Timing and controls on the delivery of coarse sediment to deltas and submarine fans on a formerly glaciated coast and shelf

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ABSTRACT

The evolution of deltas and submarine fans is often envisioned as largely controlled by relative sea-level (RSL) variations. However, in some cases, RSL can have less effect on delta and submarine fan activity than sediment supply and shelf geomorphology. In order to document the relative importance of these three factors on deltaic and submarine fan evolution in a former glaciated environment, this paper documents the delivery of coarse sediment to the Laurentian Channel (eastern Canada). The well-constrained stratigraphic and geomorphological framework of both the glacio-isostatically uplifted deltas and the modern Laurentian Channel fans allow us to document and contrast the evolution of river-fed deltas, river-fed canyon/fan systems and longshore drift-fed fans during deglacial and postglacial times. The evolution of these different types of fans can be divided into three phases. The first phase is characterized by delta progradation on the shelf while RSL was at its maximum, although already falling, and the ice-margin gradually retreated inland. The second phase is characterized by the delivery of deltaic sediment in the deep realm of the Laurentian Channel, permitted by the supply of large amounts of glaciogenic sediments derived from the retreating ice margin and the lowering of the RSL. At the same time, sediment instability along the steep Laurentian

Channel formed small incisions that evolved into submarine canyons where the narrow shelf allowed the trapping of longshore sediment. The third phase is characterized by the withdrawal of the ice-margin from the watershed of the main rivers and the drastic decrease in sediment supply to the deltas. Consequently, the delta fronts experienced strong coastal erosion, even though RSL was still lowering in some cases, and the eroded sediments were transferred onto the shelf and to adjacent bays. This transfer of coastal sediments allowed the continued activity of longshore drift-fed canyons. The retreat of the ice margin from the watersheds thus controlled the supply of sediment and induced a change in delta type, passing from river-dominated to wave-dominated. This paper highlights the role of the type of sediment supply (ice-contact, glaciofluvial and longshore drift) in the timing and activity of submarine fans in high-latitude environments. It proposes a conceptual model for high-latitude shelves where sediment delivery to submarine fans is mostly controlled by structural inheritance (watershed area and shelf geomorphology) rather than RSL fluctuations. Therefore, although RSL fell during delta progradation, this study demonstrates that it was not the main contributor to delta and submarine fan growth. This has wider implications for the extraction of sea-level information from stratigraphic successions.

INTRODUCTION

Deltas and submarine fans are the main depositional systems accumulating terrigenous sediments originating from sediment density flows (sensu Talling et al., 2012). Deltas are associated with a river source whereas submarine fans can be connected to submarine canyons fed either by rivers (e.g., Babonneau et al., 2013), longshore drift (e.g., Lewis and Barnes, 1999) or glacial meltwaters (e.g., Roger et al., 2013). Deltas and fans of limited extent can be observed in shallow waters, such as at the head of fjords (Prior and Bornhold, 1989; Conway et al., 2012; Hughes Clarke et al., 2014) and on coastal shelves (Normandeau et al., 2013; Warrick et al., 2013), providing a great opportunity for documenting sediment transport using very high-resolution mapping techniques (e.g., Hill, 2012; Hughes Clarke et al., 2014; Normandeau et al., 2014). These shallow water systems can then serve as high-resolution analogues to larger deep-water systems and improve our overall understanding of sediment density flow processes and timing in relation to sediment supply and relative sea-level (RSL).

The architecture of deltas and submarine fans is usually envisioned as largely controlled by RSL variations, where forced regressions lead to fast progradation into marine basins. However, the architecture and activity of deltas and submarine fans are known not only to be controlled by RSL, but also by tectonic settings, climatic conditions and grain-size (Bouma, 2004). RSL variations exert a major control on the activity of deltaic and turbidite systems (Porębski and Steel, 2003; Covault and Graham, 2010; Paull et al., 2014) where, at sea-level lowstands, continental sediments are easily transported to continental margins, while in sea-level highstands, sediments are trapped in estuaries (e.g., Maslin et al., 2006). However, these models were developed for passive margins with broad shelves where continental sediment supply is relatively constant over time. Such models lead to false interpretations where tectonic settings favour a direct link between coastal sediments and deep-sea settings (Migeon et al., 2006; Covault et al., 2007; Boyd et al., 2008; Romans et al., 2009; Babonneau et al., 2013) or where climatic conditions favour high sediment discharges from rivers (Ducassou et al., 2009; Rogers and Goodbred, 2010).

In glacio-isostatically uplifted shelves, the study of deltas and submarine fans is often restricted to either their modern exposed component (i.e., outcrops: Corner, 2006; Eilertsen et al., 2011; Marchand et al., 2014; Nutz et al., 2015) or to their modern submarine component (submarine deltas: e.g., Sala and Long, 1989; Normandeau et al., 2015). In these settings, since sediments composing the deltas were deposited below sea-level and subsequently glacio-isostatically uplifted in part above sea-level, both the modern exposed and marine components should be studied as a whole rather than separately. The study of deltas and submarine fans is incomplete without taking into account both their exposed and marine components. In this respect, the variety of types of deltas and submarine fans located in the Lower St. Lawrence Estuary (LSLE) provide ideal sites to examine deltaic progradation and submarine fan deposition in a glacio-isostatically uplifted setting.

While most of the uplifted deltas and fans of the LSLE have been studied inland (Bernatchez, 2003; Marchand et al., 2014; Dietrich et al., 2016a; in press), the links between them and their submarine counterparts in the Laurentian Channel have never been thoroughly examined. These systems vary greatly in size, morphology and sediment sources (Normandeau et al., 2015). Four major types of submarine canyons and channels were described in the LSLE, using a source-based classification: 1) river-fed channels; 2) longshore drift-fed canyons; 3) glacially-fed canyon; and 4) sediment-starved canyons (Fig. 1; Normandeau et al., 2015). The modern activity of these channels and canyons was shown to be dependent on their slope since sediment supply is today low at the head of these systems. However, their evolution in relation to sediment supply, RSL change and shelf geomorphology has not been addressed. Documenting the evolution of such different systems in a confined area allows determining the major controls over sediment transport processes in a formerly glaciated margin.

The extensive high-resolution bathymetric datasets and the time-constrained seismostratigraphic framework of the LSLE offer an excellent opportunity to document: 1) the type and chronology of sediment density flows related to the different types of deltas and submarine fans in a formerly glaciated margin and in a forced regression setting; and 2) the factors controlling delta progradation and submarine fan deposition in relation to sediment supply, shelf geomorphology and RSL change. This paper thus reports on the variability, timing and frequency of late-Quaternary delta and submarine fan activity in the LSLE in relation to their geological evolution by using new seismic and sedimentological data and synthesizing previous studies in the LSLE.

PHYSICAL SETTING

The Laurentian Channel forms a deep (>300 m) and long (1500 km) submarine trough in the St. Lawrence Estuary and Gulf that extends from Tadoussac to the edge of the North Atlantic continental shelf (Fig. 1). It is bordered by 0-20 km-wide coastal shelves (Pinet et al., 2011) bounded by generally steep slopes (2-20°). The coastal shelves lead landward to a series of emerged and gently sloped hills reaching few hundreds of meters in elevation. Inland, the bedrock is deeply incised (100-400 m) by steep-flanked, normally-oriented structural valleys, 0.5-3 km in width, their bottom lying between 50 m above sea level and 300 m below sea level (Lajeunesse, 2014).

The chronology of deglaciation in the LSLE was marked by four stages of glacial retreat of the Laurentide Ice Sheet (LIS) (see Shaw et al. (2006) and Occhietti et al. (2011)). Before 23.5 ka cal BP, while the LIS margin at times reached the edge of the North Atlantic continental shelf (Shaw et al., 2006), the ice thickness over the Gulf of St. Lawrence was greater than 1500 m (Marshall et al., 2000; Tarasov et al., 2012). By 14.8 ka cal BP, iceberg calving at the margin of the LIS led to its rapid retreat through the Laurentian Channel until it reached the Tadoussac region (Shaw et al., 2006). During the Younger Dryas cold episode (13-11.7 ka cal BP), the LIS margin mainly stabilized offshore (St-Onge et al., 2008) (Fig. 2). At that time, Pointe-des-Monts was the only ice-free sector of the Québec North Shore (Occhietti et al., 2011). This stabilization resulted in the deposition of grounding-zones wedges in the LSLE (Lajeunesse, 2016). Following the Younger Dryas cold episode, the LIS margin retreated inland due to climate warming starting at 11.7 ka cal BP. This stage is characterized by terrestrial melting of the LIS (Occhietti et al., 2011); the inland retreat being slower than in the second glaciomarine stage (Shaw et al., 2006). The North Shore watershed was entirely deglaciated by *ca*. 7 ka cal BP (Fig. 2).

Directly following the deglaciation of the study area, the RSL reached *ca*. 150 m in altitude (marine limit) over the entire North Shore region due to the deglacial Goldthwait Sea invasion of the glacio-isostatically flexured land (Occhietti et al., 2011). Large areas of the now-emerged land were thus flooded at that time, including the bottom of the structural valleys that then formed fjords. The glacio-isostatic adjustment led to a RSL fall that reached 2 to 4 cm.yr^{-1} in spite of the concomitant global eustatic rise (Boulton, 1990; Tarasov et al., 2012, Peltier et al., 2015; Dietrich et al., 2016b). Most often, deltaic systems fed by glaciofluvial rivers were initially confined within the fjords prior to their emergence on the coastal shelf. RSL fall led to a drastic reduction of the width of the coastal shelf and in places to its complete emergence.

The retreat of the LIS over the LSLE led to a thick sediment accumulation (> 400 m) in the Laurentian Channel (Syvitski and Praeg, 1989; Josenhans and Lehman, 1999; Duchesne et al., 2010). Duchesne et al. (2010) distinguished five main seismic units (SU) composing this Quaternary infill (Fig. 3), in addition of three secondary units observed sporadically in the LSLE succession. SU1 may consist of thin till layers or patches, but could also be composed of reworked pre-Wisconsinan sediments. SU2 was analyzed in detail by St-Onge et al. (2008) and was interpreted as ice-proximal to ice-distal sediments deposited during the rapidly retreating LIS margin in the LSLE. The deposition of this unit occurred before 11 ka cal BP. Massive clay composes SU3 and was deposited when the ice margin was located inland (Duchesne et al., 2010), between *ca.* 11 ka cal BP and *ca.* 8.4 ka cal BP. SU4 and SU5 are composed of postglacial hemipelagic sediments deposited since *ca.* 8.4 ka cal BP. SU6 and SU7 represent submarine fans and mass movement deposits that are located near river mouths and on steep slopes (Pinet et al., 2011). While SU1 to SU5 correspond to a stratigraphic succession (from the lowest and oldest to shallowest and youngest), SU6 and SU7 correspond to sedimentary bodies that were deposited within the previous units. Finally, SU8 consists of a contourite deposit located near the head of the Laurentian Channel (Duchesne et al., 2010). Today, sediments composing the Laurentian Channel seafloor mainly originate from the Québec North Shore (Jeagle, 2014) where rivers have larger watersheds than on the South Shore.

METHODOLOGY

Data and methods

Modern exposed component (outcrop)

Internal stratigraphic architecture and sedimentological content of the modern exposed component of the deltaic systems were investigated along cliffs and river banks that expose the strata. Regularly spaced sedimentary sections (1:100 scale) were logged and correlated with the help of photomosaics, in order to produce a detailed stratigraphic framework (e.g., Dietrich et al., in press). Depositional environments were deduced from both the stratigraphic architecture and sedimentological content and followed the well-documented history of RSL fall in deglacial and postglacial times (Dionne, 2001; Shaw et al., 2002; Tarasov et al., 2012). Radiocarbon dating of marine shells and plant debris sampled almost exclusively in mud-rich strata constrain the chronostratigraphic framework of the deltaic development.

Modern submarine component (multibeam and seismic surveys)

Seismic profiles were acquired using an Applied Acoustics Squid 2000 sparker system (2 kJ, *ca.* 500 Hz peak frequency, 0.75 m vertical resolution) deployed from the R/V Coriolis II in 2012. They were analyzed and visualized using the Geological Survey of Canada *SEGYJP2* software. Piston (PC) and gravity (TWC) cores were collected during the 2006 and 2012 cruise on board R/V Coriolis II. Cores were first analyzed through a *Siemens Somatom Volume Sensation* CT-Scan (97 x 97 x 400 microns/voxel, 0.4 mm thick slice). The CT-Scan allowed a non-destructive visualization of longitudinal and transverse sections of cores using X-ray attenuation. Grey levels vary according to the density, mineralogy and porosity of sediments (St-Onge et al., 2007; Fortin et al., 2013) and allow recognizing sedimentary structures and establishing a high-resolution stratigraphy (St-Onge and Long, 2009). Following this operation, the cores were opened, described and photographed. Magnetic susceptibility was then measured using a Geotek Multi-Sensor Core Logger (MSCL) at 0.5 cm intervals. Grain-size analyses were performed using a *Beckman Coulter*^{TM} *LS13320 laser sizer* or a *Horiba laser sizer* at 10 cm intervals on background sediment and at 1-2 cm intervals on selected facies. Sediments were diluted into a calgon solution for at least 3 hours and shaken, then disaggregated to an ultrasonic bath. At least three runs were averaged. Statistical parameters were obtained using Gradistat (Blott and Pye, 2001). Thin sections were made from on selected facies and were used to extract grain-size information following Francus (1998) and Francus and Nobert (2007). These grain-size results were shown to be comparable to the laser diffraction technique for unimodal distributions.

Accelerator mass spectrometry (AMS) ^{14}C dating was performed on the cores from organic matter and shell remains (Table 2).Radiocarbon ages, sampled both in exposed and submarine delta components, were converted to calendar ages using the Calib 7.0 program (Stuiver and Reimer, 1993) with the Reimer et al. (2013) Marine13 dataset. The Marine13 dataset applies a reservoir correction of 400 years (ΔR – 0 yr), which is in agreement with reservoir ages for the LSLE during the last 7.7 ka ^{14}C BP (St-Onge et al., 2003).

Study site justification

The paleogeographical reconstruction presented here focuses on deltas and fans that are documented with extensive seismic and sedimentological datasets (Fig. 1). Therefore, data from the modern exposed component of the Portneuf delta described in Dietrich et al. (in press) is used as an example for the evolution of deltas on the shelf. This cross-section is considered representative of all of the exposed deltas in the LSLE (e.g., Bernatchez, 2003) as the whole area experienced a similar history of ice margin retreat and RSL fall.

In the modern submarine component, we document newly recovered data from the Manicouagan delta. The Manicouagan delta is considered as having had the most long-lived glacier-related sedimentation of all the deltas in the LSLE because of the size and extent of its drainage basin that permitted a perennial connection with the northward retreating LIS margin (Dietrich, 2015) (Fig. 2). This glaciogenic sedimentation longevity is reflected today by the size of the Manicouagan delta, which is the largest of all the deltas in the LSLE. This delta can thus be convincingly used as an end-member of the activity of river-fed deltaic submarine fans.

The Pointe-des-Monts canyons (Fig. 1; Normandeau et al., 2014) were ignored in this analysis because they lack sediment supply at their heads. The goal of this paper is to examine the links between sediment supply, RSL and shelf geomorphology. Since the

Pointe-des-Monts canyons do not respond to typical external forcings, they are unique and are studied separately in other papers (Normandeau et al., 2014, 2015).

RESULTS AND INTERPRETATIONS

Modern exposed component of the deltaic systems

The modern exposed component of the studied deltaic systems mainly consist of large (tens to hundreds of km²) sedimentary bodies protruding in the LSLE, emplaced at the immediate outlet of structural valleys (Dietrich et al., in press). This sedimentary succession is now exposed due to RSL fall forced by the glacio-isostatic rebound but originally prograded on the shelf. Today, these deltas lack evidence of river-fed progradation; they rather experience shoreline retreat (Bernatchez and Dubois, 2004) or longshore-drift related accretion (Normandeau et al., 2015). In places, the shoreline retreat allows the observation of their internal stratigraphic architecture. These deltaic bodies are several tens of meters in thickness and consist of three main laterally juxtaposed or vertically superimposed architectural elements (Dietrich et al., in press): 1) outwash fans and glaciomarine mud; 2) glaciofluvial deltas; and 3) coastal suites (Fig. 4A).

Outwash fans and glaciomarine mud

Outwash fans form 20-60 m-thick sediment wedges and generally constitute the core of the exposed component of the deltaic system. These wedges are characterized by flat topsets and basinward-dipping clinothems. The topsets, lying at or immediately below the marine limit, consist of very coarse-grained materials (sand to boulders) and m-sized sand intraclasts characterized by faint horizontal bedding and occasional trough cross-strata (Fig. 4B). Aerial photographs reveal the presence of relict kettle holes and inactive braided channels on the topsets. Clinothems are essentially composed of sand 5 km away from the fan apex, and grade distally into silty material (>10 km away from the apex). Highly channelized, massive, normally-graded sand beds are ubiquitous (Fig. 4C). These beds are interpreted as being deposited by channelized debris flows and high-density sediment density flows respectively (Talling et al, 2012). Downslope, silty material consists of finely-laminated silt beds and fine-grained sand interbeds forming pluri-m successions. Cm-sized lonestones, interpreted as ice-rafted debris (IRD), are scattered within the silt beds. These silt and sand beds are interpreted as being deposited by low-density sediment density flows (Talling et al., 2012) in a glaciomarine environment. A discontinuous silt veneer (1 to 10 m-thick) with abundant IRD, up to boulder-sized, underlies the entire sediment wedge and drapes the underlying bedrock (Fig. 4D). Shell fragments sampled in this sandy to silty sediment wedge provided ages of 11 170 ± 70, 11 500 ± 100 and 12 250 ± 150 cal BP (Dietrich et al., 2016a).

The proximal coarse to very-coarse sediment size that distally evolves into fine-grained facies, the presence of relict kettle holes and braided channels on the apex of the sediment wedges, the presence of IRDs in mud, relatively ancient radiocarbon ages and inferred high RSL (marine limit) altogether indicate that these sedimentary bodies were emplaced in an ice-contact outwash fan during the Younger Dryas cold episode. Triggering processes of sediment density flows that deposited normally-graded beds observed throughout the depositional slopes can be the collapse of the delta lip or alternatively the direct plunging of hyperpycnal underflows derived from the nearby ice-margin. Tidal processes also likely played an important role in modulating sediment density flow events that permitted the deposition of cyclically-laminated layers but also probably in initiating supercritical flow events (tidal-drawdown process, Smith et al., 1990; Dietrich et al., 2016a).

Glaciofluvial deltas

Glaciofluvial deltas are related to extensive landforms located at or near the outlet of the structural valleys, immediately basinward of the outwash fans. Landforms left by glaciofluvial deltas, once commonly protruding in the LSLE, have their top dipping gently toward the basin and lying at elevations well below marine limit (between 150 and 40 m asl). These sediment bodies reach $\geq$ 70 m in thickness and can be identified by their well-defined tripartite architecture formed by topset, foreset and bottomset beds, interpreted as delta plain, delta slope and prodelta deposits, respectively (Fig. 4). The delta plain is composed of a $\leq$ 10 m-thick sand and gravel sheet with trough and planar cross-strata (Fig. 4E) emplaced in braided fluvial channels, some of which are observed in plan-view. The delta plain discordantly overlies the delta slope deposits. The tens of m-thick delta slope deposits are formed of seaward-dipping (average of 6°, up to 17° in places) sand beds. The latter are normally-graded, erosion-based and formed of T_b, $T_{c,}$ flamed T_e and frequent basal T_a intervals including lithic and rip-up clasts (Fig. 4F). These beds are interpreted as being deposited by recurrent high-density sediment density flows (Talling et al., 2012), commonly supercritical as indicated by T_a intervals (Postma et al., 2009). The triggering mechanisms of these sediment density flow events, whether they were hyperpycnal or induced by the collapse of the delta lip, cannot be clearly defined. Sand beds grade downward into gently sloped (<1°) and well-bedded silty facies, indicative of prodeltaic sedimentation (Fig. 4G). These facies that consist of an alternation between silt beds and sand interbeds are interpreted as deposited by low-density sediment density flows (Talling et al., 2012) and/or by settling from an overlying sediment-laden buoyant plume. Inverse grading has been observed in X-ray in silt beds possibly suggesting hyperpycnal flows (e.g., Mulder et al., 2003). Radiocarbon dating performed on shells sampled in silt beds provided ages of 9 370 ± 100, 9 535 ± 15, 10 210 ± 25, 10 415 ± 145, 10 420 ± 140 and 10 600 ± 115 cal BP. Radiocarbon dates sampled in these glaciofluvial deltas and those found in the underlying outwash fan indicate that the deltaic systems prograded rapidly at rates between 10 and 20 $m.yr^{-1}$ (Dietrich et al., in press).

As they were emplaced basinward of the outwash fans, during periods when RSL was significantly lower than marine limit –although higher than modern sea level–, the deltas of the North Shore of the LSLE are interpreted as being fed by glaciofluvial rivers delivered from the nearby but retreating land-based LIS margin (Duchesne et al., 2010; Dietrich et al., in press). The large amount of meltwater and clastic sediment supplied to the deltas is evidenced by: 1) high progradation rates; 2) the prevalence of beds deposited by sediment density flows, including those from supercritical flows; 3) the relict braided fluvial pattern; and 4) the well-defined tripartite deltaic architecture (e.g., Swenson et al., 2005). The spatial extent of these deltas showed that some of them prograded over the entire width of the coastal shelf up to the shelf break. The presence of these deltas at the outlets of structural valleys provides evidence that the latter efficiently drained to the LSLE meltwater effluents from the retreating LIS margins.

Coastal suites

The top of the glaciofluvial deltas, commonly located at elevations between 150 and 40 m asl (90 m asl in the case of the Portneuf delta), is characterized by a continuous, stepped and thin (1-5 m) sand veneer. This sand veneer, lying discordantly over the underlying glacio-fluvial delta slope, consists in its upper part of very well-sorted, well-laminated and occasionally bioturbated sand and heavy mineral placers (Fig. 4H) and in its lower part of gravel and pebble conglomerates underlied by a basal lag. Well-defined relict coastal landforms are visible on the top of this sand veneer, forming raised and stepped beaches and spits (Fig. 4I). The sand veneer is thus interpreted as a nearshore sand sheet including swash-backswash and surf zone deposits, for the upper and lower part respectively (Dietrich et al., in press). Thick sand-prone deposits (20 m) associated with the nearshore sand sheet have been observed where the underlying glaciofluvial delta slope deposits are thin and distinctively characterized by steep-sloped (up to 12°) and composite clinothems (Fig. 4A). These clinothems, composed of trough and sigmoidal cross-strata showing transverse paleo-flows compared to the master bed dips, constitutes a spit platform, over which the nearshore sandsheet prograded (Dietrich et al., in press). No datable material was found in these sand-prone deposits, neither in the nearshore sand sheet nor in the spit platform. Nevertheless, ages of deposition were inferred from the altitude of stepped paleo-shorelines by using local RSL curves (e.g., Shaw et al., 2002; Dietrich et al., in press). The highest paleo-shorelines were observed at

90 m asl in the Portneuf area (Fig. 4), indicating that the onset of the development of beach-related deposits occurred, in this particular deltaic system, at *ca.* 10 ka cal BP. Beach ridges and shorelines developed afterward in a stepped manner as RSL was rapidly falling owing to the post-glacial glacio-isostatic rebound.

Modern submarine component of the deltaic systems

The modern submarine component of the deltaic systems (SU6 of Duchesne et al., 2010) form the offshore counterpart of the modern exposed component described above, off the mouth of large rivers and valleys of the LSLE. Submarine fans are either on the shelf of the Laurentian Channel, where they are almost completely buried with a surface expression that is greatly reduced (e.g. the Portneuf submarine channels, Fig. 5A), or on the Laurentian Channel slope and basin where they are well- or better preserved (e.g. the Manicouagan submarine channels, Fig. 5B). A seismic profile collected over the Portneuf submarine channels reveals that a thick sediment accumulation overlies the main submarine fan unit (SU6; Fig. 6A). Additionally, the entire fan unit (SU6) is located within SU3, which indicates that the fan stopped being active prior to *ca.* 8.4 ka cal BP (transition SU3 to SU4) and 9.4 ka cal BP (age of middle of SU3; Duchesne et al., 2010), which confirms previous interpretations of the reduced deltaic progradation by 10 ka cal BP. A more detailed analysis of the Manicouagan submarine delta, in the Laurentian Channel, is presented here since its activity lasted longer. The analysis of the submarine deltaic deposits reveals that they are composed of three superimposed seismic units (SU, Fig. 6B): the bottomset beds, the main submarine fan and an hemipelagic sediment drape.

Bottomset beds

The lowermost unit, named SU3 and interpreted as ice-distal mud, is predominantly transparent on the seismic reflection data (Fig. 6B) and composed of massive clays (Duchesne et al., 2010). It drapes the underlying units and its thickness decreases gradually from West to East (Duchesne et al., 2010). In the Manicouagan region, these deposits are the bottomset beds (or prodelta). These sediments were deposited while the essentially sandy counterpart of the deltas, expressed by the modern exposed component, was prograding onto the shelf.

Deltaic submarine fans in the Laurentian Channel

As the delta reached the shelf edge as a result of active progradation and lowering of the RSL, deltaic sediments began to be delivered directly into the Laurentian Channel and the main submarine fans formed (SU6; Duchesne, 2005). The submarine fans have a wedge-shaped geometry and downlap the underlying SU3. In the Manicouagan delta, the submarine fans reach a thickness of *ca.* 50 m and consist of parallel to chaotic, medium to high amplitude seismic reflections (Fig. 6B). These chaotic reflections are interpreted as being the result of sediment density flows, namely debris flows originating from delta-lip failures while the parallel high-amplitude reflections are interpreted as resulting from river-derived density flows. The main submarine fan unit is located above SU3 and four channels are visible in the top-half of the seismic sequence (Fig. 5B-6B), with a conspicuous surface expression. These deposits are similar in geometry and facies to the deposits described earlier in the modern exposed component of the delta slope deposits (see section 4.1.2).

Four cores were collected on the Manicouagan submarine fan in order to constrain the final stages of fan deposition (Fig. 7). These sediment cores penetrated sediment density flow deposits at 4 m depth. These deposits consist of medium sand to coarse silt (20-200 µm) including coarsening-then-fining upward layers (Fig. 7E). They are generally thin (≤ 15 cm) and preserved parallel to wavy laminations. Their basal contact is generally sharp and erosive, and more rarely gradual. Several different types of grading patterns are observed within this facies. In core 23PC, a particular bed reveals more complex grading patterns, with stacked coarsening-to-fining upward layers or stacked normally graded layers (Fig. 7E). Their fine nature, the grain-size variability, the presence of fine laminations and their location off river mouths differentiate them from classical turbidites; they are therefore interpreted as river-derived sediment density flow deposits similar to the hyperpycnites of Mulder et al. (2003). Talling (2014) described fine-grained and very thin (mm to cm) deposits to be the result of hyperpycnal flows. The fine-grained and thin nature of the deposits are likely due to relatively slow moving and dilute flows. Hyperpycnal flows can result in inverse-to-normal grading (e.g., Mulder et al., 2003), but also in more complex grading patterns characterized by stacked inverse-to-normal or stacked normal grading (e.g., Lamb and Mohrig, 2009). Direct observations also showed that hyperpycnal flows can generate multiple pulses during a single flood (Khripounoff et al., 2009). It is however unclear how river-derived sediment density flow are triggered in this case, whether they directly plunge (hyperpycnal flow) or are related to the continuous settling from the river plume where sediment concentration is eventually sufficient to initiate turbidity currents with multiple pulses (Clare et al., 2016).

All of the cores collected on the Manicouagan fan contain series of hyperpycnite-like deposits. The base of core 16 PC is composed of four hyperpycnite-like deposits. Shell fragments and organic matter collected at 41 cm and 561 cm provided ages of 1800 ± 70 cal BP (UCIAMS-127443) and 6970 ± 90 cal BP (UCIAMS-127426) respectively. These two ages give an approximate sedimentation rate of *ca.* 0.096 cm/y for the postglacial sediments in this region. Core 17PC contains six hyperpycnite-like deposits near its base but the coring process led to the deformation of these facies. Shells fragments collected at 170 cm provided an age of 6300 ± 75 cal BP (UCIAMS-127454). In core 23PC, an hyperpycnite-like deposit is present at 750 cm near the base of the core and a very thin one (< 1 cm thick) is present at 350 cm. Shell fragments collected at 324 cm provided an age of 5530 ± 60 cal BP (UCIAMS-127444). Core 39PC contains three sediment density flow deposits that were identified between 0 and 550 cm. These deposits were disturbed due to the coring process and could either represent hyperpycnite-like deposits or classical turbidites. Three shell samples were collected for radiocarbon dating between 0 and 150 cm. The topmost sample, at 8 cm, provided an age of 5750 ± 160 cal BP (TO-13204). This age is likely inaccurate because two other dates on shell fragments collected at 91 cm and 126 cm provided ages of 1920 ± 135 cal BP (TO-13206) and 1150 ± 115 cal BP (TO-13205), respectively. Based on sedimentation rates of 0.046 cm/yr calculated from the two dates obtained, the hyperpycnite-like deposits observed in core 39PC approximately date to 4 ka cal BP, while the deposits in the other cores are generally older than 7 ka cal BP.

Hemipelagic sedimentation

Low amplitude seismic reflections drape the underlying Manicouagan submarine fan unit. These low amplitude reflections are composed of homogeneous fine to very fine silts (Fig. 7) and are interpreted as the result of the sedimentation of hemipelagic material. These sediments were essentially deposited over the sediment density flow deposits described above and are thus younger than 7 ka cal BP in the Manicouagan region. In other regions where deltaic activity ceased earlier, they can be as old as 10 ka cal BP over the submarine deltas. These hemipelagic sediments were thus deposited while coastal suites identified onshore were being constructed on the deltas near the coast (see section 4.1.3).

Laurentian Channel submarine canyons/fans

The submarine fans described in this section are unrelated to deltaic progradation and are rather related to river-fed and longshore drift-fed submarine canyons.

River-fed submarine canyon/fan

The river-fed submarine fan located offshore the Les Escoumins River is found at the toe of a submarine canyon but is unrelated to a deltaic body. This submarine canyon incises the margin of the Laurentian Channel and its source comprises exclusively the Les Escoumins River sediments since its head is confined between rocky headlands (Fig. 5C). Additionally, the head of the submarine canyon is located less than 1 km from the river mouth, providing a direct connection between river inflow and the submarine canyon. The high-resolution multibeam bathymetry imagery over this submarine canyon reveals the presence of crescentic bedforms related to the passage of relatively recent sediment density flows (Normandeau et al., 2015).

The base of the submarine fan is composed of the homogeneous mud of SU3 (Fig 6C). Above SU3, seismic reflections are chaotic and suggest the presence of sediment deposited by sediment density flows. The transition from SU3 to the chaotic seismic reflections is estimated at 9-8.5 ka cal BP according to Duchesne et al. (2010).

Core 12PC (681 cm long), collected on the Les Escoumins River fan, is composed of 14 sediment density flow deposits (Fig. 8A). Most of these deposits are a few cm thick (≤ 10 cm) and characterized by a sharp increase in CT-numbers and magnetic susceptibility. Grain-size properties indicate a fining-upward sequence with an erosive basal contact (Fig. 8C). Mean grain-size generally reaches more than 200 µm. Two types of beds were identified based on grading patterns: a first type characterized by a sharp increase followed by a fining-upward sequence and a second type characterized by a thin (≤ 2 cm) coarsening-upward sequence, followed by a thicker fining-upward sequence. Both types are interpreted as a classical turbidite (Mulder and Alexander, 2001), where the basal inverse grading is interpreted as the traction carpet associated with a prolonged shear along the base of the flow (Sumner et al., 2008).

The thickest sediment density flow deposit within the core has a different sedimentological signature. It consists of thick (> 1 m) homogeneous sand including mud clasts (Fig. 8A). Its basal contact is sharp and erosional and no apparent grading pattern is present in grain-size analysis. CT-numbers and magnetic susceptibility are generally high among this facies except where mud clasts are present. This facies is interpreted as a debris flow deposits resulting from a slope failure (Mulder and Alexander, 2001; Talling et al., 2012).

The 14 sediment density flow deposits are distributed over the entire core, yet their frequency and thickness decrease up-core. Organic matter collected at the base of core 12PC (670 cm) was dated 850 ± 65 cal BP (UCIAMS-127421) while shell fragments collected at its top (117 cm) dated 540 ± 15 cal BP (UCIAMS-127440). These dates suggest that sediment density flow deposits were frequent (5 in *ca.* 20 years) at the base of the core, gradually becoming less frequent up-core (6 in *ca.* 300 years).

Longshore drift-fed submarine canyons/fans

Nearby the Les Escoumins river-fed submarine fan, three additional submarine canyons are located where the shelf narrows westward (Fig. 5C). These submarine canyons incise the steep Laurentian Channel margin and are fed by longshore drift sediments (Gagné et al., 2009; Normandeau et al., 2015). Unlike the submarine deltas described above, they have no emerged component and have always been located below sea-level. The fan bodies are *ca.* 25 m thick and are mainly observed in the top-half of the LSLE seismic succession. They are mainly observed above SU3 and form lens-shaped and chaotic features that downlap the underlying reflections. The reflections are generally chaotic and disrupted over the fans while they are parallel and continuous on each side of them. However, chaotic reflections, interpreted as mass movement deposits, are also observed below the western fan, within the top half of SU3, while they are absent below the eastern one. The eastern fan also appears to have formed later than the western one based on its location in the seismic succession (Fig. 6D).

Core 13PC was collected on the eastern fan and is only 132 cm long (Fig. 8B). The size and morphological expression of the fans, however, suggest that their evolution was similar to the river-fed Les Escoumins fan (core 12PC) described in the previous section. Two sediment density flow deposits within core 13PC, interpreted as classical turbidites, are located at the same stratigraphic level as others in core 12PC. An age of 635 cal BP ± 20 (UCIAMS-127438) at 35 cm in core 13PC suggests a similar age for the two turbidites to those present in core 12PC (Fig. 8B).

DISCUSSION

Delta progradation and submarine fan deposition in a formerly glaciated region

The identification and dating of the different types of deposits observed at outcrop and in marine cores in the LSLE together with results from previous studies (Bernatchez, 2003; St-Onge et al., 2003; St-Onge et al., 2008; Duchesne et al., 2010), are used here to reconstruct the palaeogeographic context of delta progradation and submarine fan deposition in a deglaciation setting (Fig. 9). Based on stratigraphic architecture of the modern exposed component of the deltas, seismic stratigraphy and sediment core analysis, we build a simplified conceptual model of the approximate chronology for the transport of coarse terrigenous sediments to the LSLE since the late Wisconsinian (Fig. 9). The proposed model is divided into three major phases of delta progradation and submarine fan deposition. These three main phases overlap each other across the LSLE and no time boundaries are inferred. For instance, while the southern sector of the LSLE may pass into the second phase, the northern part may still be in the first phase. The first and/or second of these three phases may be absent in the evolution of some deltas of the LSLE, depending on the inherited local topography (width of the shelf, inland extent of drainage basin) and the pattern of ice margin retreat, as explained below. These three phases are somewhat similar to Syvitski and Praeg (1989) sedimentation models but they consider only submarine delta progradation and submarine fan formation instead of the entire sedimentation of the LSLE.

Phase 1: Deltaic progradation on the shelf

The first phase of deltaic evolution occurred during the retreat of the LIS margin and its stabilization on the Québec North Shore around 12.5 ka cal BP (Shaw et al., 2002), when RSL was ≥ 150 m higher than today (Dionne, 2001). On the shelf, the initial delta progradation was marked by the rapid deposition of outwash fans directly at the stabilized ice margin in a context of rapid RSL fall (up to 5 $\mathrm{cm.yr^{-1}}$). The deposition of outwash fans only spanned a few hundred years around 11 ka cal BP, according to radiocarbon dates sampled in these deposits.

During this initial phase of delta progradation on the shelf, ice-proximal to ice-distal glaciomarine sediments (SU2 and SU3) were deposited in the LSLE by meltwater discharges (Fig. 9A; St-Onge et al., 2008; Duchesne et al., 2010). After the progressive and spatially diachronous inland retreat of the LIS margin, glaciofluvial deltas fed by sandy and silty glaciogenic materials began to prograde onto the LSLE shelf mainly by accretion of beds deposited by sediment density flows, still in a context of RSL fall (Fig. 9A) (Bernatchez, 2003; Dietrich et al., 2016a).

This first stage is also characterized by mass movement processes (SU7) along the steepest shores of the Laurentian Channel, as observed below the Les Escoumins fans (Fig. 6D). These mass movements may have been responsible for initiating the submarine canyons by retrogressive slope failures. Duchesne et al. (2010) also reported similar chaotic reflections that they interpreted as mass movement deposits resulting from earthquakes in a rapidly uplifting margin due to crustal glacio-isostatic readjustment. These mass movements were probably triggered in response to the ongoing crustal readjustment following deglaciation (e.g., St-Onge et al., 2004). Following glacier retreat, maximum glacio-isostatic rebound generally leads to increased earthquake frequency (Johnson, 1989), which in turn likely generates mass movements along steep slopes, such as those observed in the LSLE (Pinet et al., 2015).

Phase 2: Laurentian Channel submarine fan deposition

The second phase of deltaic evolution and submarine fan deposition is characterized by the progradation of deltas into the Laurentian Channel (Fig. 9B). The delivery of sediments in the deeper waters of the LSLE was made possible by the deltaic progradation over the entire width of the shelf, and was thus achieved whenever deltaic progradation, which is dependent on sediment supply, lasted long enough to cover the entire width of the shelf. The depth of the shelf, constantly diminishing through time because of RSL fall, contributed in determining the extent of deltaic progradation. Thus, a narrow shelf and/or a long lasting glaciogenic sediment supply allowed sediments to be delivered into the Laurentian Channel. Conversely, a wide shelf and/or slow deltaic progradation did not permit the supply of deltaic material into the Laurentian Channel.

In the deep realm of the LSLE, the transition from SU3 to fan deposits is envisioned as recording the arrival of coarse-grained sediments delivered from the delta slope or river mouth in areas that were formerly dominated by the deposition of fine-grained sediment, its timing being controlled by the width of the shelf and spatial extent of deltaic progradation. This transition occurred prior to 9-8.5 ka cal BP in the case of the Manicouagan delta (SU3 to SU6; Duchesne et al., 2010) but no exact dates are available for any of the deltas. River-derived sediment density flows and debris flows were the main mechanisms of sediment transport through the submarine deltas. The presence of debris flows suggests that they were produced by high sedimentation rates at river mouths that increased the slope at the delta lip leading to frequent slope failures. Delta channels would then have been used to evacuate these high-density flows. The debris flows were also generated by seismic activity due to glacio-isostatic rebound. The late-Wisconsinan / early-Holocene experienced increased earthquake frequency which likely increased the frequency of debris flows at the delta fronts (Duchesne et al., 2003). The increased earthquake frequency may also have increased landslides in the river watershed, providing large volumes of sediment to rivers and their downstream deltas (e.g., Dadson et al., 2004). Hyperpycnite-like deposits observed in cores from the Manicouagan fans and in the Portneuf outcrops also indicate the occurrence of high sediment concentration in the rivers during the early-Holocene that also favoured the generation of river-derived density flows.

The accretion of the Manicouagan delta essentially continued until *ca.* 7 ka cal BP, according to dates from the cores collected on the submarine fans. The main activity of river-derived density flows ceased prior to 6970 ka cal BP in core 16PC (Fig. 7A). Cores located farther away from the river mouth (17PC and 23PC) show that density flows ceased as early as 9.5 ka cal BP, according to sedimentation rates derived from cores 16PC and 39PC. However, sediment density flow deposits identified in core 39PC from the Manicouagan delta appear to have been deposited near 4 ka cal BP. It is difficult to identify the exact type of deposits (slope failure vs river-derived deposits) in this core because the sedimentary facies were deformed due to the coring process. These deposits could represent exceptional flood events that allowed the formation of hyperpycnal flows. Rather, due to their younger age, we suggest that they are turbidites since sediment concentration in rivers was likely too low at *ca.* 4 ka cal BP to produce hyperpycnal flows. Accumulation of sediments on the delta front and its failure is more likely at that time. Since the Manicouagan system is considered as an end-member in terms of sediment density flow activity, the other deltas in the LSLE are considered to have ceased being active before 7 ka cal BP. For example, the activity of the Portneuf glaciofluvial delta ceased well before that date, as exemplified by the construction of coastal suites at 10 ka cal BP. Additionally, the withdrawal of the LIS from its watershed occurred at *ca.* 10 ka cal BP, which corresponds to a drastic decrease in sediment supply at the river mouth and the predominance of alongshore currents on sediment mobilization (Dietrich et al., in press). In contrast, the withdrawal of the LIS from the Manicouagan watershed occurred at *ca.* 7 ka cal BP, which corresponds to a decrease in meltwater-derived sediment supply and in sediment density flow deposits on the Manicouagan submarine fan.

Longshore transport was also active and remobilized deltaic and coastal sediments during the progradation of the deltas into the Laurentian Channel. This transport of sediment through longshore drift is suggested at that time for the onset of the western longshore drift-fed fan in Les Escoumins, in combination with increased earthquake frequency owing to crustal glacio-isostatic readjustment (Fig. 9B). Sediment supply from longshore drift to the heads of the canyons on a narrow shelf and earthquakes would have generated mass movements on the steep Laurentian Channel margin. The western fan appears to have formed slightly earlier than the eastern one (Fig. 6D), probably in relation with a slightly higher RSL; the coastal shelf being narrower at the head of the western canyon than at that of the eastern one (Fig. 5C).

Phase 3: Delta erosion and longshore drift transport

The third phase of submarine fan deposition is characterized by: 1) a drastic decrease in submarine delta progradation; 2) the erosion of deltas on the shelf by coastal processes; 3) the deposition of coastal suites; and 4) the continuation of longshore drift transport to the Les Escoumins canyons (Fig. 9C).

When the ice margin retreated from the river watersheds, sediment supply drastically dropped while RSL fall rates decreased synchronously. In the Manicouagan region, the LIS left the watershed at *ca.* 7 ka cal BP (Fig. 2). Therefore, the Manicouagan delta could no longer produce river-derived density flows or other sediment density flows due to the reduced sediment supply; instead, it experienced coastal erosion where sediments were remobilized and transported through longshore drift (e.g., Bernatchez, 2003). In the Portneuf region, the LIS left the watershed by *ca.* 10 ka cal BP which induced as well a decrease in sediment density flow activity. Here, sediments were eroded at the delta front and were remobilized and transported to adjacent bays or to areas where the coastal shelf is wider, while RSL was still falling. In the Portneuf region, most of the sediment accumulated in raised spit complexes downdrift of the former glaciofluvial delta (Fig. 4I) and in the adjacent bay to the south-west (Fig. 5A). The deposition of nearshore sand sheets and spit platforms occurred after the demise of the glaciofluvial delta progradation, as indicated by the erosion and reworking of these deltas by shore-related processes (waves and longshore-drift; Fig. 4A). The material involved within these coastal suites derived almost exclusively from the delta itself. Since in distinct delta systems the shore-related structures are found below different altitudes depending on the studied deltaic succession, an allogenic process such as an increase of the wave regime in the LSLE is unlikely. A local forcing is rather proposed to explain the diachronic onset of the development of the shore-related structures over delta systems of the LSLE. The retreat of the ice margin from the drainage basins of feeder rivers is interpreted as having permitted the development of shore-related structures by an abrupt decrease of the fluvial sediment supply / wave energy ratio (e.g., Swenson et al., 2005). At the scale of the LSLE, the onset of the development of shore-related structures was necessarily diachronic and depended on the pattern of retreat of the continental ice margin (Occhietti et al., 2011) and the northern extent of drainage basins (Fig. 2). The deposition of the shore-related structures does not relate to the deltaic progradation but rather to a redistribution of formerly-deposited glaciofluvial sediments. The timing of the transition from a deltaic progradation, either restricted to the shelf (phase 1), or having reached the Laurentian Channel (phase 2) to the erosion of the delta and the generalization of longshore-drift transport (phase 3) is then solely controlled by the inland extent of the drainage basin and the pattern of ice margin retreat. A restricted drainage basin and/or a rapid retreat of the ice margin over the drainage basin permitted an early transition to phase 3, as it was the case for the Portneuf delta (Fig. 2). To the opposite, extensive drainage basin permitted a long lasting deltaic progradation and a late transition to phase 3 (example of the Manicouagan delta, Fig. 2), even though the RSL curve was similar throughout the LSLE.

Part of the sediment from the Portneuf region, between Les Escoumins and the Portneuf delta, is believed to have been transported to the heads of the Les Escoumins canyons, allowing the eastern fan of the Les Escoumins system to form and develop (Fig. 6D). Coastal erosion on delta fronts would have been amplified during the early-Holocene due to the decrease of sediment supply from rivers, in a similar pattern as what was observed on the Moisie Delta (Dubois, 1979; Normandeau et al., 2013). This increased erosion at the delta fronts allowed an increase in sediment transport towards the longshore drift-fed canyons which in turn allowed them to remain active throughout the Holocene.

The river-fed Les Escoumins fan also continued its activity during the mid- to late-Holocene, as opposed to the other deltas in the LSLE. In this case, the river-fed Les Escoumins canyon is directly connected to the river and is located on a steep slope. Two hypotheses are invoked to explain the activity of the Les Escoumins canyon and the occurrence of debris flow deposits and turbidites: (a) sediment supply to the heads of the canyons and/or (b) earthquake-induced shaking. Earthquakes could have played a role in triggering mass movements since the Les Escoumins canyons are located *ca.* 100 km east from the Charlevoix-Kamouraska seismic zone (CKSZ), the most active seismic zone in Eastern Canada (Lamontagne, 1987). However, earthquakes were more frequent prior to 4 ka BP with recurrence rates of 300 years (St-Onge et al., 2004) and cannot explain the

14 turbidites and debrites observed in core 12PC that were deposited during the last 1000 years. Therefore, sediment supply to the Les Escoumins sector must have played a role in triggering them. Down-canyon remobilization was favoured in these sectors due to sediment supply from the Les Escoumins River (although diminished by the early-Holocene) and the erosion of the neighbouring shorelines. Wetter periods could have increased sediment supply to the river mouth, as suggested by the ages of sediment density flow activity obtained for the Les Escoumins canyons, which are also consistent with the warm and humid medieval period (Mann et al., 1999). The steep slopes present directly at the river mouth could then have favoured the generation of slope failures. The increase in sediment supply would not have been high enough to generate river-derived density flows on the other river-fed delta systems which have lower slopes and broader shelves (Normandeau et al., 2015).

Controls on the activity and location of submarine fans on a formerly glaciated coast and shelf

The delivery of coarse sediment to the LSLE continued throughout the Holocene and since the early stages of deglaciation. Three main controls are identified as playing a role in contributing to the continuation in coarse sediment delivery: 1) type (glaciofluvial, fluvial or longshore drift), rate and duration of sediment supply; 2) geomorphology of the shelf; and 3) RSL. While the type, rates and duration of sediment supply controlled the chronology of deposition and RSL controlled the location of deposition, the morphology of the shelf controlled both.

The type,rate and duration of sediment supply, which is mostly controlled by the style of deglaciation and the drainage basin (watershed area), was the primary control over sediment delivery in the LSLE. During the early stages of deglaciation, outwash fans formed at the edge of the Laurentian Highlands (Dietrich et al., 2016a). The sediments were directly delivered from a nearby glacial source, and consist, in the proximal domain i.e., on the inner coastal shelf, of very-coarse-grained deposits (gravel and boulders) emplaced through subglacial flow deconfinement processes (e.g., Russell and Arnott, 2003). However, in more distal settings but still on the coastal shelf, deposition of sand and silt by sediment density flows dominated. As soon as the ice margin retreated inland, the type of sediment supply changed from a direct ice-contact source to a glaciofluvial one. There was a fundamental difference in terms of type of sediment deposited at the coast: while the ice-contact source provided gravel and boulders to outwash fans, the glaciofluvial source essentially provided sand- and silt-sized sediments, allowing large deltas to form in the LSLE. Since glacial ice was still in the river watersheds, the deltas grew in volume and area and, in some cases, reached the edge of the Laurentian Channel (transition from Phase 1 to Phase 2, Fig. 9). Sediment supply from the rivers drastically reduced when the ice margin left the watersheds of the rivers, driving the transition from a fluvially-dominated Phase 1 or 2 to a wave-dominated Phase 3 (Fig. 9). The decrease in sediment supply from the rivers did not occur simultaneously in all the rivers since their watershed vary greatly in extent. The smaller watersheds were abandoned far before the larger ones, which explains why the Manicouagan delta is an end-member for the activity of sediment density flow due to its large size. The ice margin left the Manicouagan watershed by *ca.* 7 ka cal BP, which is consistent with a reduced sediment density flow activity near 7 ka cal BP observed in the cores. In contrast, the ice margin left the Portneuf watershed as early as *ca.* 10 ka cal BP, which explains why the channels observed offshore the river are buried and why coastal suites formed near 10 ka cal BP.

While deltas were highly constructive during the early stages of deglaciation, they began to be highly eroded following the retreat of the ice margin from the watersheds. The erosion of the delta fronts began while RSL fall rates had reduced or were close to stabilization. The erosion of the delta fronts then led to a change in the delivery of coarse sediment to the Laurentian Channel. In deltaic settings, coarse sediment delivery ceased because their fronts were eroded and the sediment was transported to adjacent bays. Additionally, the reduced rates of sediment supply due to the retreat of the ice-margin from the watersheds reduced sediment concentration in the rivers, thereby preventing the generation of river-derived density flows at the delta fronts.

Shelf geomorphology had a major influence on the sediment delivery to the Laurentian Channel. The shelf width controlled the transition from Phase 1 to Phase 2 as well as the continued sediment density flow activity in submarine canyons. For example, in the Les Escoumins river-fed fan, the shelf geomorphology allowed a continuation in coarse sediment delivery to the Laurentian Channel during postglacial times. This continuation in coarse sediment delivery was possible because the steep slopes favoured failure at the canyon head, as evidenced by the presence of turbidites instead of hyperpycnite-like deposits. Therefore, both the Les Escoumins river-fed and longshore drift-fed systems continued delivering sediment due to the narrow shelf that allowed a direct connection between a source of sediment supply and a steep slope. Conversely, the wide shelf in front of the major deltas of the North Shore (e.g., Portneuf) prevented a direct connection with the steep slopes of the Laurentian Channel, which in turn prevented locally the development of a Phase 2 in these areas.

In this formerly-glaciated marine basin, RSL did not play a major role in delivering coarse sediment to the LSLE. In fact, RSL only controlled the location of the delivery of coarse sediment. This finding contrasts with a previous study by Hart and Long (1996) that stated that RSL fluctuations was the primary driver on sediment delivery. Indeed, sediment delivery occurred during RSL fall but, as exemplified by the Portneuf delta, it did not lead to increased sediment delivery. During the early stages of deglaciation, coarse sediment accumulated mostly on the wide shelf due to a high RSL. Sediment was rapidly delivered to the deeper Laurentian Channel as the RSL was rapidly falling. Sediments were no longer being transferred to the Laurentian Channel via river-fed channels even though RSL was still falling when the ice margin left the watersheds. Unlike sequence stratigraphic models predict, the falling stages or lowstands of RSL did not favour sediment density flow activity in the Laurentian Channel, despite the transition to deep-water systems developing steeper depositional slopes, because sediment supply had diminished. Therefore, RSL did not play a key role in the chronology of the sediment transport. In combination with the shelf morphology (narrow vs. wide), it however controlled the location of sediment deposition either on the shelf or in the Laurentian Channel.

Comparison with non-glaciated margins

Covault and Graham (2010) summarized four main types of settings that lead to different timings in sediment delivery to marine basins: 1) fluvially-fed canyons that incise continental shelves to the shoreline that can exhibit continuous sediment deposition, regardless of RSL; 2) longshore drift-fed canyons that can be active only during highstands because of sediment by-passing along the shores; 3) fluvially-fed canyons located away from the shoreline that can be active during RSL highstands if sediment supply allows the deltas to prograde onto the broad shelf (e.g., Burgess and Hovius, 1998); and 4) fluvially-fed systems that are located on broad shelves that can be active only during sea-level lowstands, when there is a direct connection between river mouths and submarine canyons.

The interaction between the different types of submarine canyons/channels along a same margin are poorly documented, except along the California borderland (Covault et al., 2007; Normark et al., 2009; Romans et al., 2009; Covault and Graham, 2010) and along the Chilean margin (Bernhardt et al., 2016). In this respect, the analysis of the activity of the submarine fans along the LSLE brings new insights into the dynamics of sediment transport in a geological setting characterized by deglaciation, a rapid change in type and rates of sediment supply and a varying shelf geomorphology.

The modification of terrigenous supply to the Laurentian Channel has some similar characteristics with the deep-water turbidite systems bordering the Californian Coast (Covault et al., 2007; Normark et al., 2009; Romans et al., 2009; Covault and Graham, 2010). In the California borderland systems, canyons supplied by fluvial sediments were mainly active during sea-level lowstands while canyons supplied by longshore drift were draped by hemipelagic sediments. This difference in activity was due to a direct connection between the river mouths and the canyons which limited longshore drift towards longshore drift-fed canyons. Following the Holocene eustatic transgression, the disconnection of the canyon heads from fluvial input led to the formation of the large Oceanside littoral cell which allowed the transport of sediments to the longshore drift-fed canyon of La Jolla (Covault et al., 2007). In the LSLE, the modification in sediment delivery occurred during a forced regression. According to the conceptual model of Covault and Graham (2010) for the California borderland, it should be expected that sediment supply changes from longshore drift to fluvial in this regression context since lowstand intervals favour a direct connection between rivers and submarine channels. The opposite was observed in the LSLE where the activity of the river-fed channels in the LSLE was drastically reduced while the longshore drift-fed canyons continued to be active (Fig. 9). This modification of terrigenous supply is partly due to the different tectonic settings, where the California active margin favours the formation of canyons while the LSLE margin favours the formation of submarine deltas on which channels form. However, the key control in the LSLE is the ice-margin position within the watersheds that controlled sediment supply to the rivers, whereas the shelf width is the key control over sediment delivery on the California borderland (Covault et al., 2007).

Moreover, terrigenous sediment supply is not constant in the LSLE and is not primarily controlled by RSL fluctuations. RSL rather defined the base level at which the deltas or fans were formed. When RSL fell to its present level, sediment density flows reached the Laurentian Channel while during the Goldthwait Sea (highstand), sediment density flows were depositing coarse sediment on the coastal shelf. Terrigenous sediment supply is more influenced by the presence of a glacier in the watershed (Dietrich et al., in press) or paragacial conditions where rivers supply important amounts of sediment to the sea. Sediment supply was greater during the late-Wisconsinan due to the presence of the LIS margin which supplied large volumes of sediment capable of forming large submarine deltas (Fig. 9). The RSL fall then allowed deltas to evolve on the coastal shelf and eventually into the Laurentian Channel, although it did not control the formation of sediment density flows.

These observations are thus in agreement with Covault and Graham (2010) and Evangelinos et al. (in press) that suggested that high-latitude turbidite systems are mainly controlled by glacial sediment supply rather than RSL fluctuations. These results also support statements from Knudson and Hendy (2009) and Covault et al. (2007) that demonstrated that submarine fans with similar climatic conditions and located in close proximity with each other can have different rates of activity and different sedimentary processes, depending on their source of sediment and their geomorphological setting.

CONCLUSIONS

This study, based on the integration of terrestrial and marine datasets, demonstrates that submarine fan deposition in the LSLE since deglaciation is divided into three phases: 1) a first phase marked by the deposition of outwash fans and delta progradation on the shelf during the retreat of the LIS margin; 2) a second phase marked by high glaciofluvial sediment supply from rivers, which led to the triggering of debris flows and river-derived sediment density flows and the formation of large submarine deltas into the Laurentian

Channel; and 3) a third phase marked by a reduced sediment supply from rivers which favoured coastal erosion along the delta fronts and the transfer of sediments to canyon heads by longshore drift, where the shelf narrows.

The delivery of coarse sediment to marine basins is often viewed as essentially controlled by RSL variations. In a formerly glaciated margin, RSL variations have little effect on sediment delivery compared to the type, rate and duration of sediment supply and shelf geomorphology. The presence of glacial ice in river watersheds largely controls the volume of sediment supplied to marine basins. Therefore, during sea-level highstands and regressions, coarse sediments can be delivered to marine basins due to increased sediment supply from the glacially-fed rivers. During lowstands, when sediment transport is supposed to be active according to sequence stratigraphic models, the absence of glacial ice in the watersheds reduces drastically the amount of sediment supplied to the marine basin. Therefore, deltas change from river-dominated to wave-dominated and become largely eroded. Sediments are then transported through longshore drift in adjacent bays or to areas where the shelf narrows. In these narrow shelves, sediments are delivered to deeper marine basin because of the direct connection between longshore sediment supply and a steep slope.

Sediment dynamics in high-latitude environments such as the LSLE thus differ from lower latitudes deltaic and canyon systems because they were previously glaciated and do not respond to the same forcing mechanisms as others, namely RSL. This paper highlights the role of the type of sediment supply (ice-contact, glacio-fluvial and longshore drift) in the timing and activity of submarine fans in high-latitude environments. It also highlights how structural inheritance, which controls the watershed area and the shelf geomorphology, is more important than RSL fluctuations in maintaining deltaic activity in formerly glaciated environments.

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FIGURES

Figure 1 : Location of study area and main locations of submarine canyons and fans mentioned in the text. RC = River-fed canyon, LDC = Longshore drift-fed canyons, RDC = River-fed deltaic channels, SSC = Sediment-starved canyons

Figure 2 : Deglaciation of the Québec North Shore (modified from Occhietti et al., 2011) with the extent of three watersheds discussed in the text as well as the relative sea-level curves for the Lower St. Lawrence Estuary. (A) is from Dietrich et al. (in press) and (B) is from Dionne (2001).

Figure 3 : Seismic stratigraphic framework of the Lower St. Lawrence Estuary illustrating the five main seismic units and their ages (modified from Duchesne et al., 2010). Location of seismic profile in Fig. 1. Depths were converted from time using a velocity of 1500 m/s.

Figure 4: A) Stratigraphic architecture of a modern exposed component of the deltaic system (Portneuf) showing the lateral juxtaposition, from the proximal to distal domain of outwash fan, glaciofluvial delta and coastal suites. Letters within the sketch represents the inserts; B) faint horizontal bedding in pebbles and cobbles and sand intraclasts forming the topsets of the outwash fan; C) stacked normally-graded beds deposited from sediment density flows; D) boulder-sized lonestone in glaciomarine mud; E) trough cross-stratified sand and gravel in delta topsets; F) stacked normally graded and flamed sand beds deposited by sediment density flows, forming the bulk of the glaciofluvial delta slope; G) well-bedded silt deposits forming the prodelta; H) well-sorted sand and heavy mineral placers observed in raised beach deposits, note vertical burrows; I) seaward-dipping beds characterizing the raised beaches and spits.

Figure 5: Bathymetry of the submarine deltas and fans discussed in the text. A) The Portneuf delta illustrating buried channels at the mouth of the river and the prevalence of longshore drift landforms (spit) in the nearshore environment; B) The Manicouagan delta illustrating channels at the mouth of the river; C) The Les Escoumins region illustrating a river-fed submarine canyon to the West and three longshore drift-fed submarine canyons to the East.

Figure 6: Seismic stratigraphy of the (A) submarine Portneuf delta, (B) submarine Manicouagan delta, (C) Les Escoumins river-fed canyon/fan system and (D) Les Escoumins longshore drift-fed canyon/fan system. In all four cases, the main submarine fan units overly transparent to low-amplitude seismic reflections (SU3). The Portneuf submarine fan (A) is overlied by transparent to low-amplitude seismic reflections (SU3) and late-Holocene sediments (SU4 and SU5) while the Manicouagan submarine fan (B) is overlied by low amplitude seismic reflections (SU5: postglacial hemipelagic sediments). Location of seismic profiles in Fig. 5. Depths were converted from time using a velocity of 1500 m/s.

Figure 7: Distribution of sediment density flow deposits (hyperpycnite-like deposits (H)) in the Manicouagan delta, characterized by sharp increases in CT-numbers and magnetic susceptibility. A, B, C and D are cores collected on the submarine delta (location in Fig. 5B). E) Examples of grain-size patterns observed within the cores illustrating inverse-to-normal grading and more complex grading patterns similar to hyperpycnites.

Figure 8: Distribution of sediment density flow deposits (debrites (D) and turbidites (T)) in the river-fed (A) and longshore drift-fed (B) submarine fans of the Les Escoumins

sector. C) Thin section of turbidites illustrating the normal-grading and basal inverse-grading interpreted as the traction carpet.

Figure 9: Conceptual model of evolution of deltaic system and submarine fans in the LSLE following the retreat of the Laurentide Ice Sheet (LIS) margin. Phase 1 is characterized by a retreating ice-margin on the Québec North Shore and the progradation of a delta over the shelf (formation of outwash fans and progradation of glaciofluvial deltas) during RSL fall. Phase 2 is characterized by the delivery of sediment into the Laurentian Channel during the early-Holocene while the LIS is still present in the upper parts of the river watersheds. Phase 3 is characterized by the complete withdrawal of the LIS from the watersheds and the erosion of the deltas, the development of extensive coastal structures on the shelf and the activity of the Les Escoumins longshore drift-fed systems during the mid- to late-Holocene.

Table 1 : AMS ^{14}C dates and calibrated ages for submarine samples collected in the LSLE. A marine reservoir correction of 400 yr (ΔR – 0 yr using Marine 13 curve) was applied and calibrated ages within parentheses presented with 2σ.