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ORIGINAL

Shallow-water longshore drift-fed submarine fan deposition (Moisie River Delta, Eastern Canada)

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Abstract Submarine canyons and associated submarine fans are in some cases located at the end of a littoral cell where they act as conduits for the transfer of eroded terrigenous sediments to the marine environment. Such fans are generally found in deep-water settings at >500 m water depth. Offshore the Moisie River Delta (NW Gulf of St. Lawrence, Eastern Canada), high-resolution multibeam bathymetry and seismic data led to the discovery of an unusually shallow submarine fan (≤60 m) located at the end of a littoral cell. Sediment is transported westward on the shallow coastal shelf, as demonstrated by the downcurrent displacement of oblique nearshore sandbars where the shelf narrows to less than 1 km. The steep slope near the end of the littoral cell is incised by a channel that feeds a submarine fan composed of smaller channels and depositional lobes. According to existing Holocene evolution models for the region, the fan formed within the last 5,000 years. Its evolution is largely due to the transport of sediment by longshore drift. Multibeam echosounder and seismic data also reveal that the gravity-driven accretion of the submarine fan is characterized mainly by two processes, i.e., frequent small-scale, downslope migration of sandwaves on the slope, and more episodic slumping/turbidity-current activity in the deeper part of the fan. This study documents that, besides their common deep-water location, smaller-scale submarine fans can occur also in very shallow water, implying that they could be more frequent than previously thought both in modern environments and in the rock record.

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Introduction

Submarine gravity-driven processes typically diminish in submarine canyons and associated fans during sea-level highstands when canyon heads become disconnected from river mouths (Vail et al. 1977; Posamentier and Kolla 2003). Recent studies have demonstrated that other factors such as climate (Ducassou et al. 2009) and coastal shelf physiography (Paull et al. 2003; Khripounoff et al. 2009) can promote the occurrence of gravity flows on the seafloor. Thus, many rivers located some distance from canyon heads nevertheless deliver sufficient amounts of sediment to the coastal shelf to maintain gravity flows to submarine fans even during sea-level highstands (e.g., Weber et al. 1997). Along narrow shelves, rivers may be directly connected to submarine canyons and thereby deliver sediments to the adjacent fans without being trapped on the shelf (e.g., Mulder et al. 2001; Babonneau et al. 2002). Many studies have shown that canyons that are not associated with rivers can also be active during sea-level highstands due to a downdrift narrowing of the coastal shelf (Boyd et al. 2008; Covault and Graham 2010; Mulder et al. 2012). These canyons are in many cases observed at the end of a littoral cell and are commonly active in regions where sediment supply by longshore drift is high (e.g., Paull et al. 2005; Boyd et al. 2008; Budillon et al. 2011). This sediment transfer contributes to sediment loss along the coast (Paull et al. 2005; Boyd et al. 2008; Yoshikawa and Nemoto 2010).

Whichever the case, submarine fans are constructional, though isolated, sediment bodies that form seaward of major sediment sources, being fed by submarine channels or canyons (Stow 1985). They are typically observed in deep-sea settings (Schwalbach et al. 1996; Normark 1999; Babonneau et al. 2002; Zühlsdorff et al. 2007; Harris and Whiteway 2011) and are typically tens to hundreds of kilometers long (Nakajima et al. 1998; Deptuck et al. 2003; Kolla 2007; Wynn et al. 2007; Covault and Romans 2009). Indeed, they have rarely been documented in less than 500 m water depth (e.g., Gagné et al. 2009), such shallow-water fans being generally associated with fan deltas, where they form the subaqueous part of alluvial fans (Stow 1985).

In recent years, a series of small canyons and channels have been discovered along the northern shore of the Estuary and Gulf of St. Lawrence, especially in the Les Escoumins (Gagné et al. 2009), the Baie-Comeau (Duchesne et al. 2003), the Pointe-des-Monts (Pinet et al. 2011) and the Betsiamites (Cauchon-Voyer et al. 2008) areas, all of which have the potential to transfer sediments to deeper waters (although still at shelf depths). The very shallow-water submarine fan offshore the Moisie River Delta along the NW Gulf of St. Lawrence, Eastern Canada, is another prime example. Located only about 300 m offshore in less than 60 m water depth, as far as is known Lajeunesse et al. (2007) were the first to report the existence of such small (<4 km across) and shallow submarine fans. Based on serial high-resolution multibeam bathymetry and seismic surveys, the present study aims to identify the source and pathway of the sediment feeding it.

Regional setting

Geological setting

The study was conducted along the northern shore of the Gulf of St. Lawrence (Fig. 1) offshore the city of Sept-Îles between the Moisie River and Pointe-aux-Basques, in an area named Baie-de-la-Boule (50°11′N, 66°14′W). The submarine fan itself is located between the islands of Grande-Basque and Petite-Boule, offshore Pointe-aux-Basques.

The northern shore of the St. Lawrence Estuary and Gulf lies within the Grenville geological province (Franconi et al. 1975). Since deglaciation, thick and large sandy deltaic systems have been deposited along this coast at the mouth of major rivers (Lessard and Dubois 1984; Sala and Long 1989; Dionne and Occhietti 1996; Bernatchez 2003). The Laurentian channel (400 m deep) forms a major valley in the Estuary and Gulf of St. Lawrence, incised into the continental shelf (Shepard 1931; King and MacLean 1970). During glaciations it was a main pathway for the delivery of sediment to the Laurentian fan (Piper and MacDonald 2001; Piper et al. 2007). The Laurentian channel thus forms the base level for the sandy deltas found in the St. Lawrence. The Moisie River Delta is an exception because its base level is located on the shallow shelf along the northern shore in <200 m water depth (Loring and Nota 1973).

Two geological provinces are present off the Moisie River Delta (Faessler 1942): (1) Paleozoic sedimentary rocks of the St. Lawrence Platform, in the southern part of the study area, and (2) the Sept-Îles Intrusive Suite, an Upper Proterozoic (~565 Ma) mafic intrusion (80 km in diameter) of anorthosite, gabbros and monzogabbros found near the coast in the northern part of the study area (Higgins and Doig 1981; Dredge 1983). During deglaciation, which began around 10 ka BP (unless specified otherwise, the radiocarbon ages are reported as conventional ^{14}C ages; King 1985; Occhietti et al. 2011), the Goldthwait Sea transgression reached an elevation of 130 m above sea level (Dredge 1983). During this transgression, more than 240 m thick glaciomarine sediments were deposited near the coast. Offshore, between 25 and 125 m of Quaternary deposits lie above bedrock (Hein et al. 1993). These consist of five seismic units: (1) glacial till or ice-contact sediments, (2) ice-proximal sediments, (3) ice-distal sediments, (4) paraglacial sediments, and (5) postglacial mud (Syvitski and Praeg 1989; Hein et al. 1993; Josenhans and Lehman 1999). The sands constituting the surficial deposits on which the city of Sept-Îles has been built represent a spit formed by the Moisie River after deglaciation (Dredge 1983).

The evolution of the Moisie Delta has been described by Dubois (1979) and Hein et al. (1993), and is largely controlled by longshore drift (Fig. 2). By 7.2 ka BP, a tongue of sediment prograded offshore. Between 7.2 and 5.2 ka BP, sediments were transferred westward by longshore drift, resulting in coastal progradation. Between 5.2 and 2.8 ka BP, erosion affected the southern sector of the delta, whereas sediment continued to accumulate along the western shore. This westward transport has persisted up to the present day.

Recent coastal evolution and artificial infrastructures

Previous studies in the Sept-Îles–Moisie River Delta area demonstrated that the sediment budget along the shore has, on average, been in equilibrium since 1931, although it experienced periods of intense erosion and accumulation (Dubois et al. 2005; Bernatchez et al. 2008; Boudjerda 2010). Thus, from 1931 to 1965 the shoreline prograded at a rate of 0.43 m/year; from 1965 to 1979 it remained stable (+0.01 m/year); from 1979 to 1996 it prograded again at a rate of 0.56 m/year; from 1996 to 2006 it retreated at a rate of 0.06 m/year. Historically, the Moisie River mouth has recorded the highest rates of shoreline retreat since 1931, compared to the other sectors of the Baie-de-la-Boule farther to the west (Lessard and Dubois 1984; Dubois et al. 2005). Conversely, the western sector of the Baie-de-la-Boule experienced the highest rates of accumulation due to longshore drift from the east (Lessard and Dubois 1984). Today, erosion is concentrated mainly along the Fergusson and Monaghan beaches (Fig. 1) where coastal defenses such as rigid protective structures are more numerous (Normandeau 2011; Bernatchez and Fraser 2012).

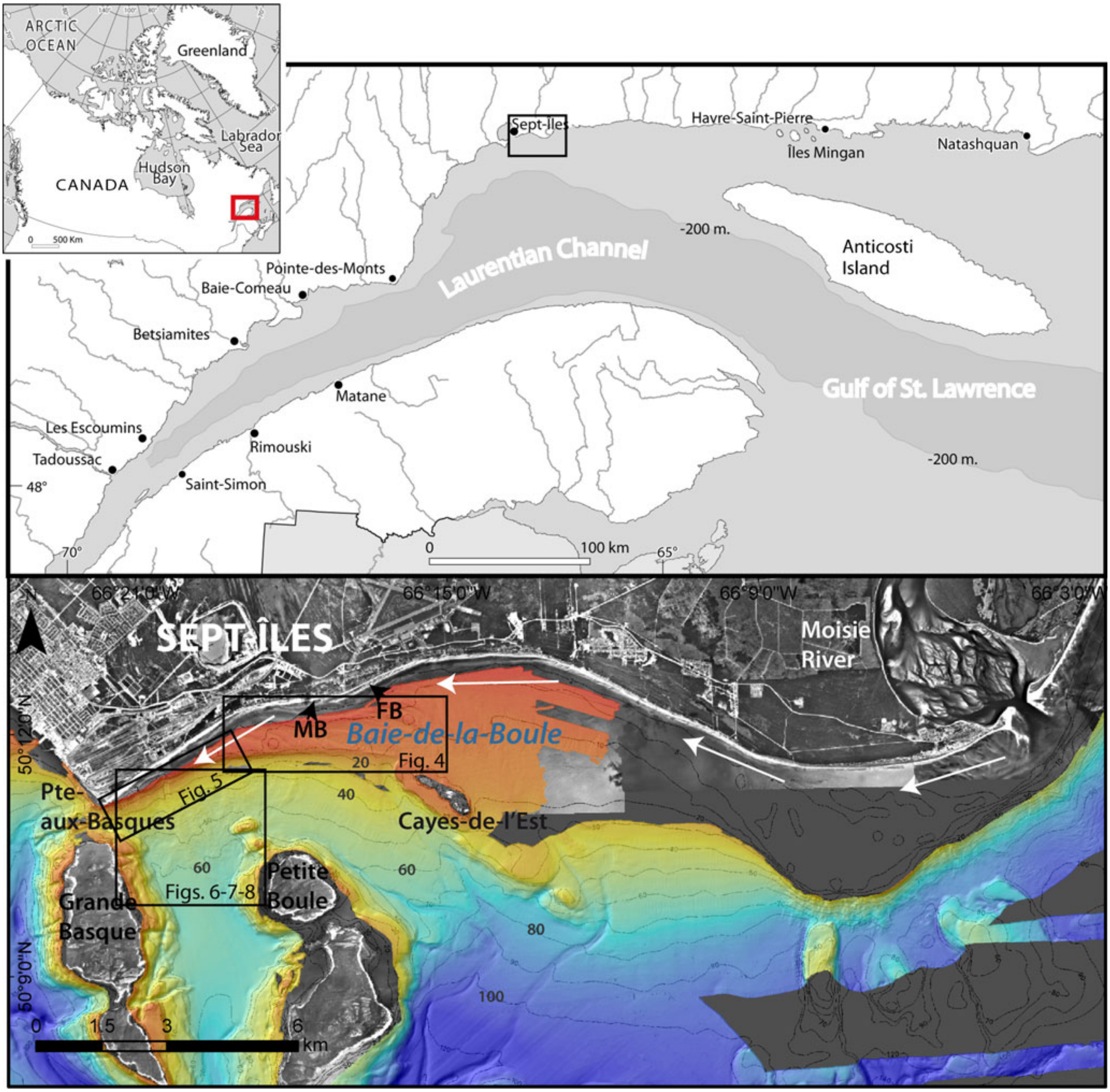


Fig. 1 Location of the study area offshore the city of Sept-Îles, in Eastern Canada. The submarine fan is located between Grande-Basque and Petite-Boule islands off Pointe-aux-Basques along the northern shore of the Gulf of St. Lawrence. *MB* Monaghan beach, *FB* Fergusson beach. *White arrows* Main longshore drift direction

Materials and methods

Three sets of high-resolution multibeam bathymetric data were collected in 2001, 2007 and 2012. In 2001, bathymetric data were collected between 30 and 300 m water depth by the *Canadian Hydrographic Service* (CHS) using a Kongsberg Simrad EM-1000 multibeam echosounder (95 kHz, 10 m grid resolution, 0.5 m depth resolution) installed on the CCGS Frederick G. Creed. Shallow-water bathymetric data of the coastal shelf (2–30 m) were collected in 2007 by the *Centre interdisciplinaire de développement en cartographie des oceans* (CIDCO) using a Reson Seabat 8101 (240 kHz, 2 m grid resolution, 0.6 m horizontal resolution, 0.2 m depth resolution) on the R/V Bec-Scie (Fig. 3). This system was also used in 2012 from the R/V Louis-Edmond-Hamelin to map the submarine fan and a sector of the coastal shelf (Fig. 3). Raw data were processed with the Caris Hips and Sips® software.

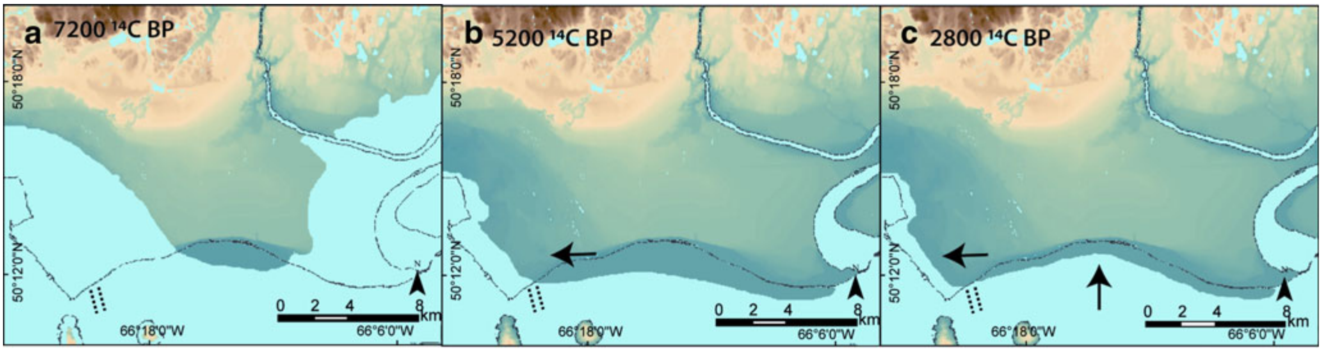


Fig. 2 Evolution of the Moisie River Delta (modified from Dubois 1979, and Hein et al. 1993): 7.2 ka BP: shoreline ~7 km from present-day location of submarine fan; 5.2 ka BP: shoreline less than 1 km from fan; 2.8 ka BP: shoreline close to present-day location, and less than 1 km from fan. *Dotted lines* Location of the channel head leading to the submarine fan

Due to bad weather conditions during the 2012 survey, the roll-and-pitch effect produced bathymetric artifacts of ≤0.2 m in the deeper areas, but these do not affect the resolution of the bathymetric comparisons. Errors in bathymetry can be due to positioning, tides, water sound velocities and misalignment of instruments. In order to minimize these errors, a Valeport Tidemaster® with a 0.01 m precision served to correct the vertical positioning of the sounding points. Water sound velocities were taken every hour in order to correct for changes in water density. Standard hydrographic patch-test calibration allowed correcting for misalignment of instruments

About 50 km of subbottom profiler data were collected by means of an Edgetech X-Star 2.1 Chirp (2–12 kHz, cm-scale vertical resolution), which had a limited signal penetration (~1–2 m) in coarse sandy sediments. Chirp lines were spaced 75–100 m apart. In order to obtain data with greater penetration, 9 km of sparker profiles were acquired using an Applied Acoustics Squid 2000 sparker system (2 kJ, m-scale vertical resolution), which achieved a signal penetration of several tens of meters in coarse sediments (Fig. 3). Both seismic systems were deployed in 2010 onboard the R/V Coriolis II.

Results

Shelf

The coastal shelf is here defined as the submarine section from the shore to the shelf break. It is 22 km long, extending from the Moisie River mouth to Pointe-aux-Basques (Fig. 1), and has a maximum width of 5.2 km near the Cayes-de-l'Est and a minimum width of 150 m off Pointe-aux-Basques. The depth of the shelf break is rather variable along the Moisie River Delta, reaching a maximum value of 30 m near the Cayes-de-l'Est. Off Pointe-aux-Basques, by contrast, the coastal shelf reaches a maximum depth of only 5 m.

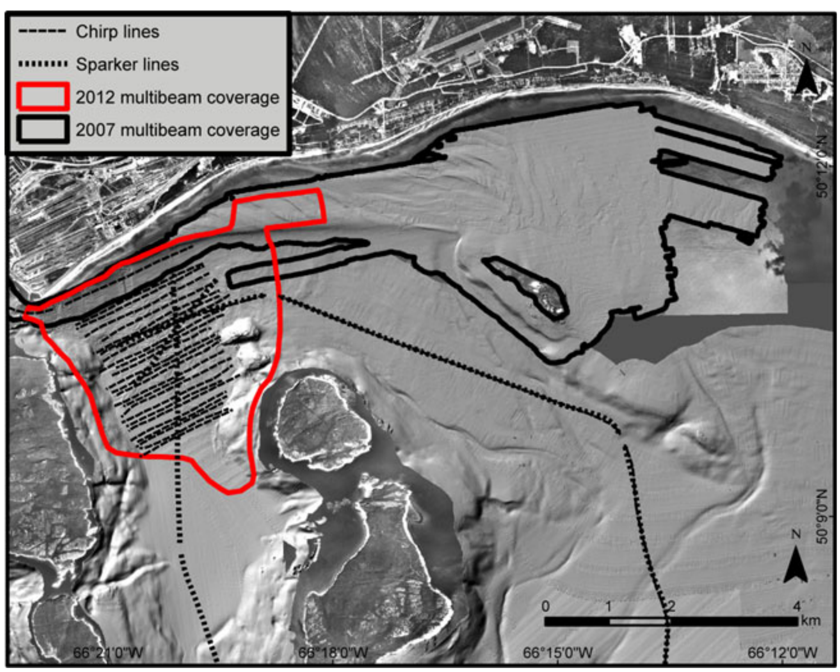


Fig. 3 Tracklines of chirp, sparker and multibeam bathymetry surveys conducted in 2007 and 2012. The 2001 low-resolution multibeam survey covered the area where the 2007 survey ends (30 m water depth), and extended down to 300 m water depth on a 10 m grid

The 2007 multibeam survey in the western half of the coastal shelf of the Moisie Delta revealed the presence of well-developed nearshore sandbars east of Pointe-aux-Basques, aligned obliquely to the coast (Fig. 4a). The bars are ~200–400 m long and 2–3.5 m high, their crests being found in <5 m water depth at <1 km from the shore. The angles with the shore vary between 30° and 50° and are oriented toward Pointe-aux-Basques. All of the bars are asymmetrical, the steeper lee slopes varying from 5–15°, the flatter stoss slopes from 0–3° (Fig. 4b).

The area of the shore-oblique sandbars was again surveyed with the same multibeam system in 2012, enabling a quantification of changes in crest locations (Fig. 4). The data revealed that, between 2007 and 2012, the crests of the two bars closest to Pointe-aux-Basques were displaced westward by 25 m in the one case and 50 m in the other case, associated with lee face accumulation of ≤3 m and crest erosion of ≤1.5 m.

Slope

Off Pointe-aux-Basques, the shelf break is located between 150 and 350 m from the shoreline. The adjoining sigmoidally shaped slope has a steep gradient that reaches 12° with an average of 3° (Fig. 5b), the gradient rapidly falling below 4° with increasing distance from the shoreline. In this sector, the slope is intersected by a channel (Fig. 5c) and small-scale sandwaves to the west (Fig. 5d). At its shallowest point the channel head is situated less than 300 m from the coast, and is 200 m wide, 160 m long and incised up to 3.5 m into the shelf. On the slope the channel is confined to a width of 150 m (margin to margin) over a distance of 390 m up to a depth of 35 m, while the relatively flat-bottomed thalweg is 100 m wide. The depth of the channel (margin to thalweg) is ≤3 m. The bottom of the thalweg consists of numerous asymmetric sandwaves with wavelengths of 10–20 m and heights <1 m. The downslope-facing lee slopes dip at ≤12°, whereas the flatter stoss slopes climb at ≤2°.

A chirp profile in the upper slope section parallel to the shoreline reveals a chaotic morphology in the thalweg (Fig. 5g). Levees are developed on the margins of the channel, which progressively evolve downslope (see bathymetric profile A–A′ in Fig. 6). The levees are ~100 m wide and ~0.5–2 m high, the western levee being better developed than the eastern one. Chaotic deposits are observed to the west on the chirp profile, associated with small-scale sandwaves. These are of the same order in size as those in the thalweg of the channel.

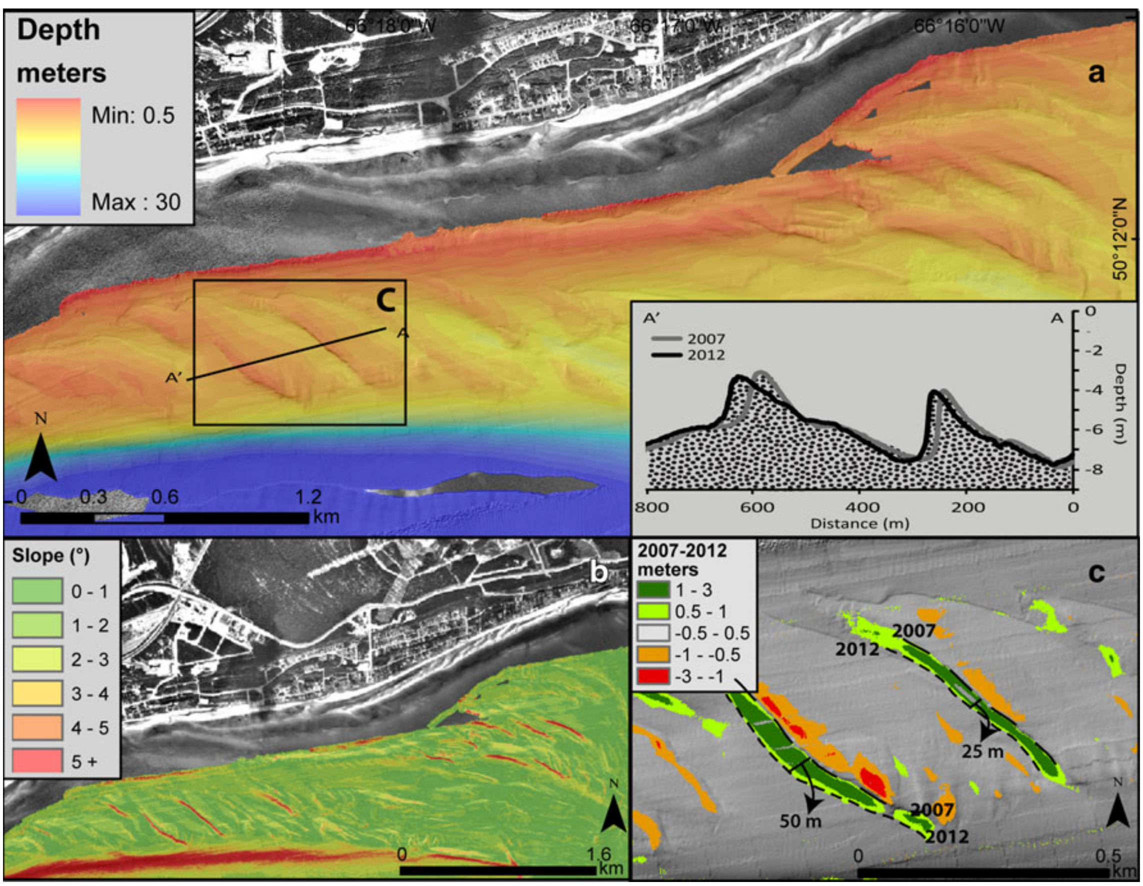


Fig. 4 **a** General bathymetry of the coastal shelf, revealing the presence of shore-oblique sandbars in the nearshore. **b** Slope of the coastal shelf. **c** Differences in depth between 2007 and 2012 over two shore-oblique sandbars, revealing substantial changes in morphology and depth over this period. *Numbers and arrows* Crest displacements of the shore-oblique sandbars

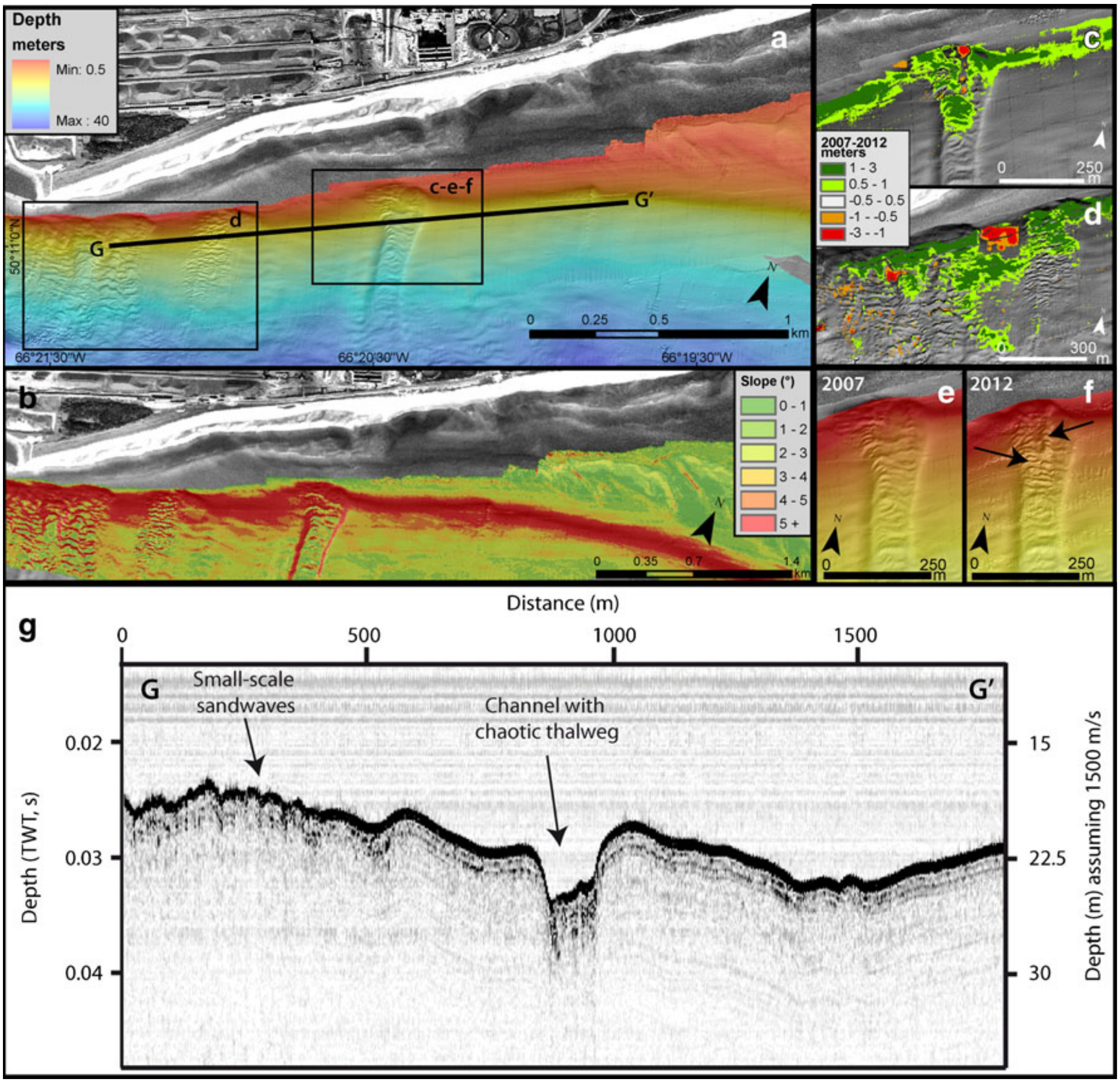


Fig. 5 **a** General bathymetry of the slope, showing channel incisions and small sandwaves. **b** Map section showing slope gradients. **c** Differences in depth between 2007 and 2012 over the channel. **d** Differences in water depth between 2007 and 2012 over the small sandwaves. **e** Multibeam bathymetry of the channel in 2007. **f** Multibeam bathymetry of the channel in 2012. **g** Chirp profile parallel to the shoreline, illustrating the confined channel and small sandwaves

The slope off Pointe-aux-Basques was mapped during the 2007 survey down to a water depth of 35 m. The repeat survey of 2012 reveals a number of changes in the channel head region. In some parts the channel accreted by ≤3 m, adding ~42,800 m^3 to the sediment volume, but locally also lost <2.5 m of sediment (~1,400 m^3) in the eastern part of the head (Fig. 5c). The sediment budget thus indicates a net gain of ~41,400 m^3 in the channel head. The two datasets (Fig. 5e, f) further reveal that the small sandwaves within the head region changed in morphology and location. In areas of sediment accumulation the sandwaves evolved downslope, while new sandwaves developed in the eroded areas. Bathymetric and morphological changes were generally small (<0.5 m in height) within the confined channel section. The small sandwaves located west of the channel also evolved between the two surveys, while new ones appeared where the slope was formerly undisturbed. Changes in morphology were thus restricted mainly to the shallower nearshore region (Fig. 5d). Unfortunately, the lower resolution of the submarine fan data acquired in 2001 did not enable any detailed depth and morphology comparisons.

Basin floor

As the channel becomes unconfined downslope, it evolves into a bird-foot fan geometry on the basin floor (Figs. 6, 7). The fan is 3 km long and ≤1.6 km across, with an average slope of 1.18° (range 0–8°; Fig. 7b). It consists of numerous smaller features such as distributary channels and depositional lobes. Thus, two small channels incise the fan in its

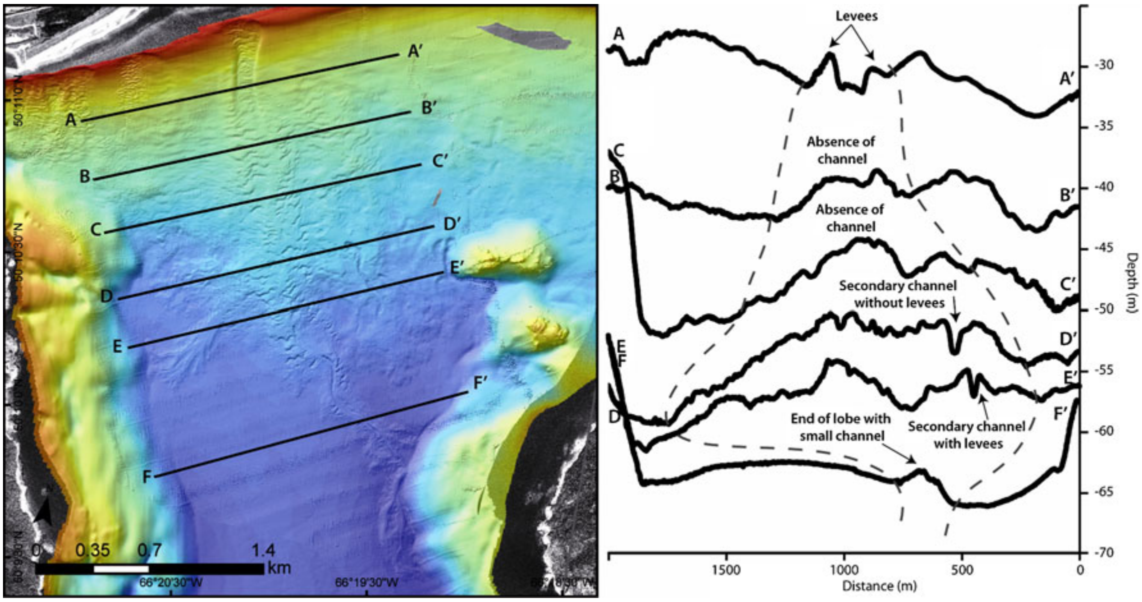


Fig. 6 Bathymetric profiles parallel to the shoreline: A–A′: upper channel confined by levees; B–B′ and C–C′: absence of channels downslope; D–D′ and E–E′: smaller channel with and without levees; F–F′: far end of fan with small channel

eastern (Figs. 6 and 7d) and southern (Figs. 6 and 7e) sectors. The eastern one, which has a downslope gradient of 0.6°, is 560 m long, <35 m wide and <2 m deep. The sinuosity index is 1.1, which falls within the straight channel category (Clark et al. 1992; Wynn et al. 2007). A bathymetric profile perpendicular to the channel axis reveals the presence of levees along its margins (Fig. 6, E–E′). The southern channel (Fig. 7e), which has a downslope gradient of 0.5°, is 930 m long, <30 m wide and <1 m deep. Its sinuosity index is 1.08. At the end the channel bifurcates into a west-facing depositional lobe, which has evidently been deflected by the steep slope of the Petite-Boule Island. Levees are also observed along the margins of this small channel.

Two small depositional lobes occur in the western sector of the fan (Fig. 7f). Small channels appear near the end of these lobes. Small sandwaves are present throughout the fan, especially in its center, following the direction of the upper main channel (Fig. 7c) and on both sides of the southern channel (Fig. 7e). They have wavelengths of <65 m and heights <2 m. The steeper leeward slopes have gradients up to 10°, whereas those of the stoss slopes generally rise at ≤1° (Fig. 7b).

Chirp profiles collected at the end of the southern channel of the submarine fan enabled identification of two seismic units (Fig. 8a, b). The lower unit (unit 4; see Regional setting) is characterized by high-amplitude parallel and horizontal reflectors at the top. The upper unit (unit 5) has low tones and weak parallel reflectors. The fan as such occurs within and above unit 5. Below the fan, the high-amplitude reflectors of unit 4 are more strongly attenuated than those located below the draping sediments of unit 5. Thus, the sediment composing the fan prevents deeper acoustic penetration. This shortcoming was overcome by running a sparker profile across this feature (Fig. 8c). The deeper penetration revealed a highly chaotic seismic facies above a low-amplitude conformably stratified unit. The lobe is ~30 m thick near the base of slope (assuming a 1,500 m/s velocity), and gradually diminishes in thickness offshore.

Discussion

Sediment source and coastal shelf sediment dynamics

The near absence of even small rivers along the littoral cell suggests that the coastal shelf sediments originate mainly from the Moisie River to the east. After deposition near the river mouth, the sediment is transported laterally along the coast at high rates (Bernatchez and Fraser 2012). Previous studies in the region have demonstrated that, over the last century, the coast has been undergoing periods of strong local erosion, due mostly to the presence of artificial infrastructures (e.g., Dubois et al. 2005; Bernatchez et al. 2008; Normandeau 2011). Such rigid structures are known to eventually generate erosion on both sides, known as the end effect (e.g., Kraus and McDougal 1996). A large part of the eroded sediment is transferred westward through a coastal sandbar system (Bernatchez and Fraser 2012).

However, sediment transport does not occur only near the coast. The presence of shore-oblique sandbars in the nearshore and the displacement of their crests suggest that there is movement of sediment obliquely offshore. These shallow-water (<6 m water depth) shore-oblique sandbars are very similar to the deeper shoreface-connected ridges widely discussed in the literature (see Duane et al. 1972; Son et al. 2012, and references therein). Although they are also similar to transverse bars (Niedoroda and Tanner 1970), they are in this case not directly connected to the coast. Other similar nearshore oblique sandbars have been observed in northern North Carolina but, unlike the bars of the Moisie River Delta area, these were found to be stable due to geological control of the substrate (McNinch 2004). According to the terminology of Ashley (1990), the sandbars could also be very large dunes based solely on their size and morphology. However, such large flow-transverse bedforms would only develop in sands coarser than about 0.25 mm, and would also not be able to reach the observed dimensions in such shallow water (Rubin and McCulloch 1980; Ashley 1990; Flemming 2013). Another hypothetical explanation could be that the bars represent ridges between rip channels incised into a convex, nearshore sand sheet (e.g., Flemming and Davis 1994). However, the bars and troughs should then be oriented NE/SW in the direction of the main longshore current, which is clearly not the case here. Moreover, the bathymetric data revealed no evidence of channelized erosion that could result from rip-current activity (Fig. 4a). Therefore, the origin of the shore-oblique sandbars remains unresolved and requires further investigation. Irrespective of their origin, the fact that the crests and troughs of the bars have been displaced between 2007 and 2012 suggests that they are mobile features transporting sediment in the direction of the longshore drift, i.e., westward.

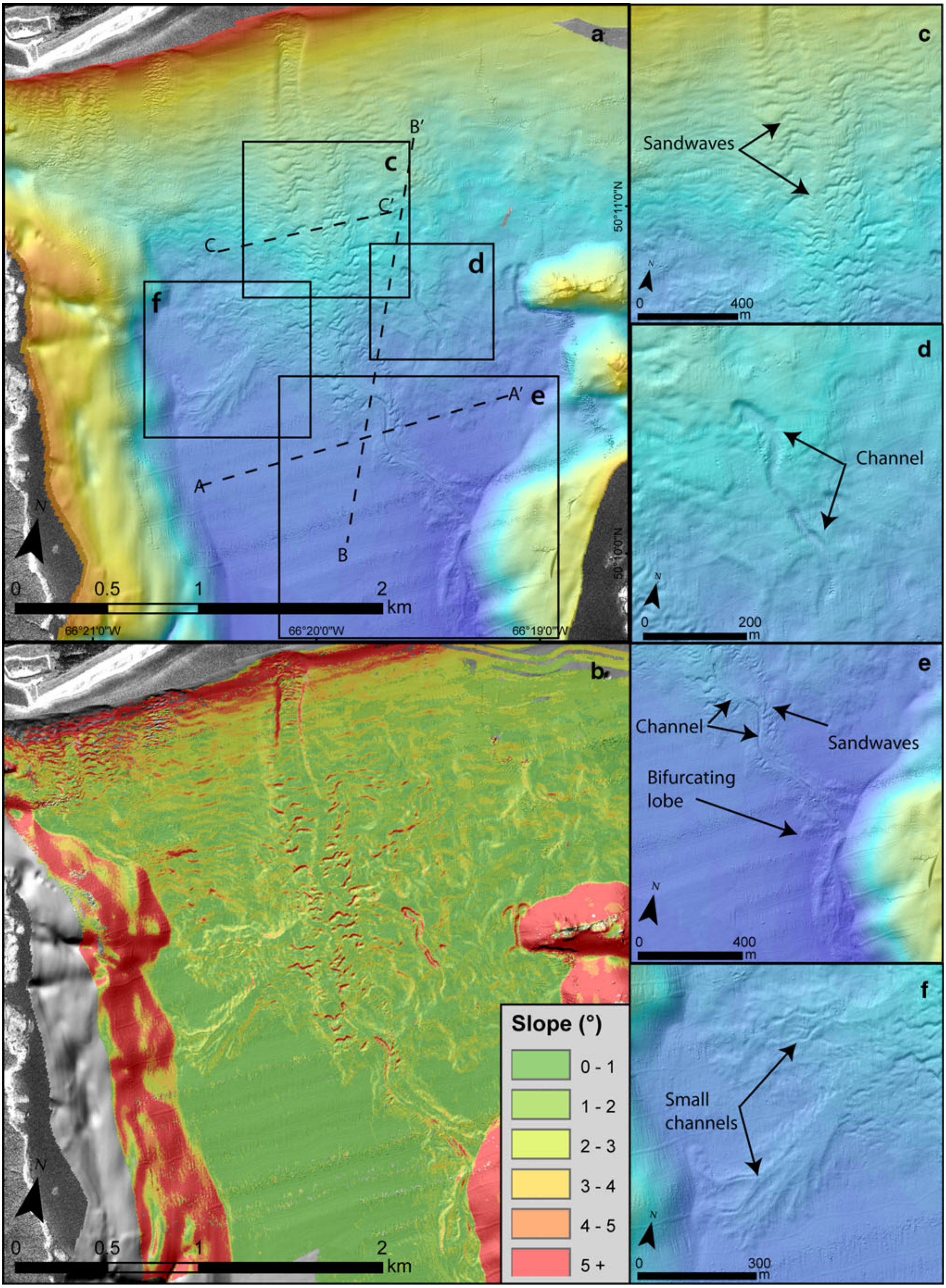
Recent deposition

Chirp profiles collected near the base of the submarine fan show a decrease in acoustic penetration directly beneath the fan (Fig. 8a, b). This indicates that it consists of coarse sediment, much coarser than that observed on both sides of the fan where much higher signal penetration was achieved in finer hemipelagic sediments (Syvitski and Praeg 1989). The narrow shelf and the high rate of sediment transport toward the channel head by longshore drift are most likely responsible for the deposition of coarse sediment on the fan and its activity in the long term.

According to the existing model of sedimentation and evolution of the Moisie River Delta, the five seismo-stratigraphic units identified offshore Sept-Îles are associated with ice retreat, glacio-isostatic rebound, and the establishment of modern conditions (see Regional setting). Units 4 and 5 identified on the chirp data were previously interpreted by Syvitski and Praeg (1989) as paraglacial and postglacial sediments, respectively (Fig. 8a, b). Those authors suggested that the transition between the two units occurred between 8 and 6 ka BP. The age of the fan must therefore be younger than the postglacial sediments (i.e., younger than 8 ka BP), because it overlies unit 5. The conceptual model of Holocene evolution for the Moisie River Delta (Dubois 1979; Hein et al. 1993) suggests that the shoreline, which is currently located at Pointe-aux-Basques, was originally located ~7 km to the east ~7 ka BP (Fig. 2, scenario A). This would correspond to the transition from paraglacial to postglacial sedimentation. At that time, the submarine fan could not have formed because it would have been too far away from any sediment source transported through longshore drift. Between 5.2 ka and 2.8 ka BP, the model places the shoreline near its current position (±1 km; Fig. 2, scenarios B, C). At that time, postglacial sediments formed the modern base level on which the fan was emplaced (Syvitski and Praeg 1989). Therefore, the onset of submarine fan deposition is here estimated at ~5 ka BP. Interestingly, the shoreline experienced a minor transgression along its southern sector during this period (Fig. 2, scenarios B, C). This transgression, on the order of 10–14 m, has been recorded in sediments and bogs from the south shore of the St. Lawrence (Dionne 2001), in Baie-Comeau (Bernatchez 2003), at Québec city (Verville et al. in press) and at Havre-Saint-Pierre (G. Magnan and M. Garneau, personal communication; Fig. 1), indicating that it affected the entire northern shore of the St. Lawrence Estuary and Gulf. This rise in relative sea level must have amplified coastal erosion and the westward sediment transport toward Pointe-aux-Basques (Fig. 2). Longshore drift on the coastal shelf could then have delivered substantial volumes of sediment toward the channel head of the fan. In the course of its evolution a steep slope evolved, which facilitated offshore remobilization of sediment by gravity flows.

The results of the present study provide no evidence for the occurrence of very recent (≤5 years) large gravity flow events. Based on the repeated multibeam bathymetry coverage in shallow water, substantial morphological changes occurred at the head of the channel between 2007 and 2012. Besides the development of small sandwaves, accumulation and erosion were observed in various places (Fig. 5), these being similar in scale to those observed in the sandwave field west of the channel. These sandwaves were most probably not produced by gravity currents, because no deposition is observed downslope. Without repeated multibeam coverage over the fan, it is currently not possible to determine whether this system has been active during the last few years. Considering the large sediment accumulation at the head of the channel (≤3 m) over the 5 years between 2007 and 2012, however, the channel would have been infilled within a few decades if downslope currents were not regularly remobilizing the sediment.

Fig. 7 **a** General bathymetry of the basin, illustrating the submarine fan and distal lobe structures. *Dashed lines* Seismic profiles shown in Fig. 8. **b** Slope gradients of the lobe. **c** Close-up view of the channel base where it becomes unconfined. **d** Close-up view of the small channel in the eastern part of the fan. **e** Close-up view of a small channel in the southern part of the fan. **f** Close-up view of two lobes in the western part of the fan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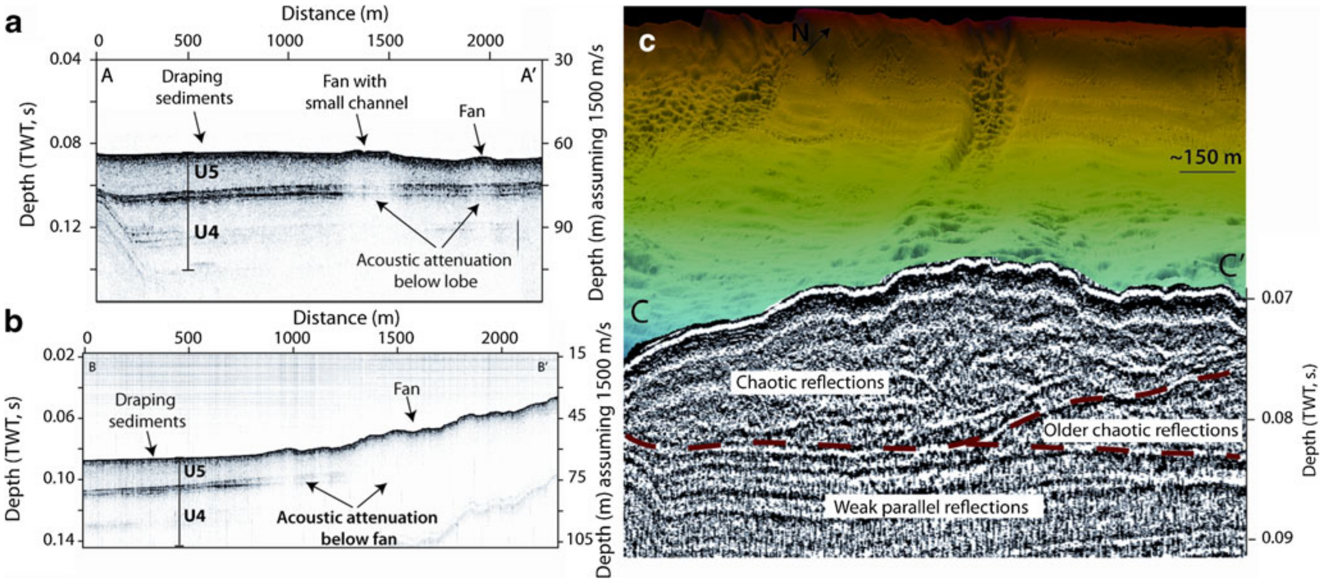

Fig. 8 **a** Chirp profile illustrating seismic units below the submarine fan across a distal depositional lobe. **b** Chirp profile illustrating seismic units below the fan, and the attenuation of the acoustic signal with increasing distance from the channel head. **c** Internal seismo-stratigraphy of the submarine fan, illustrating its chaotic nature (note that the bubble-pulse effect of the sparker obscures the surficial sediments). See Fig. 7a for locations of profiles

Gravity-driven processes

Two major sediment transport processes were identified on the Moisie submarine fan: (1) episodic transport of large volumes of sediment and (2) more frequent transport of smaller volumes.

Various mechanisms can be suggested for the episodic sediment transport events and the resulting evolution of the submarine fan over time. Chaotic reflectors observed on sparker profiles indicate that sediment was transported downslope by gravity flow processes (Sangree and Widmier 1979). Chaotic reflections are often associated with slumps and debris flows (Sangree and Widmier 1979), and their occurrence therefore suggests that such mass transport processes took place during fan evolution. Similar lobe features near the termini of submarine fans, which feather out offshore, have also been recognized in the Gulf of Cadiz (Habgood et al. 2003; Mulder et al. 2006) and on the lower Mississippi fan (Twichell et al. 1992) and, in both cases, have been attributed to gravity flows such as turbidity currents.

Some typical gravity flow initiation processes can, in the present case, be eliminated because of the location of the fan. For example, hyperpycnal currents, which are a common trigger for gravity flow initiation (Mulder et al. 2001; St-Onge et al. 2004), cannot feed this system because the mouth of the Moisie River lies 22 km to the east of the channel head; moreover, the latter is located very close to the shoreline, and could therefore not have intercepted hyperpycnal flows originating at the delta. As the channel is cut into a very narrow coastal shelf where coastal sediment transport is strongly confined, oversteepening due to rapid accumulation in conjunction with high-energy events such as storm waves are the most likely initiation mechanisms triggering downslope flow (e.g., Piper and Normark 2009).

The head of the channel forms a small depression in only 3.5 m water depth where sediment supplied by longshore drift can accumulate. This preferential accumulation has been recorded by the repeated multibeam surveys (Fig. 5c). Rapid accumulation within channel or canyon heads in the nearshore zone has been shown to cause slumping on steep slopes (e.g., Mastbergen and Van Den Berg 2003; Duchesne et al. 2003; Biscara et al. 2012; Conway et al. 2012). In addition, storm waves can cause sediment failures on steep slopes (e.g., Gaudin et al. 2006; Biscara et al. 2013). In such circumstances, sediment remobilization can also occur during earthquakes, as suggested for the Les Escoumins canyons in the St. Lawrence Estuary (Gagné et al. 2009). In fact, earthquakes were also proposed as a mechanism for triggering mass movements offshore Sept-Îles because the region is located in the Lower St. Lawrence Seismic Zone (Lamontagne et al. 2003; Lajeunesse et al. 2007). However, the absence of large historic earthquakes precludes this trigger mechanism for the recurrence rates of gravity flows in the study area, the two strongest events since 1900 having reached M 5.1 on the Richter scale and being located more than 60 km from the submarine fan (Natural Resources 2012). According to Jibson (2009), a minimum of 5 on the Richter scale is required to trigger subaqueous landslides—in the present case, this limits the role of earthquakes as the main cause of gravity flow activity in the system. Storms can also lead to resuspension of coastal shelf sediment and their downslope movement through gravity flows (Puig et al. 2004). However, only extreme storms are anticipated to generate such gravity flows in the Moisie submarine fan because the severe storms recorded between 2007 and 2012 did not lead to any recognizable gravity flows. Nevertheless, as with other longshore drift-fed systems (Paull et al. 2003; Mulder et al. 2012), coastal hydrodynamic-related processes are the most probable dominant mechanisms for the initiation of gravity flows in the study area.

Although there is no clear evidence of recent large-scale gravity processes, there is some evidence of smaller-scale activity. The small sandwaves recorded in the upper channel are possibly related to more frequent minor-scale events because they have migrated and/or changed their morphology over the 5-year period covered by the repeated multibeam surveys. The sandwaves are probably generated and reactivated by the relatively weak currents induced by coastal downwelling, tides and/or internal tides (e.g., Hotchkiss and Wunsch 1982; Xu et al. 2008). Thus, in Monterey Canyon, currents able to induce bedform migration were found to be more frequent than previously thought (Xu et al. 2008). Although the present study cannot quantify flows responsible for sandwave activation, it does suggest that they are more frequent at the head of the channel than episodic gravity-driven processes such as slumps and turbidity currents. Therefore, this study highlights the heterogeneity and the complexity of processes affecting submarine channels and fans in shallow nearshore waters.

Implication for longshore drift-fed submarine fans

Although the Moisie River Delta has undergone a forced regression since deglaciation due to glacio-isostatic rebound, its location and setting are similar to active longshore drift-fed depositional systems found worldwide under sea-level highstand conditions (Shepard et al. 1969; Paull et al. 2003; Boyd et al. 2008; Mulder et al. 2012). In these cases, canyons are located where the coastal shelf narrows to a few kilometers, enabling sediments to be intercepted by their head valleys. As, in the present case, the channel head lies less than 300 m from the coast, the Moisie submarine fan is well placed for the interception of sediment supplied by longshore drift and its downslope remobilization by gravity flows. The results presented here emphasize that, irrespective of the water depth, submarine fans can form in any place where large volumes of sediment accumulate on a narrow shelf and high-energy hydrodynamic processes can remobilize the accumulated sediments along sufficiently steep slopes to generate gravity flows.

Conclusions

The geomorphological and seismo-stratigraphic data from the western portion of the Moisie River Delta, NW Gulf of St. Lawrence, indicate that the construction of a small shallow-water submarine fan is related to the westward transfer of sediments through longshore drift along the narrow shelf, and the presence of a steep offshore slope near Pointe-aux-Basques. The steep slope resulted from the westward progradation of the delta across the shallow shelf of the northern shore during the Holocene. Large volumes of sediment transported by longshore drift and the narrowness of the coastal shelf then sustained the long-term activity of the system, maintained by frequent small-scale sandwave migration transferring small amounts of sediment into and within the channel head, and by the impact of episodic slumps and/or turbidity currents transferring larger amounts of sediment downslope. Evidently, coastal sediments can escape nearshore zones by being transferred through channels to submarine fans in very shallow marine basins (≤60 m) such as in the Moisie River Delta system. By implication, shallow-water fan systems could be more frequent than hitherto recognized both in the modern and the ancient stratigraphic record.

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