, partly infilling basins found on the bordering shelves of the estuary. Units 4 and 5 are characterized by a uniform thickness, whereas units 6, 7 and 8 were deposited by local sedimentary processes associated with submarine fans, mass wasting, and contourites along the flanks of the Laurentian Channel [6]. For example, a significant submarine fan is observed offshore the Manicouagan River ([17]; see seismic unit 6 in Figure 5).
Figure 2. Along-strike seismic stratigraphy of the Lower St. Lawrence Estuary. Illustrated are seismic units 1 to 5 (see text for details). Note the presence of seismic unit 2 throughout the profile. The top of this unit can be used as a chronostratigraphic marker (Younger Dryas). See Figure 1 for location of the seismic line. Modified from [7].
Seismic unit 1 is of unknown age, whereas stratigraphic work indicates that the upper part of seismic unit 2 can be associated with a stillstand or a local readvance of the Laurentide Ice Sheet (LIS) in the Goldthwait Sea, the proglacial sea that invaded the St. Lawrence Estuary and Gulf following deglaciation (e.g., [8-9]), at or slightly before the Younger Dryas cold interval (~12900 to 11500 cal BP or ~11100 to 10000 $^{14}$C yr BP; e.g., [10]). The coring and dating of seismic unit 2 has major implications for the understanding of the thick sedimentary sequence as it indicates that all the sediments above this chronostratigraphic marker were deposited after the Younger Dryas. In some areas, this marker reveals that more that 250 m of sediments were deposited following that event. These very high sedimentation rates can be explained by the proximity of the LIS during deglaciation, where its meltwaters were channelled into the St. Lawrence River system, allowing the deposition of a thick sequence of sediments in the St. Lawrence Estuary. Two long calypso piston cores (MD99-2220 et MD99-2221) sampled in the St. Lawrence Estuary attest to sedimentation rates as high as 30 m/ka during the deglaciation (Fig. 3), but also to a drastic reduction of these sedimentary inputs at 8500 cal BP ($7700^{14}$C yr BP; Figs 3 and 4). This drastic change in sedimentation rates is associated with the re-routing of LIS meltwaters from the St. Lawrence River system to Hudson Bay and Strait following the last outburst flood of Lake Agassiz-Ojibway at 8470 cal BP ($7700^{14}$C yr BP; [11-12]). According to Clark et al. [13], the St. Lawrence River runoff dropped from ~0.17 Sv to 0.075 Sv (1 Sv = 10$^6$ m$^3$ s$^{-1}$) following the re-routing of the meltwaters. The transition from seismic unit 3 to 4 thus marks the drastic change from glaciomarine to postglacial conditions after lake Agassiz-Ojibway final outburst flood [14]. Seismic units 4 and 5 consist of postglacial sediments. This continuous sequence can be disrupted by important mass wasting events (seismic unit 7) that can be observed either directly on the seafloor morphology or on seismic profiles. Some of these submarine landslides were sampled and consist of debris flows, slumps, turbidites or blocky landslides (see section 5).

Figure 3. Age-depth relationship for core MD99-2220 (see Fig. 1 for location). This figure illustrates the sharp transition in sedimentation rates at 8500 cal BP (black vertical line). SR=Sedimentation rate. Modified from [15].
As mentioned above, seismic unit 1 was never cored in the St. Lawrence Estuary. The upper part of seismic unit 2 was sampled and consists of ice-proximal glaciomarine sediments associated with the Younger Dryas overlain by glaciomarine ice-distal and postglacial sediments. The glaciomarine facies in the St. Lawrence Estuary is characterized by a coarser, sandier proximal facies incorporating ice rafted debris and a finer facies characterized by faintly laminated, massive or plastic silty clays or clayey silts [7, 14, 16]. These glaciomarine sediments are grey to dark grey, but lighter in color than the overlying postglacial sediments. Seismic units 4 and 5 mostly consist of dark grey bioturbated silty clays to sandy muds in the Laurentian Channel and coarser material on the shelves. The stratigraphy of the Lower St. Lawrence Estuary summarized in the model shown in Figure 5 reveals significant sediment accumulation in two troughs identified in the Laurentian Channel: Les Escoumins (LET) and the Forestville (FT) troughs. This figure also highlights the seaward thinning of the sedimentary sequence and the presence of several large submarine landslides (seismic unit 7; see also section 5). The seaward thinning of the sequence thickness indicates that the two troughs acted as important sediment traps during the Quaternary.
3. High-resolution Holocene magnetostratigraphy
The high sedimentation rates (1.2 to 30 m/ka) and the relatively fine material observed in the postglacial sediments of the Laurentian Channel allowed the reconstruction of the Earth’s geomagnetic field variability during most of the Holocene [14]. Using a suite of cores collected in the Laurentian Channel from its head to its mouth, Barletta et al. [16] constructed paleomagnetic master curves based on changes in inclination, declination and relative paleointensity. These master curves were used to determine the high frequency geomagnetic field behaviour in Eastern Canada, but they also have the potential to be used for detailed Holocene magnetostratigraphy and dating purposes.

4. Modern sedimentation in the St. Lawrence Estuary
The seaward thinning of the sedimentary sequence is also expressed in modern sedimentation rates as they diminish exponentially from about 0.74 cm/yr at the head of the Lower St. Lawrence Estuary to 0.04 cm/yr in the Gulf of St. Lawrence to about 0.01 cm/yr at the mouth of the Laurentian Channel in the Atlantic [14, 18, 19, 39]. In addition, major changes in the sedimentation rates are observed in the Lower St. Lawrence Estuary from the Late Holocene to the present, with sedimentation rates increasing from 0.15 to 0.28 cm/yr and finally to 0.74 cm/yr (Fig. 6). These changes are consistent
with land-use changes associated with the agricultural development of the European settlement in Eastern Canada, and with the industrialisation, development and growth of the towns along the St. Lawrence River during the second half of the 20th century [14]. The increase in sedimentation rates during the second half of the 20th century coincides with an increase in organic matter fluxes to the seafloor associated with eutrophication due to enhanced nutrient input since the industrialisation [20].

**Figure 6.** Changes in sedimentation rates derived from $^{210}\text{Pb}$ measurement of core AH00-2220 (see Figure 1 for location). Modified from [14].

**Figure 7.** Example of submarine canyons (C) and fans (F) identified along the North Shore of the St. Lawrence Estuary, located East of Les Escoumins. See Fig. 1 for location. A channel-levee (CL) is visible on the fan located on the right side of the image. A small gully (g) is also visible along the headscarp of canyon A. With kind permission from Springer Science+Business Media: [21], © Springer-Verlag 2009.
Modern changes in sedimentation are also observed on the shelf, especially on the North Shore of the St. Lawrence Estuary where coastal erosion significantly increased during the last decades [22]. Multibeam bathymetric data reveal the important role of submarine canyons (Fig. 7) in transferring the eroded coastal sediments from the coast to the bottom of the Laurentian Channel, contributing to the negative sediment budget observed along the coast [21]. Indeed, cores taken in fans at the base of some of these canyons (cores 76 and 77BC, see Fig. 1) revealed a quasi-exponential increase in sand inputs during the last few decades, but also the presence of a turbidite possibly associated with either the 1860 AD Rivière-Ouelle (M≈6) or 1870 AD Baie-Saint-Paul (M≈6–6.5) earthquakes [23]. Several other fans and channels can be observed on multibeam bathymetric and subbottom profiler data along the North Shore of the St. Lawrence Estuary and can be associated with modern rivers [40]. Similarly, along the North Shore of the Gulf of St. Lawrence, multibeam data collected near the city of Sept-Îles, revealed the presence of a submarine “bird-foot” channel-levee system (Fig. 8). This system most likely reflects significant recent transfer and offshore deposition of coastal sands [24].

![Figure 8. Bird-foot channel-levee system observed offshore the city of Sept-Îles (see inset in Fig. 1 for location).](image)

5. Natural hazards in the St. Lawrence Estuary
The Lower St. Lawrence Estuary is located in the Lower St. Lawrence seismic zone, where about 30 M≥2 earthquakes are recorded annually [25]. The largest historical earthquake (M=5.1) recorded in this zone occurred in 1999, about 60 km south of Sept-Îles [25]. The Lower St. Lawrence Estuary is also situated near the most active seismic zone in Eastern Canada, the Charlevoix-Kamouraska seismic zone. During the last 350 years, it was struck by at least 5 earthquakes of magnitude 6 or higher on the Richter scale (e.g., [26]), including the 1663 AD earthquake. The precise epicenter and magnitude of this earthquake are still debated [27], but it likely had a magnitude higher than 7 and occurred either in the Lower St. Lawrence Estuary or in the Saguenay Fjord. A rare combination of high-resolution geophysical, geotechnical and sedimentological terrestrial and marine observations acquired in the
Betsiamites area revealed important terrestrial and submarine features associated to that earthquake, but also to older earthquakes that occurred in the early Holocene [28-29]. Similarly, several seafloor instability features were observed in the Outardes River delta using multibeam bathymetry and were linked to the 1663 AD earthquake [30], whereas a 15-m thick turbidite was observed in the Saguenay Fjord and associated with that event [31]. In addition, Campbell et al. [32] revealed geomorphological and geophysical evidence of Holocene seafloor instabilities features on the southern slope of the Lower St. Lawrence Estuary. These features include lateral spreading, possible liquefaction, rotational slumps, debris flow, and blocky submarine landslides. According to Poncet et al. [33], some of these submarine instability features may have been sufficient to generate a tsunami. This is notably the case for a blocky submarine landslide with a 4 km long headwall escarpment near the city of Saint-Siméon (Fig. 9).

![Image of submarine landslide](image)

**Figure 9.** The Saint-Siméon submarine landslide. See Fig. 1 for location. With kind permission from Springer Science+Business Media: [33], © Springer-Verlag + Business Media B.V. 2010.

The presence of these submarine instability features can be explained by a combination of several factors in the St. Lawrence Estuary. As mentioned above, the area is located near the most seismically active zone in Canada. Furthermore, this location experienced extensive glacio-isostatic rebound (e.g., [9]) and very high sedimentation rates following deglaciation. Finally, as illustrated below, the presence of gas in the sediments is also well documented in this sector. All these factors are likely interplaying and favour the generation of submarine landslides in the St. Lawrence Estuary.

### 6. Pockmarks and gas seeping

According to Lavoie et al. [34], over 1900 pockmarks were recognized in the Lower St. Lawrence Estuary (Fig. 10). In the Matane area alone, more than 109 aligned pockmarks were counted [35]. The pockmarks in the St. Lawrence Estuary generally range from less than 100 m to ~700 m in diameter, whereas the seafloor depression associated with them ranges from a few meters to 25 m deep [34, 36]. They are predominantly observed in the Laurentian Channel and on its northwestern shoulder [36]. On
the northwestern shoulder of the Laurentian Channel, high-resolution seismic profiles acquired over pockmark fields reveal some local enhancement of reflections, as well as seismic chimneys that are common below individual pockmarks. These chimneys do not root down to the bedrock. On the other hand, most of the seismic chimneys observed in the Laurentian Channel sediments extend down to the top of the bedrock reflection, suggesting that gas is migrating from the bedrock through the Quaternary sediments and escaping at the seafloor, contributing to the formation of the pockmarks. Underwater video surveys ([37]; see video (Animation 1) in the Supplementary Data accompanying this paper), core sampling and geochemical analyses in some of these pockmarks reveal gas bubbling as well as the presence of carbonate crusts and microbial mats typical of active methane venting submarine environments [34]. These observations led Lavoie et al. [34] to conclude that the pockmarks observed in the Laurentian Channel are the result of active thermogenic gas seeps, while those observed on its northwestern shoulder are likely associated with biogenic gas due to 1) the absence of seismic chimneys rooting down to the top of the bedrock, 2) their association with submarine landslides and 3) possible higher sediment accumulation rates close to organic-rich Quaternary river inputs along the North Shore of the St. Lawrence Estuary [36].

Figure 10. Distribution of pockmarks observed on the Lower St. Lawrence Estuary seafloor. Also illustrated are the Matane pockmark train (MPT) and identified submarine landslides (red polygons). Modified from [38].

7. Conclusions
The findings highlighted in this paper partly details the Quaternary stratigraphy of the Lower St. Lawrence Estuary, a semi-enclosed basin where more than 450 m of sediments were deposited under
very high sedimentation rates. These high sedimentation rates allowed the preservation of a continuous Quaternary sediment package and suggest that the St. Lawrence Estuary has a unique potential as a long coring site to study waxing and waning phases of the Laurentide Ice Sheet and long-term environmental changes at an unprecedented resolution. The work summarized in this short paper also illustrates evidence of several significant submarine landslides and their possible association with strong earthquakes, as well as recent changes in sedimentation rates and the potential role of submarine canyons and channels to transfer coastal sediments offshore. Finally, this paper highlights the presence of an important number of pockmarks on the seafloor and the presence of active hydrocarbon seeps in the Laurentian Channel and along its shoulders.

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