Marine Geology 357 (2014) 243–255

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margeo

Morphodynamics in sediment-starved inner-shelf submarine canyons (Lower St. Lawrence Estuary, Eastern Canada)

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ARTICLE INFO

Article history:
Received 12 April 2014
Received in revised form 1 August 2014
Accepted 12 August 2014
Available online 3 September 2014

Keywords:
Submarine canyons
Inner-shelf
Internal waves
Slope failures
Crescent-shaped bedforms
Lower St. Lawrence Estuary

ABSTRACT

The contemporaneous activity and sedimentary processes in a series of inner-shelf submarine canyons located in the Lower St. Lawrence Estuary were examined using high-resolution multibeam bathymetry and backscatter data. The presence of crescent-shaped bedforms (CSBs) displaced upslope at the bottom of the canyons between 2007 and 2012 indicates that they are currently active through the remobilization of sediment by gravity flows. However, the shelf and shores of the region are characterized by the absence of sediment. Our results indicate that gravity flows currently eroding the canyon floors do not transport new material downslope coming from the shelf but rather remobilize in-situ deglacial sediments within the canyon thalweg. We suggest that slope failures and internal tides/waves are responsible for sediment remobilization in these canyons, although their role in the upslope migrating CSBs is unclear. This paper provides evidence that sediment supply is not a prerequisite for the modern activity of inner-shelf submarine canyons when processes such as slope failures and internal tides/waves are frequent enough to remobilize in-situ sediments.

1. Introduction

Submarine canyons are the main conduits for the transport of coarse continental and shelf sediments to deeper marine basins where fine-grained hemipelagic or pelagic sediments are usually deposited. Sediments flowing through submarine canyons mainly originate from rivers (Migeon et al., 2006; Chiang and Yu, 2008; Babonneau et al., 2013), ice-sheets (Jenner et al., 2007; Roger et al., 2013), longshore drift (Lewis and Barnes, 1999; Smith et al., 2005; Yoshikawa and Nemoto, 2010; Normandeau et al., 2013) or the remobilization of shelf sediment (Mountjoy et al., 2013). Recent studies demonstrate that some submarine canyons are active despite the present day sea-level highstand that is believed to diminish or stop their activity (Paull et al., 2003; Boyd et al., 2008; Babonneau et al., 2013). However, their modern activity is not controlled by sea-level change but rather by their proximity to a sediment source, as canyon activity depends largely on sediment supply rate at their head and on the prevailing oceanographic and climatic conditions (Puig et al., 2014). Therefore, canyons are generally considered inactive when no sediment is available on their neighboring shelf.

Sedimentary processes and their resulting morphological expression on the seafloor are still highly addressed in marine geological studies (Talling et al., 2013). In recent years, the advances in high-resolution multibeam bathymetric surveys have allowed to increase the detail of studies on sedimentary processes along submarine canyons (Lastras et al., 2009, 2011; Babonneau et al., 2013; Biscara et al., 2013). In these systems, triggers of submarine gravity flows were identified based on morphological features observed and described at canyon heads (García-García et al., 2012; Hill, 2012; Hughes Clarke et al., 2014), while bedforms were imaged and associated with certain types of sediment gravity flows (Puig et al., 2008; Paull et al., 2010). However, the link between bedforms and gravity flows is still subject to debate (Talling, 2014).

Here we report on a series of small-scale, inner-shelf submarine canyons located off Pointe-des-Monts, in the Lower St. Lawrence Estuary (Eastern Canada; Fig. 1) from high-resolution bathymetric data. Processes involved in their recent morphological change are discussed

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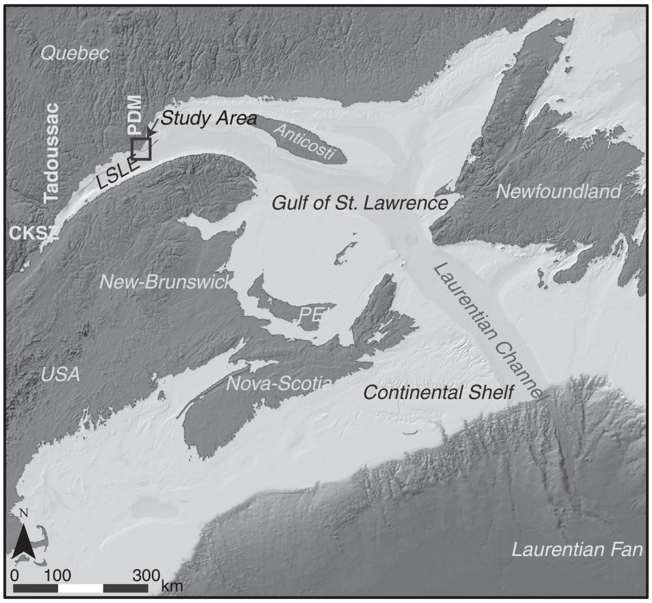

Fig. 1. Location of the Pointe-des-Monts (PDM) canyons, east of the Lower St. Lawrence Estuary (LSLE). The DEM comes from the Geological Survey of Canada (GSC).

based on the morphological features observed at the head and along the canyons. These observations indicate that the canyons are active today despite the absence of a sediment source at their head and their disconnection to a terrestrial drainage system.

2. Regional settings

Pointe-des-Monts is located in the Lower St. Lawrence Estuary (LSLE), at the western edge of the Gulf of St. Lawrence (Fig. 1). The north shore of the LSLE is underlain by Grenvillian metamorphic rocks of the Canadian Shield (Franconi et al., 1975). The submarine geomorphology of the LSLE is mainly characterized by the Laurentian Channel: a deep (365 m) and large-scale trough that extends from Tadoussac to the edge of the continental shelf (Piper et al., 2007). Within the inner-shelf of the Estuary and Gulf of St. Lawrence, the deepest depths are observed along the Laurentian Channel (~350 m in the LSLE). The margins of the Laurentian Channel are generally steep, reaching a mean of 7–9° in some areas, which allowed inner-shelf submarine canyons and channels to form (Duchesne et al., 2003; Gagné et al., 2009; Pinet et al., 2011). The origin of these canyons is still undocumented, although Pinet et al. (2011) indicated that they are Holocene in age. The steep slopes also favored the generation of mass movements in the LSLE (Duchesne et al., 2003; Cauchon-Voyer et al., 2008). These mass movements, with the Colombier landslide being the largest (Cauchon-Voyer et al., 2008, 2011), are mostly related to earthquakes from the Charlevoix–Kamouraska Seismic Zone (CKSZ). The largest event probably occurred in 1663, when a M ≈ 7 earthquake produced numerous mass movements in the province of Quebec, notably in the St. Lawrence Estuary and Saguenay Fjord (e.g., Locat, 2011; St-Onge et al., 2012). More recent events (1860, 1870—M ~ 6–6.5) were also hypothesized to have produced local slumping (Gagné et al., 2009), near the CKSZ (Fig. 1). During deglaciation, sedimentation rates were very high in the LSLE, which led to the deposition of >200 m of ice-proximal, ice-distal, paraglacial and postglacial sediments along the margins of the Laurentian Channel (Syvitski and Praeg, 1989; St-Onge et al., 2008; Duchesne et al., 2010).

The LSLE is a hydrodynamic environment driven principally by the semi-diurnal tides (~3 m tidal range), river runoff and wind (Koutitonsky and Bugden, 1991). The summer water column is continuously stratified but for the sake of simplicity it can be conveniently subdivided into four major layers: 1) an upper warm stratified layer (8–18 °C; 0–30 m); 2) a cold intermediate layer (−0.5–2 °C; 30–100 m); 3) a permanent thermocline (1.5–4 °C; 100–200 m) and; 4) a lower relatively warm layer (3–7 °C; 200–400 m) (Loring and Nota, 1973; Drinkwater and Gilbert, 2004). The combined effect of stratification, hydrodynamic and complex bathymetry leads to the presence of internal tides and higher frequency internal waves in the region (Forrester, 1974; Saucier and Chassé, 2000). These internal waves are thought to be predominantly generated at the shallow sill (20 m) found near the head of the Laurentian Channel where they have been mostly studied. Such internal waves are likely generated at various other places along the estuary, not yet documented.

3. Methods

The activity of the Pointe-des-Monts submarine canyons was assessed by using two sets of high-resolution multibeam bathymetric data. The first dataset was acquired in 2007 by the Canadian Hydrographic Service (CHS) with a Kongsberg EM-1002 multibeam echosounder (95 kHz) between 20 and 350 m water depth (3 m-grid) on board the F.G. Creed. The second dataset was acquired in 2012 with 1) a Kongsberg EM-2040 at a frequency of 300 kHz on board the R/V Coriolis II (1 m-grid) at depths of 20–350 m and 2) a Reson Seabat 8101 (245 kHz) at depths of 5–20 m (3 m-grid) on board the R/V Louis-Edmond-Hamelin (Fig. 2). A DGPS was used in each case, so the horizontal uncertainty does not exceed 2 m. The vertical uncertainty of the two echosounders is typically less than 0.1 m. However, the vertical uncertainty between the two datasets is greater for different reasons: 1) Tidal variations were not collected during the surveys and are based on corrected tidal variations recorded

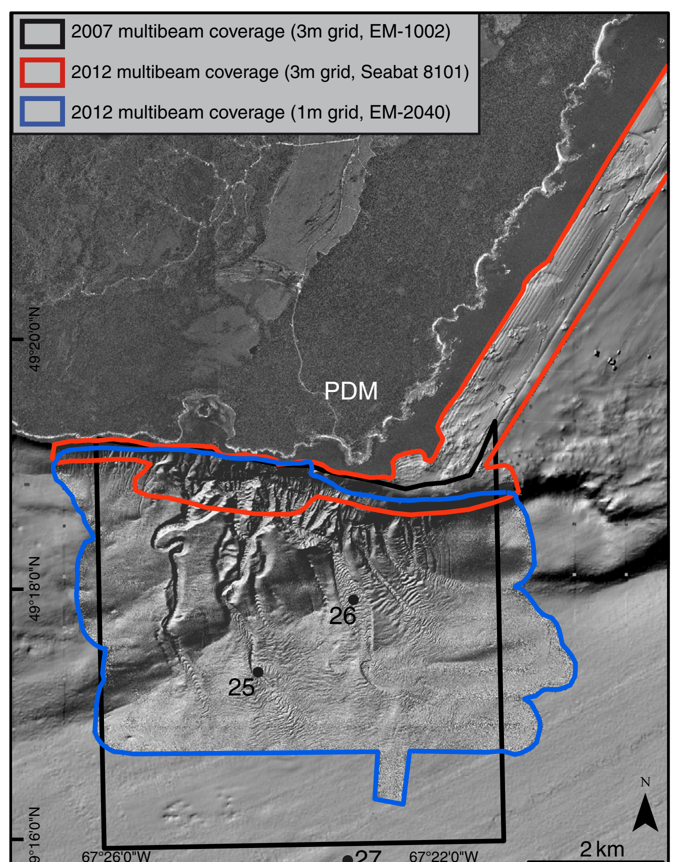

Fig. 2. Outline of multibeam surveys used in this study and conducted in 2007 and 2012. Location of surface sediment samples (25, 26, 27) are also shown.

at Rimouski by the CHS (co-tidal zone 00515 for Pointe-des-Monts); 2) The two multibeam echosounders have different numbers of beams (111 for the 2007 survey against 400 for the 2012 survey) and different beam width ($2^\circ \times 2^\circ$ for 2007 against $1^\circ \times 1^\circ$ for 2012), which can lead to vertical differences, especially on steep slopes; 3) Slopes in the region are steep and can also lead to vertical errors if the navigation is off by 1 or 2 m; 4) Alignment and offset errors of both surveys; 5) Refraction residual errors due to the complex water density change in the LSLE. The 2007 bathymetric data was also processed for a 15 m grid resolution by the CHS. They were able to produce a 3 m grid but vertical precision is diminished, limiting the fine-scale analysis of vertical changes in this study. For these reasons, spatial changes (x, y) were also analyzed when depth differences were important in order to validate them.

Grain-size analysis on three samples collected in the Pointe-des-Monts region was performed using a Horiba LA-950 laser diffraction particle size analyzer. Samples were diluted in a calgon solution and shaken, then submitted to an ultrasound bath. The grain-size distributions and mean grain size are presented in this paper.

The physical oceanographic conditions prevailing offshore Pointe-des-Monts were examined with a three-dimensional coupled sea ice–ocean model for the Gulf of St. Lawrence developed by Saucier et al. (2003). The 2007–2012 water density and maximum vertical kinetic energy density from the 5 km grid over the submarine canyons region were extracted from the model and used as indicators for internal motions. Idealized two-dimensional nonhydrostatic numerical simulations comparable to those described in Bourgault et al. (2013) were also carried out in the Pointe-des-Monts area in order to assess the shoaling effect of nonlinear high-frequency internal waves in the sector. For this idealized simulation, the background flow is quiescent and the background density profile (in kg/m^3) is set to $\rho = 1029.7 \exp[0.4/(z + 52.5)]$ (with the vertical axis z being positive downward) which represents a climatological profile for the LSLE.

Internal waves were also characterized from satellite data. This was based on an analysis of the band 5 (1.55–1.75 μm) of Landsat TM sensor, which have been used to detect solitary and non-linear internal waves in other coastal zones (Artale et al., 1990). Here, a Landsat-5/TM image collected on 15 May 2006 over the study area was obtained from the U.S. Geological Survey EarthExplorer web site (L1G). The total radiance in Band 5 (in DNs) was enhanced to maximize the contrasts over the water body, which is mainly due to specular reflection of the sky radiance and/or the direct sun beam at the air–sea interface, known as sunglint. Sunglint depends on the sun and sensor viewing geometry and the wave facette geometry (Cox and Munk, 1954). Internal waves were outlined on satellite imagery by the changes in surface roughness and the bands of calm water between different internal wavetrains (e.g., Pomar et al., 2012).

4. Results

4.1. Coastal, shelf and canyon morphology

The shoreline and shelf of the Pointe-des-Monts area almost entirely consist of metasedimentary gneisses and crystalline limestone (Dredge, 1983) (Fig. 3). A few thin and isolated sand beaches occur along the coast. Within the 5 km east and west of the canyons, 16% of the shoreline consists of sand beaches while 84% consists of bedrock or till/bedrock (Fig. 3). The two largest rivers in the region are the Baie-Trinité and Godbout rivers, located respectively 12 km east and west of the canyons. Streams are also observed between Baie-Trinité and Pointe-des-Monts, but they are absent at the head of the canyons. The shelf near the head of the canyons is generally less than 500 m wide. East of Pointe-des-Monts, thin isolated sediment patches are observed on the shallow coastal bedrock shelf. These patches do not reach the head of the canyons.

Three distinct and well-developed submarine canyons incise Quaternary sediments along the slope offshore Pointe-des-Monts (C1, C2 and C3 in Fig. 3). Canyons C2 and C3 have similar physical settings. They are found at a distance of 300 m from the shore and reach a length of 4.5 km, from the head to the terminus of the fans. Their width greatly varies, ranging from 100 to 300 m. Their slope can be divided into three sections (Fig. 4): (1) near the head, where the seafloor consists of bedrock, the slope is steep (~20°) down to ~75 m water depth (Upper slope a—USa in Fig. 4A–E). (2) Between 75 and 125 m water depth, a thin layer of sediment lies over bedrock and the slope decreases to 15° on a 200 m distance (Upper slope b–USb in Fig. 4A–E). This section consists of many small gullies that are connected to the main tributaries of the canyons. Gullies are separated by sediment ridges that are thin (less than 50 m large) and that have a smooth morphology (e.g., absence of scarps) and produce a "washed-out" surface (Fig. 5A). (3) The slope of the canyon floor then decreases to 2–3° where it incises into sediments, from 125 m to 300 m water depth (Main slope—MS in Fig. 4). The relief of the canyons (margins–thalweg) varies between 10 and 40 m. Small scarps ($\leq$100 m large) are observed along canyon walls (Fig. 5C). Canyon C1 presents slightly different characteristics (C1 in Fig. 3). Its head consists of a smoother morphology, interpreted as sediment. It shows shallow gullies and appears to be slightly draped (Figs. 3–5C). The head of canyon C1 has a slope of 12° that gradually decreases to 2° downslope (Fig. 4). The relief varies between 10 and 30 m. Gullies are also observed east of the three main canyons. Their heads are $\geq$150 m deep and onlap the bedrock slope (Fig. 5E). Small scarps are also present along these gullies.

Many crescent-shaped bedforms (CSBs) are present within the thalweg of the canyons and gullies (Figs. 3–5). The canyon floor of C1 shows faint CSBs that are less distinct than those in canyons C2 and C3 (Figs. 3–5C). These CSBs are observed from the canyon floor near the head down to 270 m deep. CSBs are also present along the gullies floor (Fig. 5E) and some small-scale CSBs are present near the bedrock slope, on the thin layer of sediments (Fig. 5D). Most CSBs are asymmetric downslope with stoss angles of ~2.5° and mean lee slopes varying between 9 and 15° (Fig. 4C). They have 20–60 m wavelengths and are ~1–3 m high. CSBs are observed on the higher reaches of the canyon thalweg, in some cases only 200 m from the upper bedrock slope (Fig. 5A). Undulations are observed on the lower margins of C3 and in the eastern gullies (Fig. 5D). Unlike the CSBs, the undulations are all located outside of the present canyons (Fig. 5F). They have approximately the same wavelengths (30–100 m) and heights as the CSBs, but are more or less symmetric and linear, unlike the CSBs (Figs. 4D–5D).

4.2. Reflectivity map and grain-size

The backscatter map is divided into two regions: the coastal shelf, mapped with the Reson Seabat 8101, and the submarine canyons, mapped with a Kongsberg EM-2040, both surveyed in 2012. On the coastal shelf, the reflectivity map shows two distinct acoustic facies (Fig. 6). The first facies is characterized by high intensity backscatter (pale gray) and covers 72% of the coastal shelf between Baie-Trinité and Pointe-des-Monts. The surface morphology of the high backscatter intensity is rough and irregular, indicating the presence of bedrock. The second facies observed on the coastal shelf shows lower intensity backscatter (dark gray) and covers 28% of the mapped region. Its surface morphology is gentle and smooth, without the presence of ripples, dunes or other bedforms. These characteristics indicate it consists of shelf sediments.

Three acoustic facies were identified in the submarine canyons region using the EM-2040 multibeam echosounder (Fig. 6). The first facies is observed at the head of the canyons and is characterized by high backscatter intensity (pale gray). The high backscatter intensity and the rough bottom observed on the bathymetric data indicate the presence of bedrock outcrops. The second facies is observed over the canyons, on the slope, and is characterized by medium intensity backscatter. Two sediment samples collected over fans C2 and C3 indicate that this facies is composed of very fine sand, with mean grain-sizes of ~90 μm

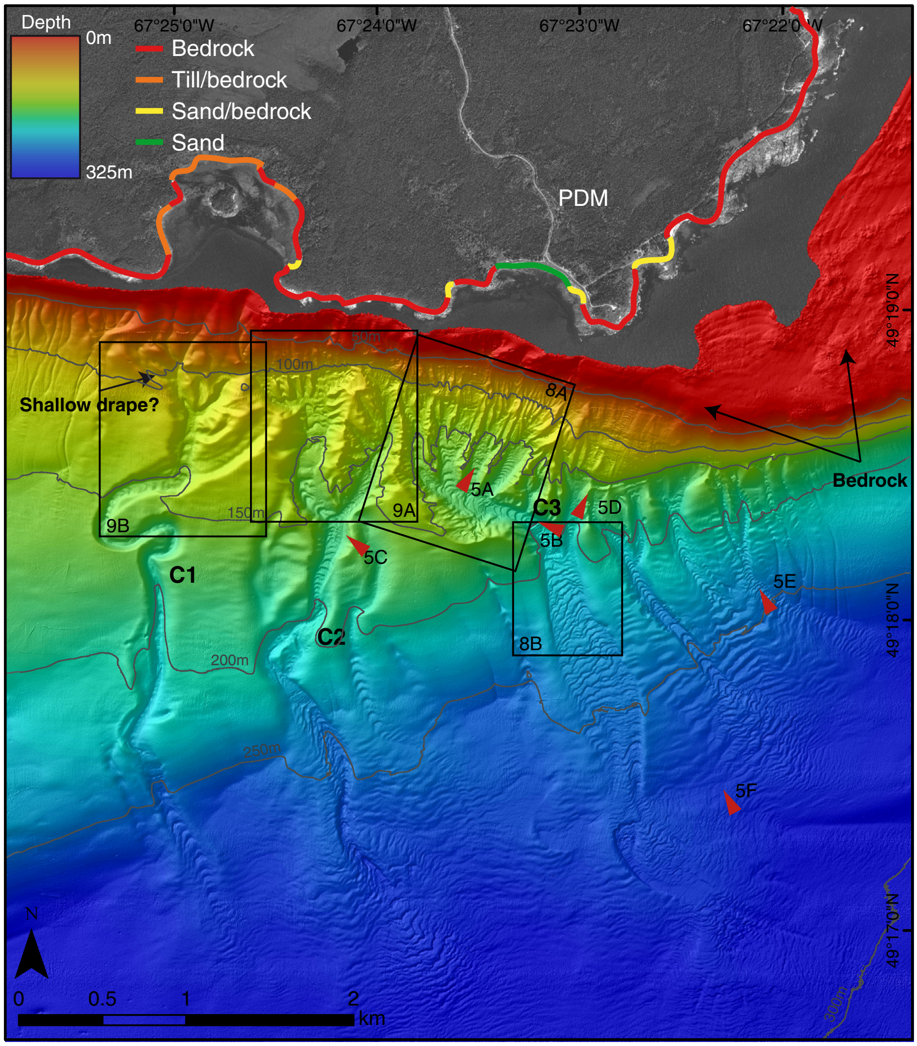

Fig. 3. Morphology of the coast, shelf and canyons. The shelf and coast consist of bedrock with a low proportion of sediments (<30%). Black squares illustrate the areas presented in Figs. 8 and 9. The red arrowheads illustrate the areas presented in Fig. 5. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(Fig. 7). In the absence of more samples, the reflectivity map does not allow differentiating grain-sizes between the thalweg and the margins. The third facies, consisting of low intensity backscatter, is observed off the submarine fans, in the Laurentian Channel. A sample collected off the submarine fans reveals a slightly bi-modal distribution, with a mean grain-size of 13 μm. This indicates the presence of fine silts in this sector.

4.3. Morphological change

The location of the crest of the CSBs was extracted from the two datasets to document their overall displacement. In canyon C3, the displacement of the crests is measurable between the two surveys (Fig. 8). Net displacement is observed up canyon and is ≤25 m, but mostly varies between 4 and 15 m. Upslope migration could be traced from the head of the canyons to 230 m deep in canyon C3. Deeper than 230 m where the fan starts, bedform movement is no longer observed. Only one sector (dashed circle in Fig. 8, profile C–C′) apparently shows downslope movement. However, this apparent downslope movement could also represent a more important upslope displacement since it occurs in a sector where the canyon becomes narrower and where bedform migration could be more active. In canyon C2, upslope crest movement is indicated by only one bedform (profile A–A′ in Fig. 9A) while in canyon C1 no movement of bedform is observed between the two surveys (Fig. 9B). The difference in crest location between the two surveys cannot be attributed to horizontal errors in the multibeam datasets because: 1) some CSBs were found to remain stable during this period, notably in the westernmost canyon (canyon C1) where no movement is observed (Fig. 9B); 2) some crests observed within the same sector were displaced considerably more than others (Fig. 8); 3) the canyon rims remained stable in sectors where CSBs crest were displaced, indicating that it is the CSBs that moved (Fig. 8); and 4) the overall form of the CSBs, although similar from one survey to another, was slightly modified due to their displacement. Moreover, the observed displacement can be confirmed upslope because the CSBs are quite similar from one survey to another. This precludes the possibility that the observed upslope displacement is in fact a more important downslope movement.

A depth difference map was produced by subtracting the 2012 dataset to the 2007 one (Figs. 8–9). 1–2 m positive changes are observed episodically along canyon slopes. Because of multibeam echosounder errors on steep sloping topography described in the methods section, some of these changes are considered false since no morphological changes were observed at these sites. Nonetheless, the depth difference map indicates that most of the changes occurred along the canyon thalwegs, especially along canyon C3 (Fig. 8). The depth differences reveal that erosion occurred at the crest while sedimentation occurred downslope from the 2007 crest location. The erosion of some of the crest is not always observed due to the less than 1 m of vertical erosion, which is lower than the vertical resolution of

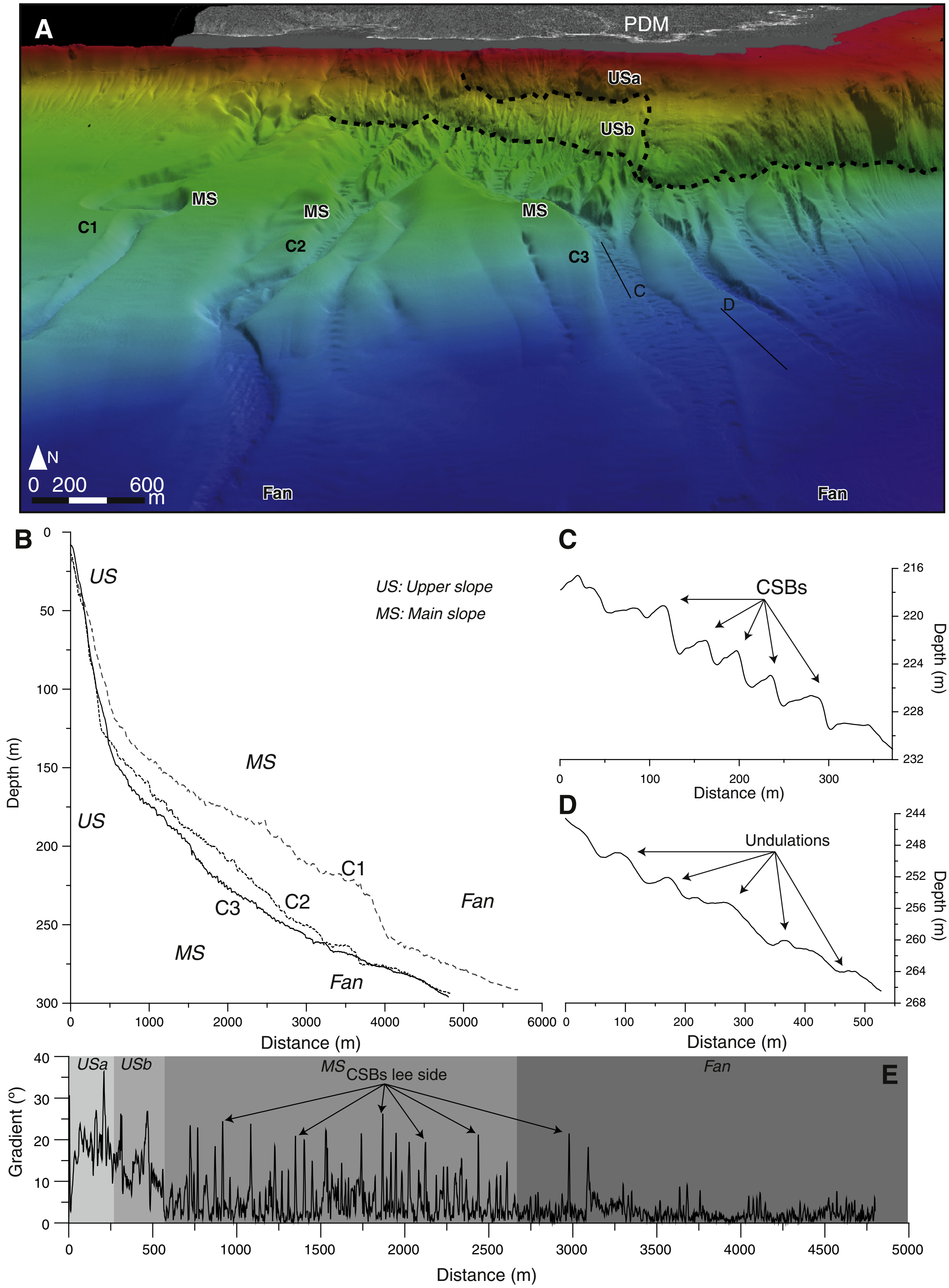

Fig. 4. A) Multibeam image of the submarine canyons with Upper slope a (USa), Upper slope b (USb), main slope (MS) and the fans; B) Longitudinal profiles of the thalwegs of the three canyons; C) Longitudinal profile of CSBs within canyon C3; D) Longitudinal profile of undulations observed on the margins of canyon C3; E) Gradient profile of canyon C3 illustrating the three main slopes, the fan and the CSBs (peaks in gradient).

the analysis. However, the profiles in Fig. 8 clearly show that the crests migrated upslope and that accumulation due to bedform movement is observed downslope of each crest. Furthermore, depth difference maps illustrates that no major change (≥1 m) is observed at the head of the canyons while CSBs migrated in the topmost parts of them (Fig. 8). No major morphological change is observed when visually comparing the 2007 and 2012 datasets, except for one possible minor mass movement and the displacement of CSBs (Fig. 10). In canyon C1 and C2, depth changes are mostly limited to the slopes and most of these changes were not visually constrained by morphological changes, suggesting

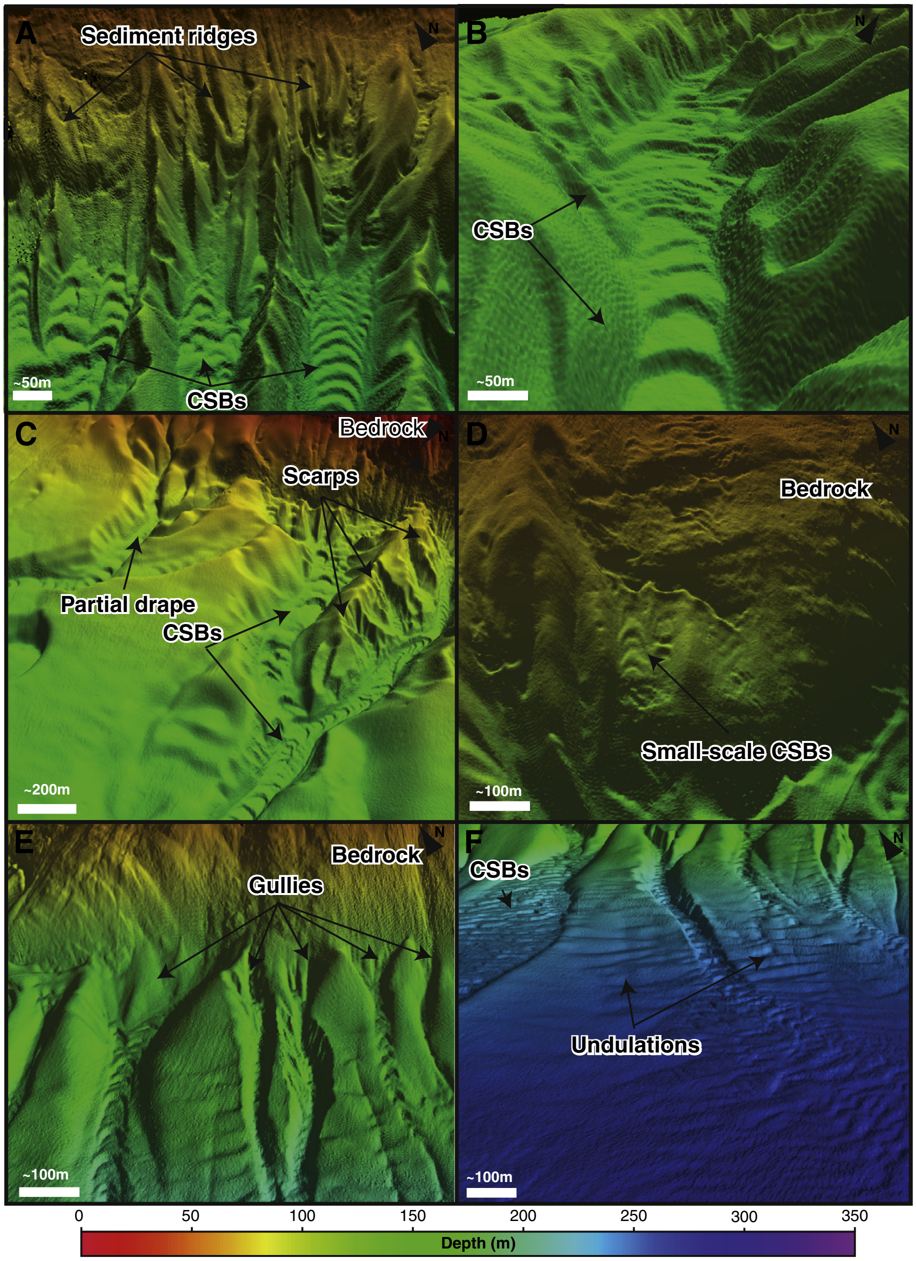

Fig. 5. Multibeam images of bedforms observed within the submarine canyons: A) CSBs and sediment ridges at the head of the submarine canyons; B) CSBs observed in the middle of canyon C3; C) Head of submarine canyons C1 and C2 illustrating a partial drape and scarps along the walls. D) Small-scale CSBs on a thin layer of sediment near canyon C3; E) Gullies located east of canyons C3 with the presence of CSBs in their thalwegs; F) CSBs and undulations found near the fans and one of the eastern gullies. Vertical exaggeration = 4.

that most of them are related to errors described in the methods section. Only one bedform migrated upslope in canyon C2 while no migration was observed in canyon C1 (Fig. 9). Again, no significant changes related to mass movements were observed at the head of the canyons.

4.4. Oceanographic conditions

Modeled physical oceanographic conditions in the LSLE for the 2007–2012 period reveal that the Pointe-des-Monts sector experienced relatively strong vertical kinetic energy density compared to other sectors of the LSLE. It is the second most affected sector after the head of the Laurentian Channel, which is well known for its strong upwelling and internal tide generation (Forrester, 1974) (Fig. 11A). A harmonic analysis of the modeled vertical current time series in the Pointe-des-Monts sector has been performed. It reveals that the amplitude of the semi-diurnal (M2) component is strongest at depth between 145 and 165 m. The semi-diurnal vertical displacements of the isopycnals seen in Fig. 11B are clear manifestations of the semi-diurnal internal tide with displacements reaching up to almost 100 m. These internal tides are likely coincident with higher frequency and shorter (wavelength typically <1 km) internal waves not resolved by this 5 km resolution hydrodynamic model. Fig. 11C illustrates the wave-induced currents that a single 15-m amplitude high frequency internal wave may generate as it interacts, breaks and reflects off a shoaling bottom comparable to the bathymetry off Pointe-des-Monts, based on our idealized non-hydrostatic numerical simulations. This model predicts that the wave-induced up- and down-slope currents may well exceed 0.5 m s^{-1}.

The enhanced contrasts of Band 5 in the Landsat 5/TM imagery allowed to better visualize the trains of internal waves present in the LSLE. Four distinct internal wavetrains were interpreted in Fig. 12. The

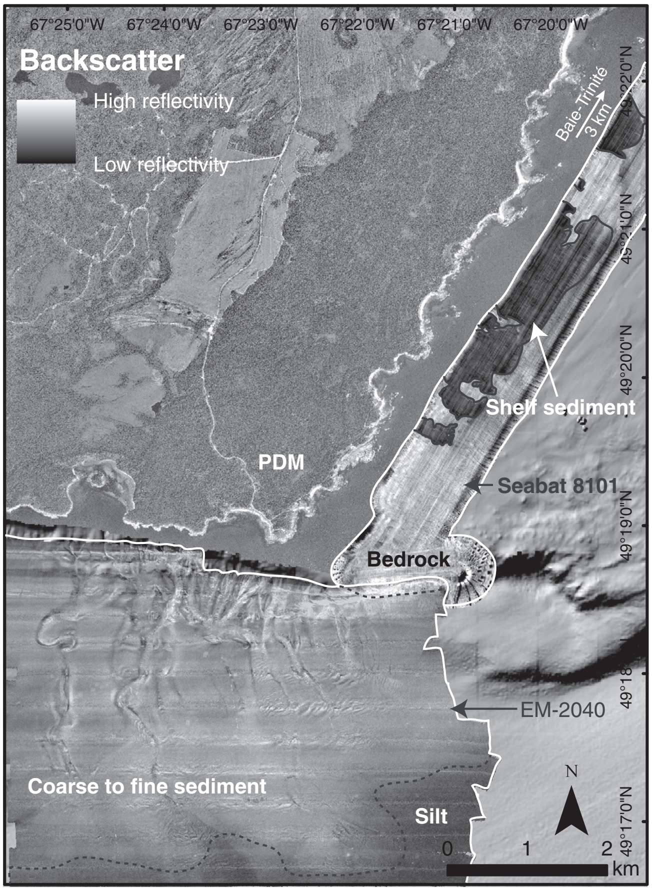

Fig. 6. Reflectivity map of the canyons and shelf derived from the 2012 survey. As two different multibeam echosounders were used, the canyons and shelf were interpreted separately. On the shelf, two facies are recognized, interpreted as bedrock and shelf sediment. Over the canyons, three facies were interpreted as bedrock, fine sand and silt-size particles.

first internal wavetrain occupies the largest portion of the imagery and propagates eastwards towards Pointe-des-Monts. The second and third wavetrains are much more localized and propagate northward. The fourth wavetrain is located directly offshore Pointe-des-Monts and may be due to the reflexion of an incident wavetrain.

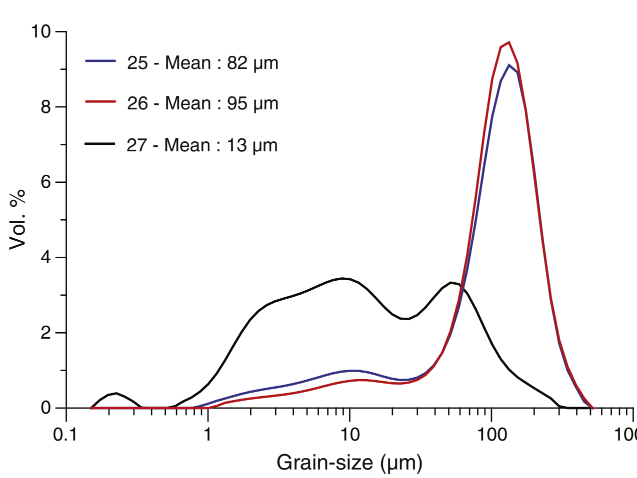

Fig. 7. Grain-size distributions of samples 25, 26 and 27. Samples 25 and 26 were collected over the submarine fans while sample 27 was collected offshore from them. See Fig. 2 for location.

5. Discussion

5.1. Source of sediments

The Pointe-des-Monts coastline is almost entirely rocky and is overlain only by very thin and isolated sediment patches (Fig. 3). The coastline is stable along the rocky shoreline and the highest rates of accumulation are of 0.06 m/year on the isolated beaches near the head of the canyons (Dubois et al., 2005). Multibeam and backscatter data collected in shallow water provide evidence for the limited volume of sediments nearshore and the impossibility for coastal shelf sediments to reach the head of the submarine canyons due to the rocky nature of the seafloor (Fig. 6). These canyons are not supplied in sediment either by rivers, longshore drift or the remobilization of shelf sediments. In fact, they are not fed in sediment in any ways as demonstrated by the absence of sediments at the heads of canyons C2 and C3. The St. Lawrence River and the Saguenay Fjord are not responsible for bringing important sediment to this region because they are located too far away (>200 km to the SW).

Between 2007 and 2012 no major sedimentation zones occurred at the head of the canyons. The only sites where accumulation during this period is observed are on the slopes of the sediment ridges and the canyons. However, this accumulation is most likely due to small errors in the multibeam data because such accumulation should have been widespread over the head rather than localized on the slopes. Some accumulation on the slope could also be due to the passage of gravity flows that deposited sediment on the margins. The absence of a sediment source indicates that these submarine canyons are currently remobilizing sediments already present within them or originating from the erosion of the canyons themselves. There is no new sediment supplied to these systems from the shelf as generally observed in active submarine canyons (Kudrass et al., 1998; Lewis and Barnes, 1999; Kripounoff et al., 2009; Biscara et al., 2013). Non deposition explains the "washed-out" surface observed at the head of the canyons where sediments are constantly being remobilized downslope without further input (Fig. 5A).

5.2. Activity of the canyons

The multibeam data reveal that while canyon C1 is partially draped in its thalweg and head, canyons C2 and C3 have well-defined CSBs. Similar CSBs were observed within the thalwegs of the Étang-Salé and Saint-Étienne canyons (La Réunion) (Babonneau et al., 2013), Monterey, Santa Monica, Mugu, Redondo, Carmel and La Jolla canyons (California) (Paull et al., 2010, 2011, 2013), Capbreton canyon (Mazières et al., 2014) and Squamish delta (British Columbia) (Hughes Clarke et al., 2014). CSBs are formed by gravity flows that remobilize sediments (Smith et al., 2005; Xu et al., 2008; Paull et al., 2010) and their presence is indicative of active submarine canyons (Paull et al., 2010). When CSBs are observed, sedimentological and mooring data show that the frequency of gravity flow is high, sometimes ≥1/year (Paull et al., 2010; Hughes Clarke et al., 2014). The presence of CSBs in the Pointe-des-Monts canyons thus suggests that frequent flows likely occur in order to maintain these bedforms.

The comparison of repeated multibeam surveys is a method that was successfully used to assess canyon morphological change and activity (Smith et al., 2007; Conway et al., 2012; Hill, 2012; Biscara et al., 2013). Here only two datasets were used, limiting defining precise rates of movement. However, the 2007 and 2012 datasets clearly illustrate that CSB crests in canyons C3 and C2 were displaced upslope during these five years. Such a displacement has been routinely observed in Monterey Canyon (Smith et al., 2007) and on the Squamish prodelta (Hughes Clarke et al., 2014). In Monterey canyon, Smith et al. (2007) observed upslope migration of 0–22 m for 32 days in the Autumn of 2004. The same magnitude of migration was routinely observed subsequently by Paull et al. (2010). In Squamish, upslope

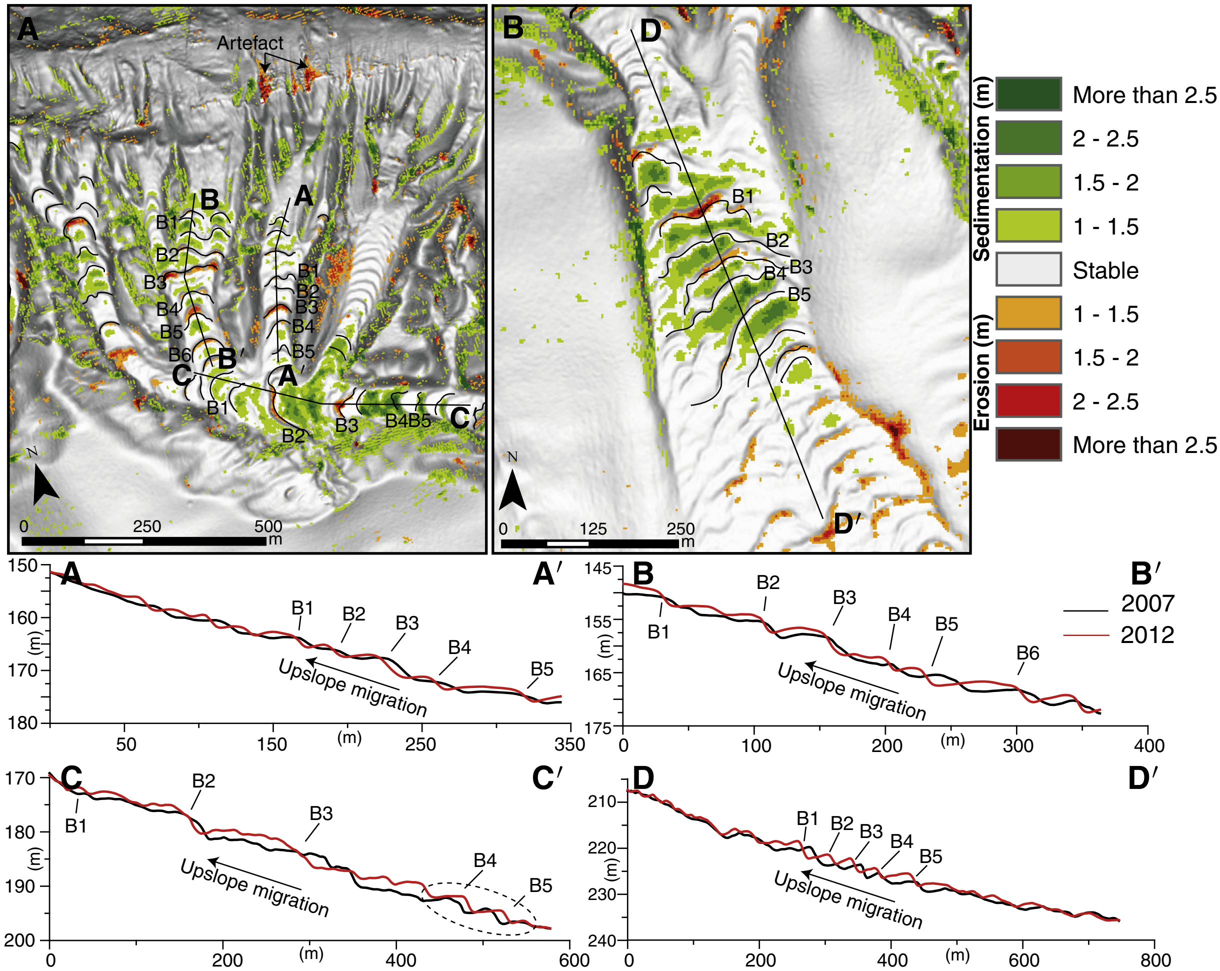

Fig. 8. Depth difference maps of canyon C3 head (A) and base of slope (B). Note that depth differences mainly occurred along the canyon floor. Black lines represent the crest location of the CSBs in 2007 and the background shaded relief image is the 2012 dataset. Horizontal bedform movements are shown on the profiles extracted from the 2007 and 2012 datasets and illustrate the upslope migration of CSBs.

migration of bedforms was observed routinely in 2011 during 93 sequential surveys (Hughes Clarke et al., 2014). In canyon C3 of Pointe-des-Monts, the observed upslope migration does not appear to be as frequent as in the two regions described above. Migrations of 0–25 m in Pointe-des-Monts are similar to those observed in Monterey and Squamish, but the number of individual events responsible for the migration of bedforms in Pointe-des-Monts is unknown. It is possible that one or multiple events are responsible for their migration. Their rates of upslope migration would be similar to the other settings if only one short-term event occurred during the analyzed five years period. Conversely, these rates would be relatively low if multiple events were responsible for the observed change. In the first case, this would mean that flows capable of bedform migration are less common than in the other settings. In the second case, it would mean that each individual flows responsible for bedform migration are less energetic and lead to smaller upslope displacement of CSBs than Monterey or Squamish.

Undulations observed at the base of the submarine canyons, outside of the channels themselves, also suggest the passage of gravity flows. The passage of gravity flows was suggested as a mechanism for the formation of similar bedforms on the Fraser delta (Hill, 2012), the Western Gulf of Taranto (Rebesco et al., 2009) and the Rhône delta (Girardclos et al., 2012). Their location on the margins of the submarine canyons and gullies also supports the interpretation that they are sediment waves resulting from unconfined gravity flows (e.g., Girardclos et al., 2012; Hill, 2012). There is no indication on the bathymetric data that they could be relict features representing ancient CSBs that would have been filled through time, although this hypothesis cannot be ruled out. Slow deformation processes such as creep are unlikely since the undulations are located on a 2.6° slope, which is relatively low to generate such features (e.g., Rebesco et al., 2009).

5.3. Sedimentary processes

Currents need to flow down-canyon to maintain CSBs in the canyon thalwegs. The main mechanisms responsible for a wide range of gravity flows in modern submarine canyons reported in the literature are storm-induced resuspension of shelf sediments, hyperpycnal currents, submarine slope failures, dense shelf water cascades and internal tides/waves (Puig et al., 2014). Storm-induced turbidity currents are known to transport sediments in canyons (Puig, 2004; Xu et al., 2010) but they require the existence of shelf sediments and eventual downslope remobilization. These mechanisms are unlikely to be at work here because there are no sediments on the Pointe-des-Monts shelf. Hyperpycnal currents caused by river inputs (Mulder et al., 2003; Warrick et al., 2013) can also be rejected because the nearest river mouths are located too far away from the canyon heads to have any significant impact (~12 km west and north of the sector).

Submarine slope failures are known to generate and maintain upslope migrating bedforms such as CSBs in other canyon systems, especially where sediment supply to the head of the canyons is high (Paull et al., 2010, 2013; Hughes Clarke et al., 2014). Slope failures have also

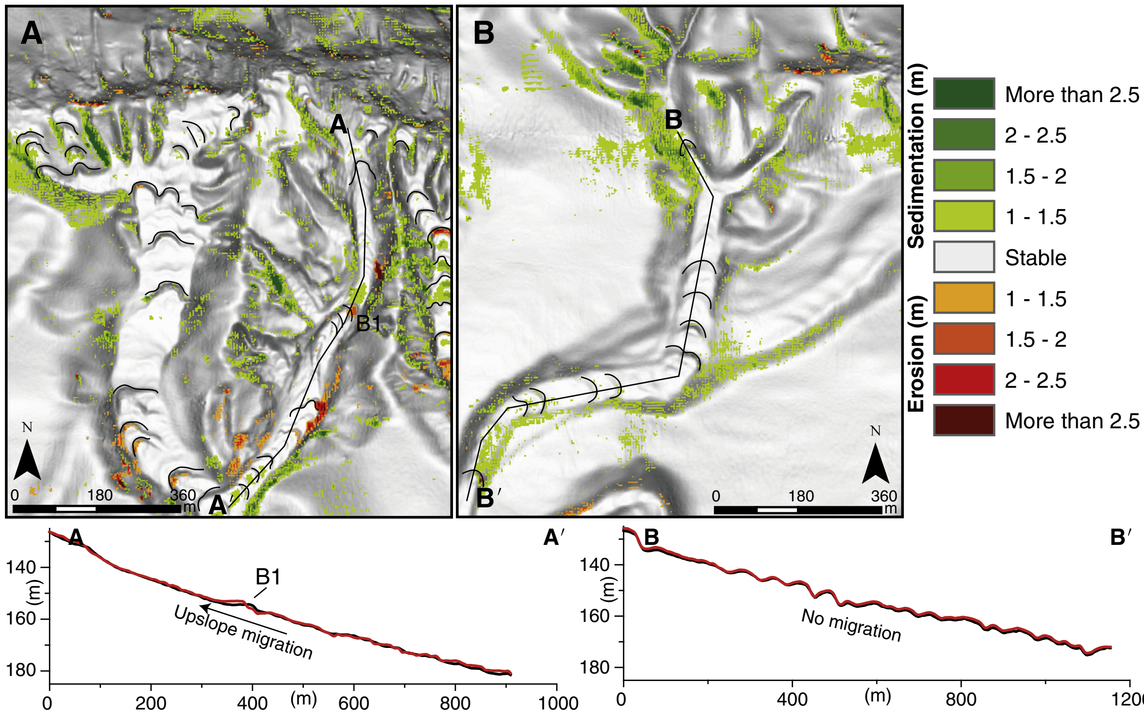

Fig. 9. Depth difference maps of the head of canyons C2 (A) and C1 (B). Depth differences are less accentuated on the canyon floor compared to canyon C3. Black lines represent the crest location of the CSBs in 2007 and the background shaded relief image is the 2012 dataset. Horizontal bedform movements are shown with the profiles extracted from the 2007 and 2012 datasets and illustrate the upslope migration of only one CSB in canyon C2, while no migration was observed in canyon C1.

been documented in the LSLE near Baie-Comeau (Duchesne et al., 2003), Betsiamites (Cauchon-Voyer et al., 2008) and Les Escoumins (Gagné et al., 2009). These slope failures occurred during major earthquakes >100 years ago and are not frequent in the LSLE. Many small scarps are observed along the walls of the Pointe-des-Monts canyons, indicating that slope failures occur occasionally and probably maintain upslope migrating CSBs. As there is no sediment supplied to the head of the canyons, lip growth and failure related to high sediment supply (e.g., Smith et al., 2005; Hughes Clarke et al., 2014) cannot be responsible for the slope failures in Pointe-des-Monts. Another mechanism for triggering slope failures must then play a role.

Slope failures are most probably not the sole mechanism for upslope migrating CSBs in Pointe-des-Monts. The sediment ridges separating the canyons and gullies are generally smooth and without scarps (Fig. 5A). CSBs are present within these gullies and thus cannot be formed by slope failures because scarps are not observed upslope and the volume of sediment is limited. Moreover, small-scale CSBs, although they may have a different origin than the CSBs described within the canyons, were observed on the thin layer of sediment overlying the bedrock near the canyon heads (Fig. 5D). Their presence in this environment limits the role of slope failures for their formation. Slope failures could probably not explain the flows responsible for the upslope displacement of the CSB crests between 2007 and 2012 because major erosion related to slope failures were not observed except for one possible minor scarp (Fig. 10). Hughes Clarke et al. (2014) also observed that CSBs sometimes migrated upslope in the absence of slope failures, which also supports the hypothesis that other mechanisms are at play. If slope failures were responsible for the migration of the bedforms

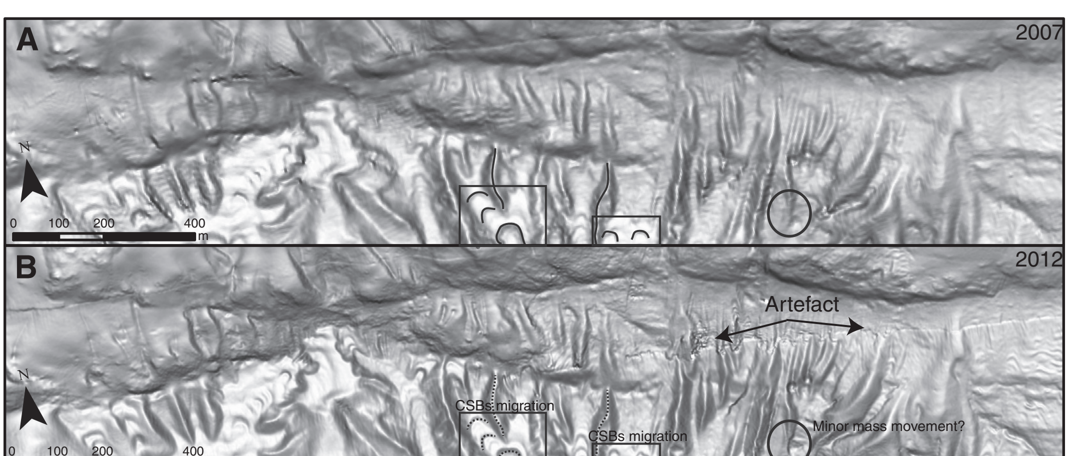

Fig. 10. Head of canyons C2 and C3 in 2007 (A) and 2012 (B). Recognizable morphological change is restricted to CSB movement (black squares) and one possible small scarp (black circle).

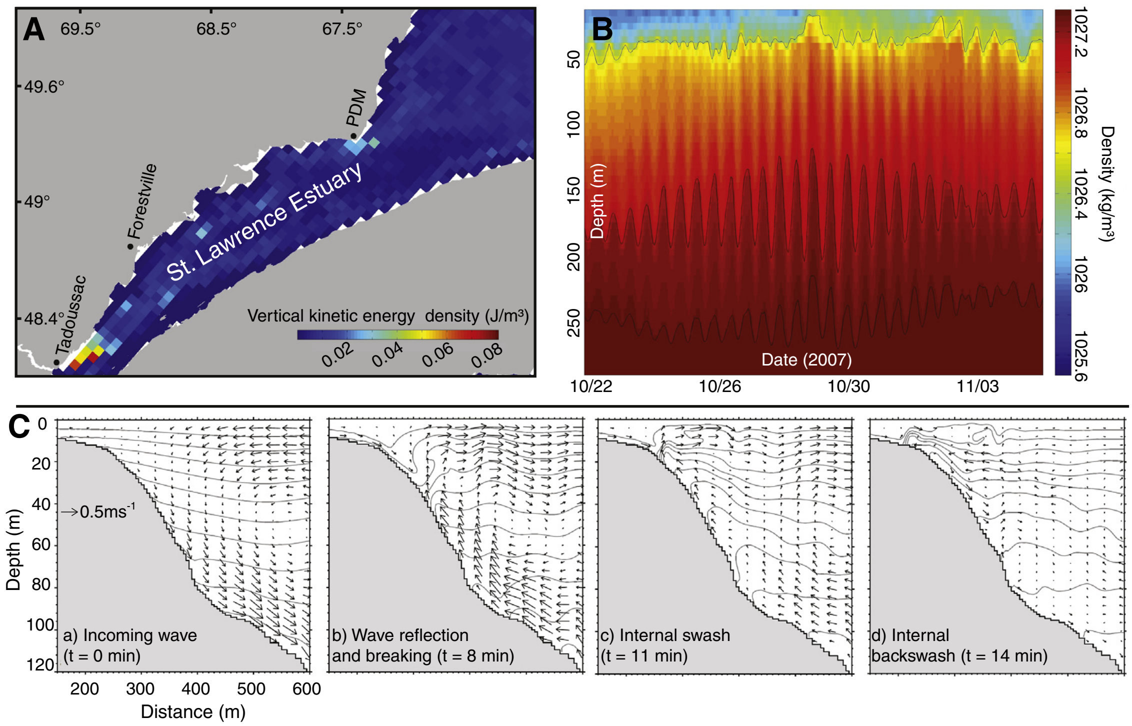

Fig. 11. A) Spatial distribution of maximum kinetic energy density (J/m^3) related to vertical motion for the 2007–2012 period. Harmonic analysis of the vertical speed time series associated with the hotspot around Pointe-des-Monts (PDM) revealed a strong amplitude of the semi-diurnal (M_2) component at depths between 145 m and 165 m (depths associated with maximum vertical kinetic energy density at Pointe-des-Monts), suggesting the presence of an internal tide. This is illustrated in (B) where isopycnals ($\rho = 1025.5$, 1027 and 1027.3 kg/m^3) are superimposed to the time series of water density for depth = 0 m to 280 m; C) Results of two-dimensional, non-hydrostatic and nonlinear numerical simulations illustrating the interaction during the shoaling and reflection of a large amplitude nonlinear internal wave with the sloping bottom off Pointe-des-Monts.

in Pointe-des-Monts between 2007 and 2012, the scarps were not resolved by analyzing the depth difference map. Therefore, the erosion of the seabed related to slope failures would have been less than 1 m.

In the absence of sediment supply and the limited role of slope failures in canyon activity, oceanographic processes could explain sediment movement within the canyons. Among oceanographic processes widely studied, dense shelf water cascading is known to be a mechanism responsible for generating gravity flows in many canyons of the world (Canals et al., 2006; Gaudin et al., 2006). However, such cascades are considered unlikely in the Pointe-des-Monts sector due to the year-round strongly stratified nature of the LSLE. There has not been to date any reported indication of local deep-water formation or shelf water cascades within the Estuary or the Gulf of St. Lawrence. The only water mass locally produced is the cold intermediate layer which is formed every winter by surface mixed-layer deepening due to wind mixing and winter convection occurring over the entire gulf (Galbraith, 2006; Smith et al., 2006). It is unlikely that cold water could be formed in less than 10 m on the shelf and be dense enough to cascade down the cold intermediate layer. Furthermore, dense shelf water cascades usually produce furrows within the thalwegs of canyons (e.g., Puig et al., 2008). Such bedforms are not observed in the Pointe-des-Monts canyons. Although the water cascade hypothesis cannot be completely ruled out, it is considered unlikely in the light of current understanding of water masses formation in the estuary and gulf.

One possible oceanographic mechanism that can generate bottom shear stresses sufficiently large to mobilize sediments within submarine canyons is the downslope currents induced by internal tides and/or higher frequency internal waves. Internal tides/waves can generate strong up- and down-canyon currents in many submarine canyons around the world to depths down to ~800 m (Pomar et al., 2012; Puig et al., 2014). These up- and down-canyon movements are often related to the semi-diurnal (M_2) component of the tide (Shepard, 1976; Xu et al., 2008; Xu and Noble, 2009; Mulder et al., 2012), which lead many authors to conclude that they are frequent processes for sediment suspension within the head of submarine canyons. For example, internal waves are responsible for the movement of particles in the Baltimore (Gardner, 1989), Hudson (Hotchkiss and Wunsch, 1982) and Halibut (Puig et al., 2013) canyons among others.

Internal waves have long been known to exist in the LSLE either as seaward-propagating internal tides emanating from the head of the Laurentian Channel near Tadoussac (Forrester, 1974) or as high-frequency internal waves shoaling on topography (Richards et al., 2013). The hydrodynamic model developed by Saucier et al. (2003) shows that maximum vertical kinetic energy density is stronger near Pointe-des-Monts than in most other sectors of the LSLE (Fig. 11A), suggesting that internal motions (mainly internal tides) are stronger off Pointe-des-Monts. The region could be a hotspot for internal tide activity. Moreover, our idealized nonhydrostatic numerical simulations show that currents from a single internal wave can reach more than 0.5 m s^{-1} (Fig. 11C) which is sufficient to mobilize the fine sediments observed in the canyons. In reality, such wave rarely exists alone but rather propagates as wavetrains composed of several consecutive waves, therefore providing much more energy available for sediment mobilization (Bourgault et al., 2013). The Landsat 5/TM imagery shown in Fig. 12 clearly illustrates the presence of internal wavetrains and that they can propagate in many sectors of the LSLE. Based on in-situ observations elsewhere in the St. Lawrence Estuary and modeling simulation, we propose that internal waves could have an influence on sediment mobilization in Pointe-des-Monts.

Currents generated by internal waves can exceed 0.5 m s^{-1} on sloping topography, which can be sufficient to mobilize sand-size particles observed in Pointe-des-Monts. In Monterey canyon, the currents induced by internal waves (0.5–0.8 m s^{-1}) were found to be strong enough to transport fine sands (Xu et al., 2008). However, although first hypothesized to result from internal tide related currents, the origin of the CSBs present in submarine canyons is still subject to debate (Paull

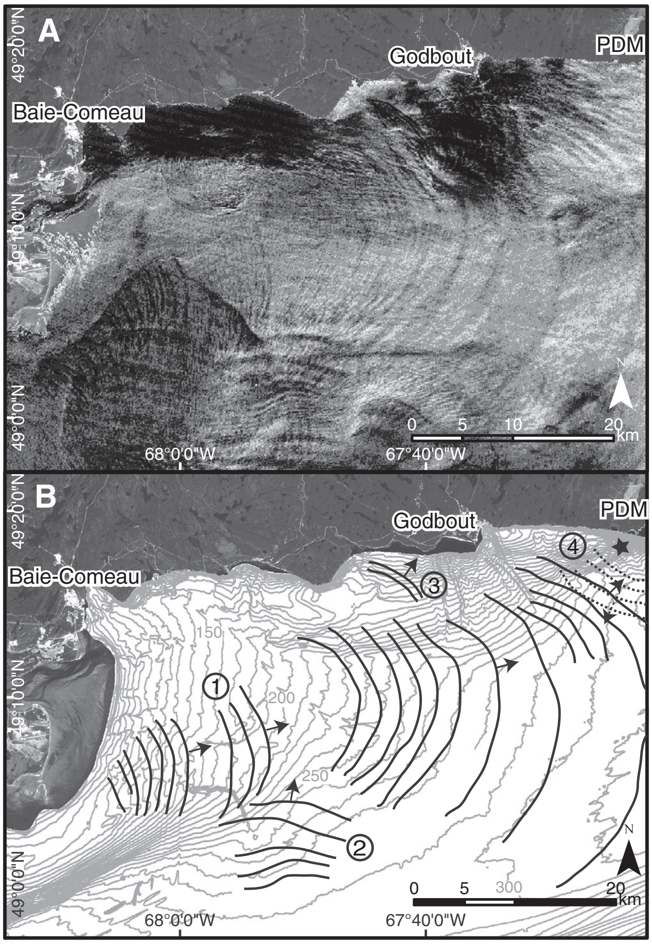

Fig. 12. A) Landsat-5/TM data collected on May 15 2006, 15:15 GMT over the LSLE (path: 12, row: 26) and obtained from the U.S. Geological Survey EarthExplorer web site. The image was rectified and geolocated (L1G) and shows the total radiance in Band 5 (in DNs) enhanced to maximize the contrast over the water body; B) Interpreted image revealing the presence of four internal wave trains along the north shore of the Lower St. Lawrence Estuary.

et al., 2010; Cartigny et al., 2011; Kostic, 2011; Talling et al., 2013). Xu et al. (2008) suggested that relatively slow moving currents related to internal tides could be responsible for their migration, but they assumed that the bedforms migrated downslope. Because coarse material, cobbles and mud clasts were found in the CSBs of Monterey canyon, it was improbable that slow-moving tidal currents would be responsible for their migration. Furthermore, boulder-sized concrete monuments were deployed in Monterey and were displaced downslope by more than 1 km in 2 years (Paull et al., 2010). Paull et al. (2010) thus suggested that CSBs can be formed by erosion associated with cyclic steps or internal deformation during slumping. Hughes Clarke et al. (2014) also deployed concrete monuments in 2011. During their surveys, bedforms migrated even when monuments were not displaced. The spatial patterns of erosion and deposition were similar to when the monuments were displaced. Talling (2014) thus proposed that CSBs can be a general property of supercritical flows or of loosely packed sediments that can be easily disturbed by different triggers, mostly related to slope failures. However, Hughes Clarke et al. (2014) mention that bedform movement also occurred when no recognizable scarps are observed in the Squamish delta, which is similar to the case in Pointe-des-Monts. Off Pointe-des-Monts, the sediments do not consist of coarse material as observed in Monterey, but rather consist of fine sand (Fig. 7). Therefore, relatively slow moving currents (0.5–0.8 m s^{-1}) related to internal tides/waves would be able to transport these fine sands within the canyons, but their role in CSB migration was previously rejected (Paull et al., 2010). If internal tides/waves were responsible for bedform migration, bedforms should be expected to have been displaced in all three canyons, unless the steeper slope of canyon C3 plays a role in amplifying downslope currents. The presence of CSBs high near the canyon heads, where no sediment is observed upslope, is however intriguing because slope failures are not observed. It suggests that downslope currents produced by oceanographic processes could be responsible for their presence, although it would not be in agreement with the current state of knowledge of CSBs and their migration. In any case, the currents induced by internal tides/waves would be responsible for preventing the deposition of fine sediment within the canyon axis, as observed in other settings (e.g., Mulder et al., 2012). Further studies on CSBs off Pointe-des-Monts and elsewhere will have to explain their presence and migration where there is possibly very low concentration of sediment upslope and where no slope failures occurred.

6. Implications and conclusions

The hydrodynamics of submarine canyons are generally dominated by two types of currents: 1) internal tides/waves which generate slow-moving currents that transport particles in the head of the canyons and; 2) high energy turbidity currents which transport large volumes of sediment to the deep-sea floor and which considerably contributes to the erosion and deposition within a canyon system (Xu and Noble, 2009; Normandeau et al., 2013). Such high-energy events are believed to be the main mechanisms acting on sediment mobilization and bedform migration in canyons and to be active when sediments are supplied to canyon heads and subsequently remobilized downward. Even in the absence of littoral drift or a river connection, some submarine canyons can also be fed in sediments by shelf currents (Mountjoy et al., 2013). The case of the Pointe-des-Monts canyons is different because no sediments are transported on the shelf to their head. Therefore, in the absence of sediment supply, slope failures are believed to be important mechanisms for downslope sediment transport (e.g., Mountjoy et al., 2013). The scarps observed along the walls of the Pointe-des-Monts canyons suggest that they are indeed a process contributing to the migration of CSBs. However, they cannot be responsible for all the morphological changes observed between 2007 and 2012 because slope failures were not observed during this period.

Internal waves, possibly related to internal tide activity such as observed in many submarine canyons around the world, could be responsible for maintaining frequent up- and downslope currents. However, the effect of internal tides/waves on upslope migrating CSBs have been previously discarded (Paull et al., 2010; Talling et al., 2013). The presence and migration of CSBs in the Pointe-des-Monts canyons thus remains intriguing without further investigations similar to those reported by Paull et al. (2010) and Hughes Clarke et al. (2014). In any case, in-situ sediments are currently being remobilized downslope off Pointe-des-Monts without further input at the head of the canyons. Our analysis thus demonstrates that submarine canyons located in shallow waters can remain active and frequently transfer sediment towards base-level in the absence of sediment supply.

Acknowledgment

We thank the Canadian Hydrographic Service, particularly Richard Sanfacon and Louis Maltais, for providing the 2007 multibeam data. This study was supported by the Natural Sciences and Engineering Research Council of Canada through Discovery and Ship-time grants to P.L., G.S., D.B. and Jacques Locat (Université Laval), the Fonds de Recherche Québécois–Nature et Technologie through a scholarship to A.N. as well as the Canadian Foundation for Innovation and the Ministère de l'Éducation du Québec through equipment grants to P.L. David J.W. Piper, Jonathan Warrick and an anonymous reviewer provided very constructive comments that greatly improved the final version of this paper.

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