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ORIGINAL

Recent transfer of coastal sediments to the Laurentian Channel, Lower St. Lawrence Estuary (Eastern Canada), through submarine canyon and fan systems

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Abstract Multibeam sonar data, acoustic sub-bottom profiles and box cores were used to study the activity of submarine canyons and fans near the city of Les Escoumins, on the North Shore of the Lower St. Lawrence Estuary (Eastern Canada). The multibeam data were used to generate a high-resolution digital terrain model that reveals the presence of a large number of canyons and fans along the northern slopes of the Laurentian Channel. This paper focuses on two of the larger canyons, and their associated submarine fans. The sub-bottom profiles on the fans reveal high-amplitude reflections at the sediment/water interface and near the seafloor surface, indicating the occurrence of layers of coarse material. A turbidite was observed in a box core sampled in one of the fans, confirming the nature of the coarse layer. Geophysical and sedimentological data indicate that the canyons and fans play an important role in transferring coastal sandy sediments to the deeper marine environments by longshore drift-initiated turbidity flows, and thereby contribute to the negative sediment budget along the coast. The morphology of the canyons indicates that they were produced by a combination of erosive turbidity flows and retrogressive failures. The two box cores sampled on the fans reveal a recent (~last 60 years) quasi-exponential increase in sand content near the surface of the cores, possibly reflecting recent deforestation and/or increased coastal erosion.

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Introduction

Submarine canyons are initiated by failures on depositional oversteepenings of continental slopes that produce bathymetric lows along which erosive sediment flows are preferentially routed (Pratson et al. 1994). Sediment flows further incise and widen canyons, leading to retrogressive failures along their walls (Pratson et al. 1994) and head (Pratson and Coakley 1996; Green et al. 2007). Submarine canyons can play an important role in evacuating large volumes of alongshore transported sand over the shelf edge and to the deeper marine environment in areas where the shelf changes in orientation (Boyd et al. 2008).

The North Shore of the St. Lawrence Estuary and Gulf (Fig. 1) is characterized by significant coastal erosion and high-energy alongshore currents (e.g., El-Sabh 1979; Drapeau 1992; Bernatchez and Dubois 2004; Morissette 2007). A recent study has shown that eroded coastal sand in the Sept-Îles area, in the NW Gulf of St. Lawrence (Fig. 1), is currently being transferred offshore by gravity flows in a submarine channel-levee system, leading to a negative sediment budget along the coast (Lajeunesse et al. 2007). Similar processes have also been reported in the St. George's Bay area (Newfoundland) located in the NE Gulf of St. Lawrence (Shaw et al. 1997). However, the extent and nature of the processes implicated in the transport of

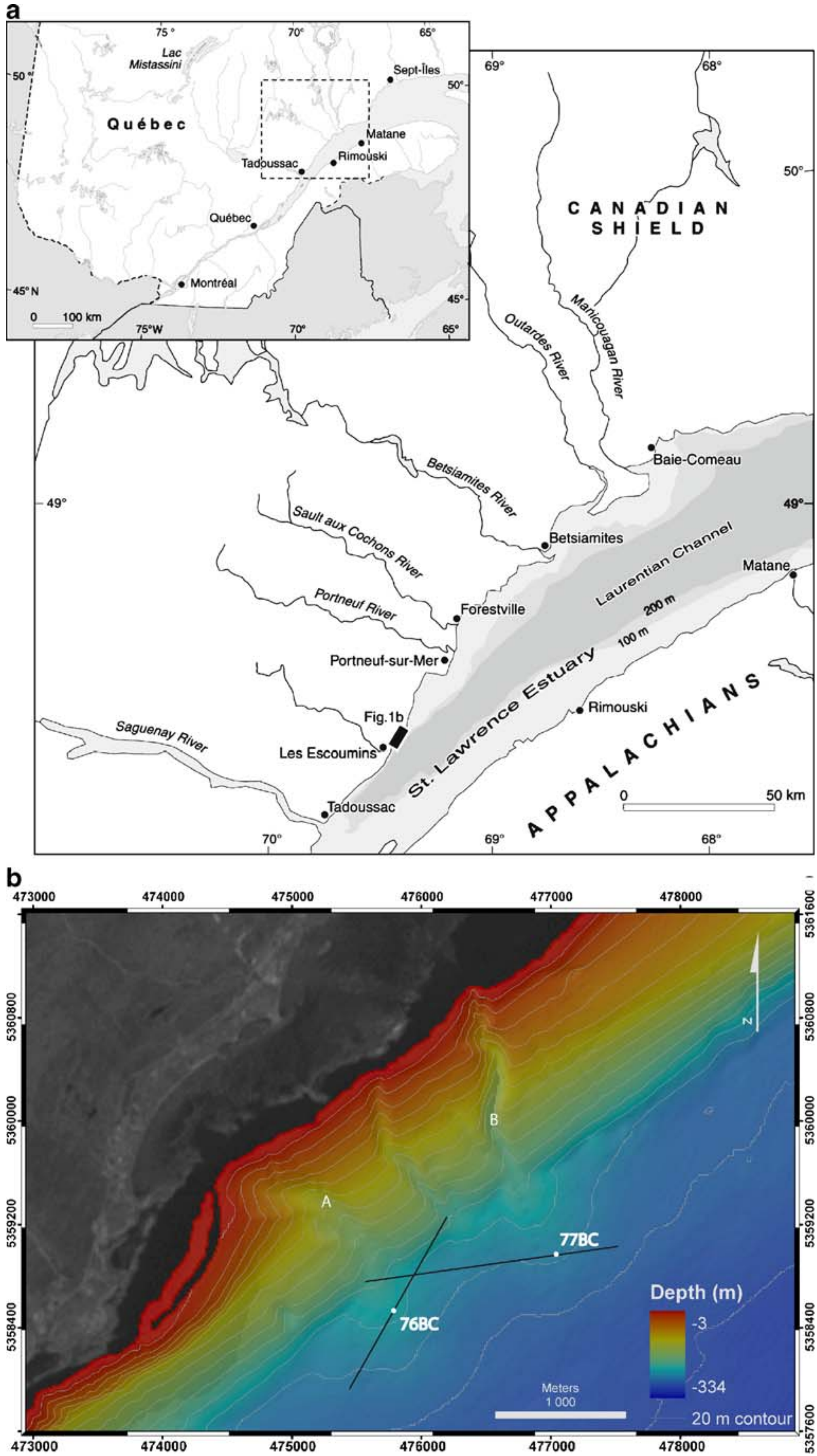

Fig. 1 **a** Location of the study area offshore Les Escoumins, in the Lower St. Lawrence Estuary (Eastern Canada). **b** Bathymetric map of the two studied canyons (*A*, *B*) and their associated fans. The locations of box cores 76BC and 77BC, and of the chirp profiles on these core sites presented in Fig. 3 are also shown. The Landsat TM image in the background shows the coastline on the *upper left side* of the figure

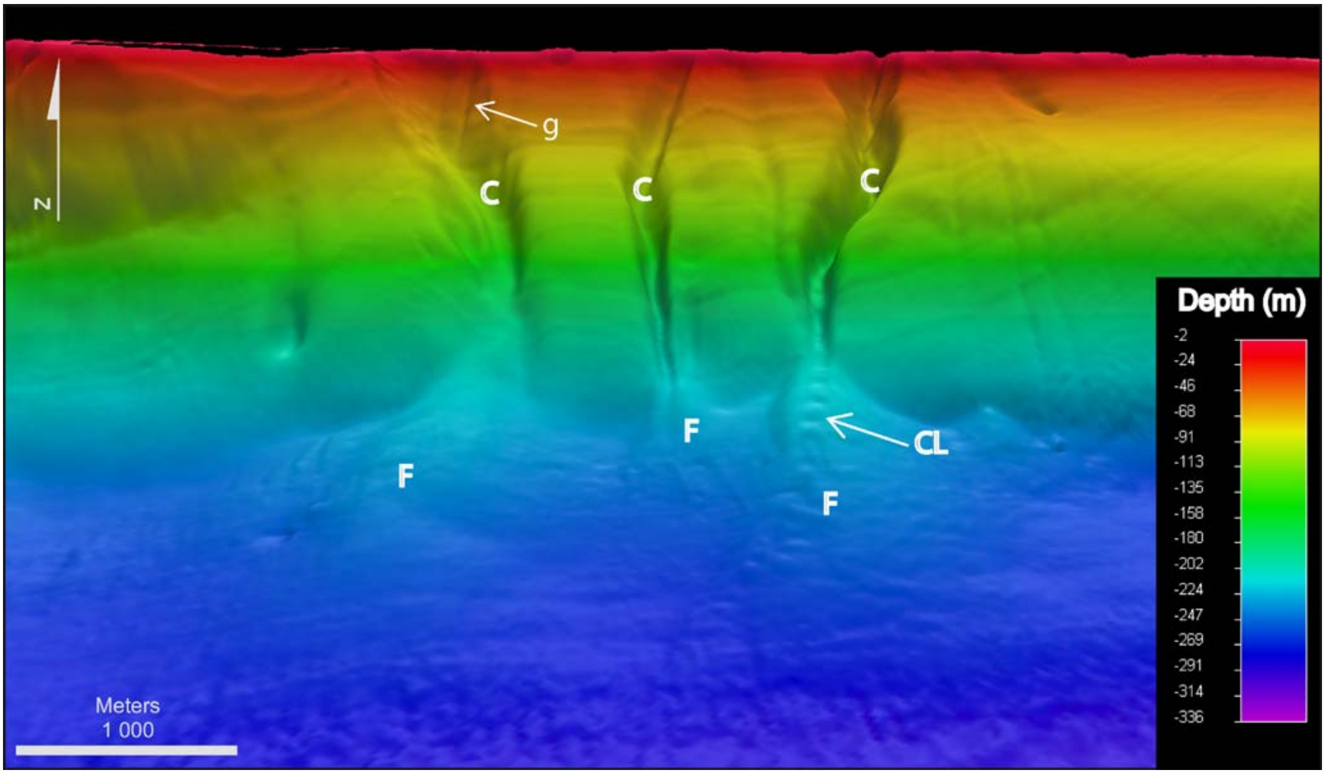

Fig. 2 Three-dimensional seafloor image of the canyons (*C*) and fans (*F*) located east of Les Escoumins. A channel-levee (*CL*) is clearly visible on the fan located on the *right side* of the image. A small gully (*g*) is visible along the headscarp of canyon A

the eroded coastal material to the deeper marine environment remain mostly unknown in the St. Lawrence Estuary and Gulf. Although submarine canyons are well documented along the continental slope of Eastern Canada (e.g., Piper 2005; Jenner et al. 2007), their presence near the coastline of the St. Lawrence Estuary and Gulf, and their possible influence on the negative coastal sediment budget of this region remain undocumented.

In this paper, we report and describe systems of submarine canyons and fans recently revealed by multibeam sonar and sub-bottom profiler surveys offshore Les Escoumins, Lower St. Lawrence Estuary (Québec, Canada; Figs. 1, 2). These submarine features are located at the limit between the coastal shelf edge and the Laurentian Channel, a prominent E–W-oriented U-shaped submarine valley of depths that grade westward from 240 to 300 m in the region (Fig. 1). The objectives of this paper are to determine whether these canyons and fans are active systems, and whether they play a role in transferring coastal sandy sediments to the bottom of the Laurentian Channel.

Study area and physical setting

The systems of submarine canyons and fans discussed in this paper are located at the edge of the coastal shelf offshore Les Escoumins (48°23′N, 69°19′W, Lower St. Lawrence Estuary (Eastern Canada; Figs. 1, 2). This shelf forms a relatively flat, 500–to 600-m-wide surface with a maximum slope of 2º and depths of up to 10 m. Slope gradients increase abruptly to 15º beyond the shelf edge over a distance of 1,500 m to reach the Laurentian Channel. Bedrock geology of the coastal shelf consists mostly of late Proterozoic Grenvillian igneous and metamorphic rocks (Hocq 1994; Duchesne et al. 2007), whereas the basement of the Laurentian Channel consists of autochthonous Paleozoic rocks of the St. Lawrence platform (Sanford 1993; Pinet et al. 2008). In the Lower St. Lawrence Estuary, the Laurentian Channel is characterized by a thick sequence of Quaternary sediments that can reach >400 m (Syvitski and Praeg 1989; Duchesne et al. 2007), including <250 m of postglacial sediments (St-Onge et al. 2008).

In this sector, the coastal currents dominantly flow in an E–W direction (El-Sabh 1979). The sand bars of the Portneuf Peninsula and offshore Portneuf-sur-Mer (Fig. 1a) are the result of this NE–SW longshore drift (Morissette 2007). Deep-water sediments collected by two long piston cores in the Laurentian Channel offshore Rimouski consist of dark gray, bioturbated silty clays and dark gray, bioturbated sandy mud (St-Onge et al. 2003). Shallow-water sediments collected on the northern shelf of the Lower St. Lawrence Estuary consist of homogenous, dark, massive silty clays with sand layers and traces of bioturbation (Cauchon-Voyer 2007). Nota and Loring

(1964) also report poorly sorted, coarse-grained nearshore sands and soft pelites in the deeper parts of the Estuary.

Recent sedimentation rates in the Lower St. Lawrence Estuary derived from ^{210}Pb measurements vary between 0.29 and 0.11 cm year^{-1} on the shelf in the Betsiamites area (Cauchon-Voyer et al. 2008), and between 0.74 and 0.28 cm year^{-1} in the Laurentian Channel offshore Rimouski (St-Onge et al. 2003). According to Smith and Schafer (1999), sedimentation rates in the Laurentian Channel decrease exponentially with distance seaward, from 0.70 cm year^{-1} near the head (Les Escoumins) to 0.04 cm year^{-1} in the Gulf of St. Lawrence. Offshore Sept-Îles, on the northwestern shelf of the Gulf of St. Lawrence, Lajeunesse et al. (2007) calculated an average sedimentation rate of 0.14 cm year^{-1}.

Materials and methods

The multibeam data were collected in 2007 (Bolduc et al. 2007) by the Canadian Hydrographic Service (CHS) onboard the CCGS *F.G. Creed*, using a Konsberg-Simrad EM-1002 (95 kHz, <−30 m), and the CCGS *Guillemot* in 2007, using an EM-1000 (95 kHz, >−30 m). DGPS uncertainties for the multibeam data are ±1 m; vertical resolution of the data is ±20 cm.

Three-dimensional visualization of the seafloor was realized using the Fledermaus® software. Two kilometers of chirp profiles (EdgeTech X-Star 2.0, 2–24 kHz) and two box cores were collected on submarine fans in 2006 onboard the R/V *Coriolis II* (Fig. 1b). Core positioning was obtained using the acoustic tracking system Trackpoint II, yielding a precision between 5 and 50 m.

The box cores (COR0602-76BC and-77BC) were run through a Geotek multi-sensor core logger for the determination of wet bulk density by gamma ray attenuation. The top and bottom 4 cm of each core were excluded to avoid erroneous data created by the integration of voids. The cores were also run through a CAT-scan for the identification of sedimentary structures and extraction of CT numbers with a 1-mm downcore resolution (e.g., St-Onge et al. 2007; Gagnoud et al. 2009). CT number profiles primarily reflect changes in bulk density (e.g., St-Onge et al. 2007). The cores were then split, photographed, and described.

Color reflectance measurements were performed on the split cores using a hand-held X-rite DTP22 digital swatchbook spectrophotometer. Reflectance data are reported as L* from the widely used Commission Internationale de l'Éclairage (CIE) color space, in which L* ranges from 0 (black) to 100 (white).

Grain-size distributions were determined with a Beckman Coulter (0.04 to 2,000 µm) laser sizer at 1-cm intervals on disaggregated samples, and processed with the Gradistat program (Blott and Pye 2001). The results of at least three runs were averaged.

Sedimentation rates were derived using ^{210}Pb measurements on sediments of the two box cores following routine

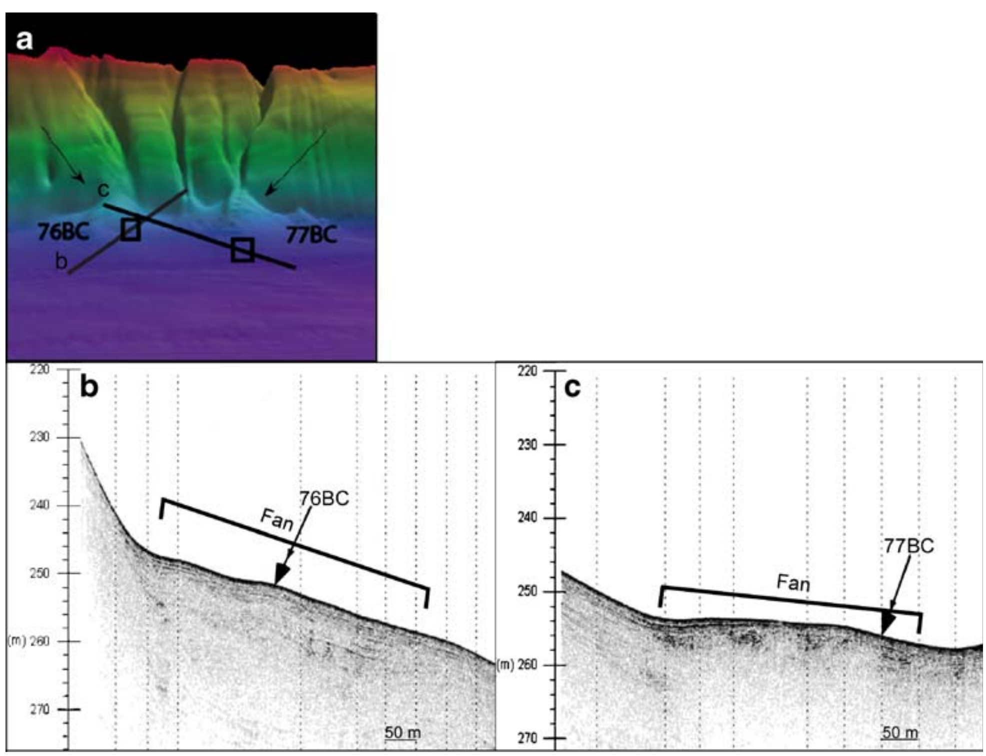

Fig. 3 Location of 76BC and 77BC coring sites, and of the chirp profiles on these sites. **a** Location of the two box cores (*squares*), and the two chirp profile lines over the fans. The two fans are located below the *arrows*. **b** Chirp profile at the sampling site of core 76BC. **c** Chirp profile at the sampling site of core 77BC

procedures at the GEOTOP research centre (Zhang 2000), using the formula

$$SR = -[\ln(2)/(slope*22.3)]$$

where SR is the average sedimentation rate, assuming a constant rate. The slope is calculated on the ln $^{210}Pb_{excess}$ versus depth graph.

Results

The multibeam data reveal the presence of two large canyons and their associated fans, as well as another smaller central canyon and its associated fan offshore Les Escoumins (Fig. 1b). These canyons are the first three of a series of canyons that spread between Les Escoumins and the Saguenay Fjord mouth. Fans are observed at the base of the shelf slope, and often coalesce below the canyons. Canyon A, located in the west, is 1,500 m long, 25 m deep, and 400 m wide. Its associated fan is 1,400 m long, 35 m high, and 600 m wide. Canyon B, located in the east, is 1,500 m long, 45 m deep, and 300 m wide. Its fan is 1,600 m long, 45 m high, and 800 m wide. Both canyons terminate at ~250 m water depth. Both canyons have headscarp heights of 15 m. The headscarp slope is 13° in canyon A and 23° in canyon B. The distance from headscarp to toe is 1,000 m in canyon A and 1,300 m in canyon B. The slope runout is 6 to 7° in both canyons. A <40 m wide and >200 m long gully is visible along the eastern side of the headscarp slope of canyon A (Fig. 3), and indicates the activity of erosive turbidity currents. Other gullies of smaller size are faintly visible along the headscarps of these two canyons. The canyons breach the shelf edge, canyon A extending ~200 m and canyon B ~150 m onto the shelf. They are located near the coastline in a sector where the shelf is narrower than elsewhere (Fig. 1). Both canyons broaden headwardly.

Chirp profiles on the fans show convex high-amplitude reflections located at the sediment/water interface (Fig. 3), suggesting the presence of coarse sediments. Many short, convex high-amplitude reflections are also observed near the surface, suggesting the occurrence of layers of coarse

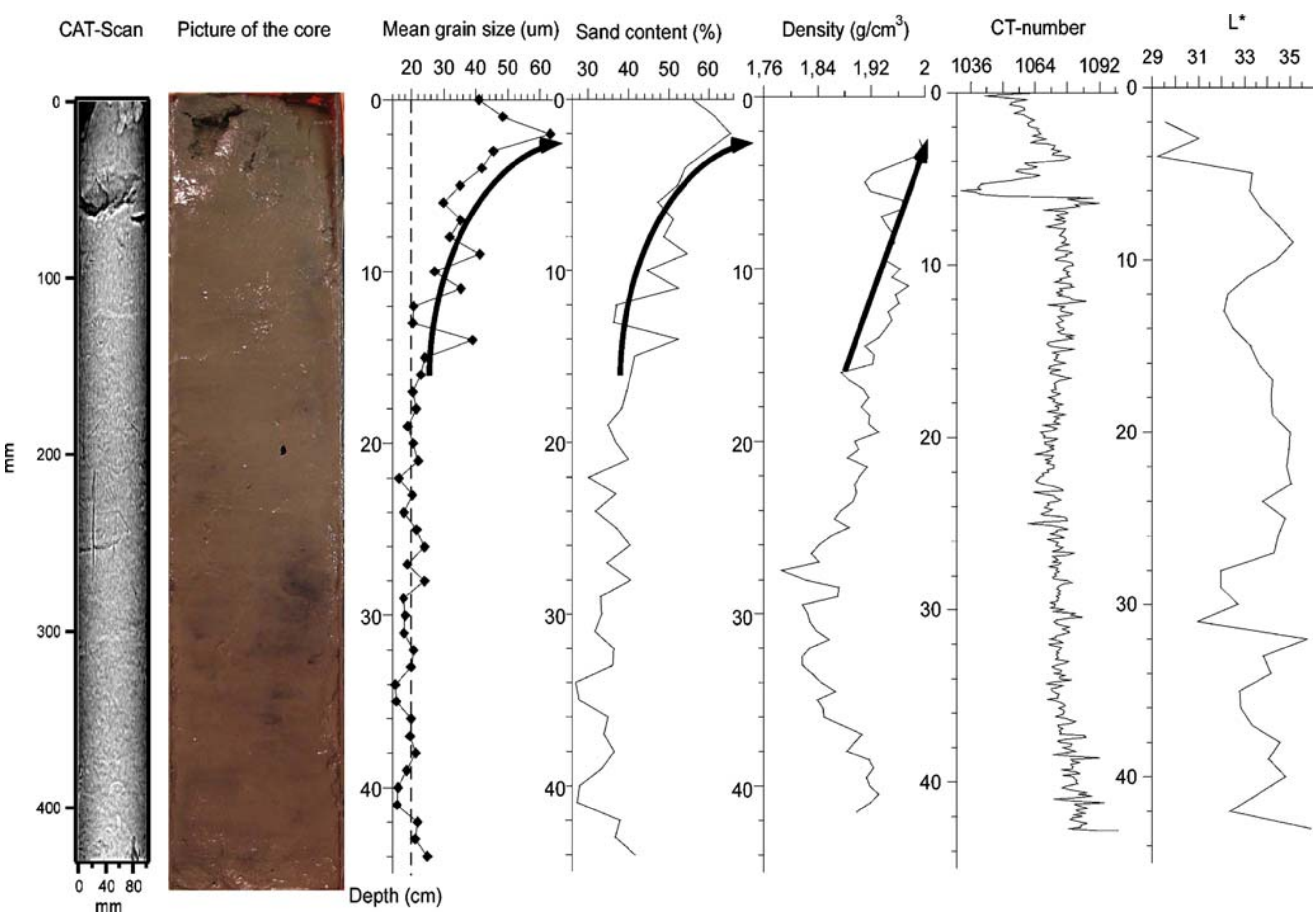

Fig. 4 Sedimentological and physical properties of core 76BC. The *arrows* illustrate the increase in sand content near the surface (above 16 cm), and its effect on the wet bulk density. The *dashed line* illustrates the mean grain size of "normal" hemipelagic sediments (20 µm)

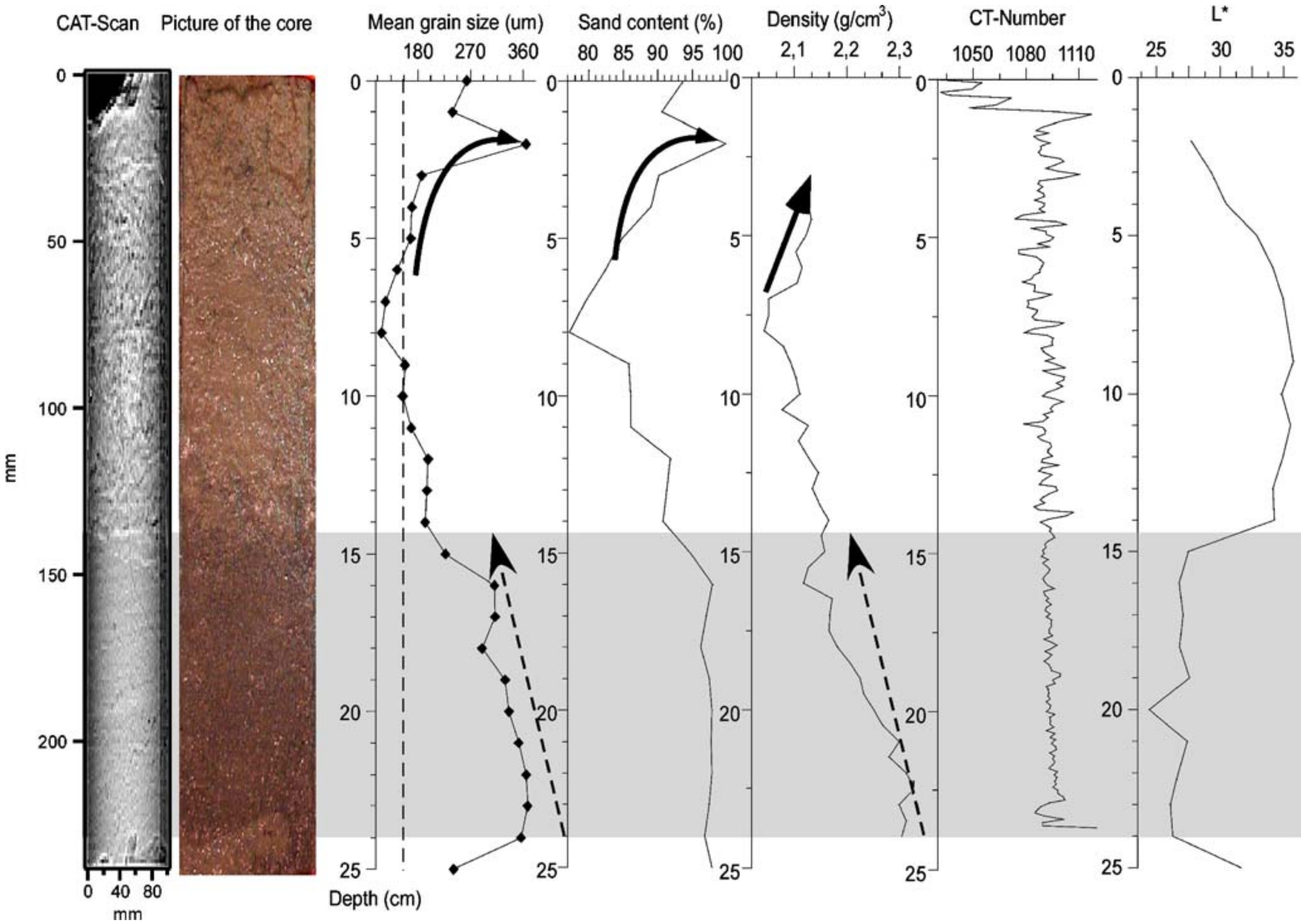

Fig. 5 Sedimentological and physical properties of core 77BC. *Solid arrows* illustrate the increase in sand content near the surface (above 5–6 cm), and its effect on the wet bulk density. The *dashed line* illustrates the mean grain size of "normal" hemipelagic sediments (157 µm). The *gray zone*, and corresponding *dashed arrows* highlight the turbidite discussed in the text

material. The fans are formed by a build-up of such hyperbolic reflections.

Core 76BC is composed primarily of silty sand. The data on this core (Fig. 4) reveal a coring artifact at 6–7 cm that produces a depression in the CT number and density curves. From a depth of 16 cm upward to 1–2 cm, a quasi-exponential increase in the mean grain size and in the sand content is observed (20 to 65 µm). Above 1–2 cm, the mean grain size decreases to 40 µm. Below the increase in sand content, the sediments are composed of approximately 35% sand, 45% silt, and 15% clay (<2 µm). The mean grain size of the "normal" hemipelagic sediments is 20 µm (Fig. 4).

The analysis of core 77BC (Fig. 5) reveals the presence of a normally graded layer between 14 and 24 cm, which contains numerous shell fragments**.** The base of this layer is characterized by an erosional contact clearly visible on the CAT-scan image and the core photograph (Fig. 5). Above this erosional contact, from the bottom to the top, massive sands, sands with parallel laminations, followed by cross-laminated sands are observed within the graded interval. The mean grain size is lower above and below this normally graded and laminated sandy bed. The sandy bed is also characterized by a darker color, as revealed by both the core photograph and L* values, whereas the normal grading is highlighted by a decrease of values on the density profile, and by a stability of the CT numbers (i.e., less variations than above and below the bed; Fig. 5). A quasi-exponential increase in the mean grain size starts at around 5–6 cm (155 µm), reaches its maximum at 2 cm (380 µm), and then decreases again (~250 µm). The peak at 2 cm is composed of almost 100% sand. The mean grain size of the "normal" hemipelagic sediments is 157 µm (Fig. 5). Overall, the sediments of core 77BC are coarser than those of core 76BC.

^{210}Pb analyses indicate sedimentation rates of 0.28 cm year^{-1} for the top 26 cm of core 76BC, and 0.09 cm year^{-1} for the top 11 cm of core 77BC (Fig. 6). Based on these rates, the quasi-exponential increase in sand contents observed near the surface of both cores must be a recent feature (last ~60 years).

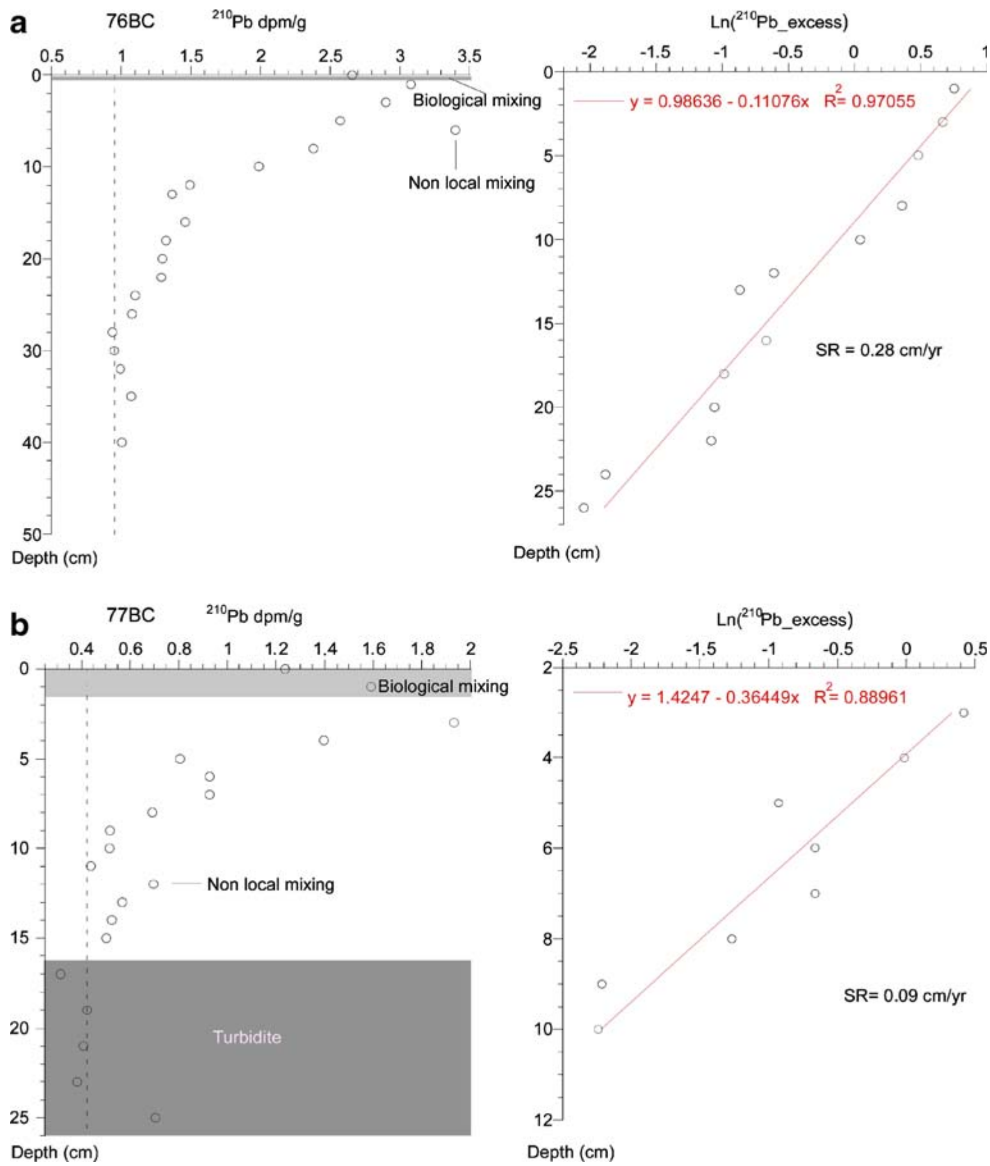

Fig. 6 ^{210}Pb measurement of cores **a** 76BC and **b** 77BC. The graphs on the *left* illustrate the ^{210}Pb activity, those on the *right* the ln($^{210}Pb_{excess}$). *SR* Sedimentation rate, *dashed vertical lines* supported ^{210}Pb

Discussion

Turbidite

We interpret the normally graded and laminated sand bed of core 77BC (14–24 cm) as a classical Bouma-type turbidite (Bouma 1962). This interpretation is supported by the presence of many shell fragments, and the erosion surface at the base of the turbidite. A high-amplitude reflection near the surface of core 77BC (~25 cm deep; Fig. 3c) can be correlated with the turbidite. This relation indicates that the convex high-amplitude reflections of the fans may correspond to sand layers such as those observed in the turbidite of core 77BC (e.g., Wang and Hesse 1996; Weaver et al. 2000; Bourillet et al. 2006). The convex and rounded geometry of the fans probably originated from the build-up of such mass movement deposits that were channelized by the canyons.

As mentioned above, the sediments in the turbidite are darker (Fig. 5), possibly resulting from the incorporation of terrestrial organic matter. Remobilization of terrestrial organic matter was actually noted by Cauchon-Voyer et al. (2008) in a debris flow observed in a core from the Betsiamites area (Fig. 1). This turbidite could thus have resulted from a terrestrial mass movement event. By using the ^{210}Pb-derived sedimentation rate for core 77BC (0.09 cm year^{-1}), the top of the turbidite was dated at about 1850, which is in the range of the 1860 A.D. Rivière-Ouelle (M~6) or 1870 A.D. Baie-Saint-Paul (M~6–6.5) earthquakes (Smith 1962; Gouin 2001). The earthquake may have caused a landslide that initially evolved into a debris flow, and then into a turbidite (Piper et al. 1985, 1992). The epicenters of these two earthquakes were approximately 100 and 120 km off the Les Escoumins area, respectively. Cauchon-Voyer et al. (2008) dated a debris flow in the Betsiamites area belonging to the same period (1860–1870). Alternatively, the landslide could have been initiated below sea level.

Increase in sand content near the surface

The quasi-exponential increase in sand content near the surface of cores 76BC and 77BC is associated with a trend that began, as indicated by the ^{210}Pb measurements, around 60 years ago. Cauchon-Voyer (2007) observed such a surficial sandy layer in cores collected in the Betsiamites area (Fig. 1). The higher sedimentation rate observed in core 76BC (0.28 cm year^{-1}/0.09 cm year^{-1}) is probably related to the distance between the mouth of the canyon and the position of the core on the fan, as core 76BC was sampled closer to the mouth of canyon A than core 77BC from canyon B. Core 77BC was sampled at the edge of the fan of canyon B (Fig. 3c). Both rates suggest very recent sedimentation, being within the same range as observed in the Betsiamites area (Cauchon-Voyer et al. 2008), in the St. Lawrence Estuary and Gulf (Smith and Schafer 1999; St-Onge et al. 2003), and in the Sept-Îles area (Lajeunesse et al. 2007).

Two mutually non-exclusive hypotheses are invoked to explain this trend:

1. Recent deforestation of the Les Escoumins–Forestville area and other sectors of the North Shore. The Les Escoumins–Forestville area was marked by an important increase in population and extensive deforestation after the Second World War (Savard 1998). This change in land use could have led to an increased delivery of sand to the marine environment due to increased rates of soil erosion in deforested territory, whereas the decrease in sand in the upper 2 cm of both cores could reflect a recent change in the practice of logging companies that now keep a riparian buffer zone between their cuttings and the river banks (Savard 1998), thereby reducing sediment yields (e.g., Sheridan et al. 1999).
2. A recent increase in coastal erosion rates along the North Shore. For example, the Forestville coastline has an 8-km-long and 40–85 m high sandy cliff (Fig. 7) that has been eroding at rates reaching 0.4 m year^{-1} between 1931 and 1987 (Soucy 1988). Similarly, erosion along the sandy coast of the Portneuf peninsula (Pointe-au-Boisvert; Fig. 2) is also strong, reaching ~1.4 m year^{-1} between 1964 and 1990 (Lamontagne 1996). Morissette (2007) also reported high erosion rates in the Forestville area. Erosion rates occurring before these periods are unknown. This regional erosion promotes the transfer of large volumes of sand from the coastline to the marine environment, and is probably the most important source of sediments for the formation of the submarine fans offshore Les Escoumins. The quasi-exponential increase in sand observed in both cores could thus also be explained by an increase in the coastal erosion rate in second half of the 20th Century.

Fig. 7 Eroded coastal cliff near Forestville, Québec North Shore (photograph courteously provided by Antoine Morissette, Université du Québec à Rimouski)

The recent increase in coastal erosion may have been caused by changes in storm frequencies and/or energy (Bernatchez and Dubois 2004; Lozano et al. 2004; Hansom and Hall 2007). Indeed, according to Lamontagne (1996) and Bernatchez and Dubois (2004), the main erosion agents for the sandy cliffs of the St. Lawrence Estuary and Gulf are storm waves and tidal currents. However, a recent increase in storm frequency in this region has not yet been clearly demonstrated.

Formation of the submarine canyons and fans

Relatively high sand contents (an average of 35% for core 76BC and 80–90% for core 77BC) are observed in the hemipelagic sediments of both cores. Indeed, these sand contents are higher than those observed in the sediments of the Laurentian Channel, which are generally composed of silty clays to clayey silts (Nota and Loring 1964; St-Onge et al. 2003; Cauchon-Voyer 2007; Cauchon-Voyer et al. 2007). The Les Escoumins–Forestville area is today characterized by high rates of coastal erosion, high-energy currents, and an east–west longshore drift (e.g., El-Sabh 1979; Drapeau 1992; Bernatchez and Dubois 2004; Morissette 2007). The system of canyons and fans is located to the west of three relatively large river deltas (Sault-aux-Moutons, Portneuf, and Sault-aux-Cochons rivers, Fig. 1), and a high sandy cliff (the Forestville cliff, Fig. 7). The combined geophysical and sedimentological data suggest that the system of canyons and fans was constructed by sediment delivery to the Laurentian Channel from the coastline and the nearby river deltas. In the same manner as the longshore drift-initiated turbidity flows observed along the southeast coast of Australia (Boyd et al. 2008), coastal sandy sediments of the Les Escoumins area have evidently been transported by longshore drift and intercepted at the head of the canyons in a coastal sector where the shelf becomes very narrow. These sediments were then diverted off the shelf, and delivered to the fans by turbidity flows that eroded the canyons at the same time, highlighting the recent activity of currents and mass-wasting in this area. The headward-broadening aspect of the canyons, and the presence of gullies along their headscarps suggest that they were produced by the downcutting of erosive turbidity flows that steepened canyon walls and may have caused retrogressive failures (Pratson and Coakley 1996).

Conclusions

The geophysical and sedimentary data presented in this paper enable the following main conclusions to be drawn:

1. The submarine canyons and fans observed offshore Les Escoumins are active systems, and play an important role in the transfer of large volumes of coastal sands to the Laurentian Channel.
2. In the Les Escoumins–Forestville area, sandy sediments were transferred from the coast to the Laurentian Channel by longshore drift-initiated turbidity flows through the local canyon systems as recently as 60 years ago.
3. The export of coastal sand to the Laurentian Channel may contribute to the negative sediment budget along the coast.
4. This study emphasizes the need to clearly define locations of sediment instabilities and transport pathways in the St. Lawrence Estuary in order to assess the volume of recent coastal sediments lost to the Laurentian Channel, and to identify the precise coastal sectors where this sediment transfer is taking place.

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