Reconstructing ice-margin retreat using delta morphostratigraphy

Pierre Dietrich1,2, Jean-François Ghienne3, Alexandre Normandeau3, & Patrick Lajeunesse4

The paleogeographic reconstruction of the successive inland positions of a retreating ice sheet is generally constrained by mapping moraines. However, deltaic complexes constructed by sediment-charged meltwater can also provide a record of the retreating ice-margin positions. Here, we examine a series of ice-contact, ice-distal glaciofluvial and paraglacial depositional systems that developed along the Québec North Shore (eastern Canada) in the context of falling relative sea level during the northward retreat of the Laurentide Ice Sheet (LIS). Ice-contact depositional systems formed when the LIS was stillstanding along the Québec North Shore. Subsequent inland retreat of the ice margin generated glacial meltwaters feeding sediment to glaciofluvial deltas, leading to their rapid progradation. The retreat of the ice margin from drainage basins was marked by the onset of paraglacial processes such as the shutdown of delta progradation, severe fluvial entrenchment, and deposition of shallow-marine strata. Four end-member scenarios describe the spatial and stratigraphic distribution of these three depositional systems (ice-contact deposits, ice-distal glaciofluvial deltas, and paraglacial suites). They reflect both the inherited drainage basin physiography and the retreat pattern of the ice margin. Applied to twenty deltaic complexes, these end-members allowed us to refine the model of LIS-margin retreat over southeastern Québec.

The pattern of final inland glacial retreat of ice masses is generally less constrained than those tied to earlier, marine-based deglacial stages that offer better constrained temporal framework1–3. Final deglaciation relates, however, to major continental-scale re-organization of ice flows and drainage basins as well as to global climate change. In eastern North America, fragmentation of the Late Wisconsinan Laurentide Ice Sheet (LIS) and drainage of Lake Agassiz are suspected to have triggered the 8.2 ka cooling event4. The subsequent disintegration of the residual Québec-Labrador ice sector probably had a major impact on climate and ocean circulation5,6. Defining the final LIS retreat pattern and chronology is thus a crucial issue when deciphering Early Holocene climate forcings.

Morainic complexes, eskers and glacial lineations deposited during the retreat of the Québec-Labrador ice sector are well-expressed landforms1,3,7–9 but with poorly constrained chronologies awaiting systematic direct dating on the basis of cosmogenic exposure ages2 and luminescence10. In contrast, marine and coastal depositional systems tied to earlier deglaciation stages are characterized by detailed temporal framework due to the abundance of datable material11–13. In particular, delta morphostratigraphies that are in part controlled by change in meltwater and sediment supply, itself intimately tied to the history of ice-margin retreat throughout drainage basins14–17, constitute integrative systems which the unravelling delivers crucial information about their formative processes and penecontemporaneous deglacial evolution. Indeed, such sedimentary archives have a great potential to provide additional and independent age constraints for ice-sheet retreat history in delta river drainage basins.

Here we integrate geomorphological and sedimentological results from twenty deltaic complexes constructed since deglaciation along the Québec North Shore (QNS, NW Estuary and Gulf of St. Lawrence). Interpreting deltaic complexes along ~1500 km of coastline allows us to map the positions of Late Pleistocene–Early Holocene inland ice margins of the retreating Québec-Labrador ice sector of the LIS during the progressive deglaciation of the adjacent drainage basins of these deltas, together representing an area of more than 250,000 km² (Fig. 1).
Deglacial history
Following the Last Glacial Maximum (LGM) ca. 24 ka (ky cal BP) ago, the LIS began to recede by collapse and iceberg calving13 (Fig. 1). By ca. 12 ka, the LIS margin stabilized over the QNS 13,18. Then, the retreat was mainly achieved by ablation of land-based glaciers up to the final disappearance of the Québec-Labrador ice sector at ~6 ka1,9,19. Meltwaters and glaciogenic material fed deltaic complexes positioned at the mouths of steep-flanked structural valleys and distributed along formerly glacio-isostatically flexured lowlands of the QNS (Fig. 1). These valleys hence formed fjords immediately after the ice margin retreated and postglacial sea invasion. Marine limit, i.e., the highest elevation reached by marine invasion on the glacio-isostatically depressed land, is recorded ~150 m (asl) in the area (Fig. 1) and large strips of now-emerged land expose sets of down-stepping landforms and deposits that have been recording the contemporaneous glacio-isostatic rebound and deltaic developments. Related thick deltaic successions emplaced in a context of RSL fall (Fig. 2) accumulated as long as the drainage basin remained connected to the retreating LIS margin3,17,20.

Depositional systems
Deltaic complexes of the QNS typically show three superimposed or laterally juxtaposed depositional systems: 1) ice-contact deposits, formed by ice-contact subaqueous fan that sometimes evolved as ice-contact delta, 2) ice-distal glaciofluvial delta, and 3) paraglacial suites20. Although the deltaic complexes of the QNS are characterized by a common deglacial framework and RSL fall history—based on radiocarbon dating—they may vary in terms of depositional architectures. Figure 2 outlines three archetypal morphostratigraphies of the QNS deltaic complexes20. As related depositional systems have specific and unique morphological and surficial expressions, they can confidently be identified on satellite and aerial imagery and/or on digital elevation models.

Ice-contact deposits represent volumetrically massive sediment wedges forming the core of some of the deltaic complexes. They were constructed immediately after local deglaciation during major ice-marginal stillstands at the outlet of structural valleys that have most likely been favored by bedrock thresholds21. Note that backstepping grounding zone wedges may in some case have been emplaced at earlier—and deeper—stillstand positions18,22. Ice-contact subaqueous fan and ice-contact delta architecture includes boulder-bearing pebbly topsets20 deposited from either subaqueous or subaerial meltwater outflows23, and foreset beds alternating siltstones and thick graded sand beds deposited by low- and high-density turbidity currents, respectively24, and commonly supercritical25. The topmost surface of ice-contact deposits is flat to very gently-sloped (<1°) and stands at or slightly below the marine limit (Fig. 2). The subsequent retreat of the ice margin forced the abandonment of the ice-contact depositional system and led to its reworking by shore-related processes through the ongoing RSL fall.

Ice-distal glaciofluvial deltas refer here to deltas fed by a fluvial network issued from the retreating ice margin and where the hydraulic regime was adjusted to sediment-charged meltwater flows26,27. Initially confined within the structural valleys invaded by the sea (fjord-head deltas), glaciofluvial deltas rapidly expanded on the St. Lawrence coastal shelf owing to high rates of delta progradation17,20. Even though the ice margin might have
been located tens of kilometers further inland, sediments were transferred to the coast throughout the structural valleys via the riverine network and permitted a perennial delta accretion. The stratigraphic architecture of glaciofluvial deltas typically shows flat- to gently-sloped topsets deposited by braided streams, upper foresets consisting of stacked graded sand beds deposited by high-density turbidity current, and gently-sloped lower foresets formed by low-density turbidity currents. In spite of high rates of RSL fall forced by the glacio-isostatic rebound, no coeval fluvial entrenchment was identified at least in the early part of this stage. The absence of incision in

Figure 2. LiDAR imagery of morphostratigraphic architectures and imbrications of the three depositional systems (ice-contact, ice-distal glaciofluvial delta and paraglacial suites) constitutive of the Portneuf, Sault-au-Cochon and Longuerive deltaic complexes. The insert represents the RSL fall of the study area. The LiDAR map was generated using GlobalMapper® GIS software.
Pre-existing sediments is due to the large amount of glacially-derived sediment supply that maintained a fluvial equilibrium profile steeper than the shoreline trajectory. The extensive (several tens of km²) top surfaces of the glaciofluvial deltas, which locally preserve relict braided channels and isolated beach ridges, stand well below the marine limit (100–20 m asl, Fig. 2).

Paraglacial suites include stepped coastal deposits and meander belts, which the onset arose when the ice margin melted out of the river drainage basins. Paraglacial suites hence correspond to the product of the reworking of the then inactive glaciofluvial delta due to the shutdown of glaciogenic sediments previously delivered to the coast (i.e., middle to late paraglacial sensu Hein et al.16). Coastal deposits consist of stepped beach and shoreface wedges deposited along inherited foreset slopes of the ice-contact deposits and/or glaciofluvial delta. Occasionally, coastal deposits forming thicker (>15 m) sand wedges correspond to coastal spit platforms characterized by composite offlapping geometries (Fig. 2). Coastal deposits are genetically associated with incised meander belts, which the formation resulted from the entrenchment and repeated channel avulsions of the fluvial...
system within the abandoned glaciofluvial delta throughout the ongoing RSL fall. Surficial expression of coastal deposits and meander belts are well-recognized as they form stepped, linear or curvilinear sand ridges, paleo-terraces, spits and cusps, and stepped and abandoned meandering fluvial terraces, respectively (Fig. 2).

Similar sedimentological and stratigraphic evolutions built up by ice-margin retreat and associated RSL fall forced by the glacio-isostatic rebound have been observed elsewhere throughout Quaternary successions 32, in particular in Greenland 33, Scandinavia 34–36 as well as in the Hudson Bay 37,38.

Evolution of deltaic complexes
Stratigraphic relationships between the three above-described morphosedimentary systems arise in a generic architectural framework, which have been investigated from a selection of seven deltaic complexes (Figs 1, 2 and 3). This stratigraphic framework has been expanded and adapted to the entire QNS based on aerial and satellite photographs, LiDAR and digital elevation model datasets, as each of the three type of depositional system has a specific morphological expression allowing to confidently identify them on aerial imagery (Fig. 2). Thus, thirteen additional deltaic complexes are accounted for (Fig. 4), for which the ages of landforms and deposits have been essentially extrapolated from regional RSL curves 13 (Fig. 2 and Table 1). The diversity of observed stratigraphic architectures is categorised into four end-member scenarios representative of combined interactions between patterns of ice-margin retreat and inherited topographies (e.g., valley depths, extent of drainage basins, Fig. 5).

Underfilled dammed valley. In this scenario, an extensive ice-contact depositional system initially develops at the outlet of the valley on a bedrock threshold during a stillstand of the ice margin. Sediment aggradation combined with subsequent RSL fall may ultimately result in development of an initial ice-contact subaqueous fan into an ice-contact delta depending on sediment availability, duration of glacial stillstand and RSL fall rates 34,39. After further ice-margin retreat from its temporary stable position at the valley mouth, the coarse-grained fan — or any bedrock sill on which the fan was anchored — dams a fjord lake at the head of which a lacustrine ice-distal

Figure 4. The thirteen other deltaic complexes along the Québec North Shore for which no or limited sedimentological and stratigraphic datasets are available. The top surfaces of the ice-contact depositional systems are recognized owing to their proximity with the marine limit; the top surfaces of glaciofluvial deltas are delineated based on the gently-sloped extensive delta plain distinctively lying well-below the marine limit; and, paraglacial suites are characterized by steep-sloped deposits consisting of stepped terraces. Ages of the geomorphological features were extrapolated from their elevation providing local relative sea level curves that can be inferred from isobase maps 13. Altitudes of the marine limit were either derived from local relative sea level curve or geological/geomorphological maps when available 7,44,47–49.
glaciofluvial delta develops\(^{31,39}\). The foresets of the then-abandoned ice-contact fan or delta are actively reworked by shallow-marine processes through the ongoing RSL fall. The lake remains underfilled of sediment\(^{40}\) either because it is too voluminous to be filled or/and owing to an early LIS-margin retreat from the drainage basin.

In the **Underfilled dammed valley** scenario, beach ridges and marine terraces are stepped from the top of the ice-contact depositional system down to modern sea level. As the lake acts as a perennial sediment trap, any delta development over the coastal shelf has been inhibited up to today, as lakes still exist nowadays. The Longuerive, Pentecôte and Maggie deltaic complexes, and which lakes are dammed by boulder-rich ice-contact deposits potentially lying on bedrock threshold, relate to this first end-member (Figs 1, 2 and 3). Lakes dammed by both Quaternary deposits and bedrock sills are also included in this scenario (e.g., Manitou or Lake St. Jean\(^{41}\)).

### Table 1.

| Deltaic complex   | Altitude | Ages (kyr cal BP) | Depositional system | Latitude | Longitude |
|-------------------|----------|------------------|---------------------|----------|-----------|
| Les Escoumins     | 120      | 12.5             | Ice-contact system  | N48°21'  | W69°23'   |
|                   | 60       | 9.5              | Glaciofluvial delta |          |           |
| Longuerive        | 135      | 11               | Ice-contact system  | N48°34'  | W69°17'   |
| Portneuf          | 90       | 10.1             | Glaciofluvial delta | N48°38'  | W69°06'   |
| Sault-au-Cochon   | 140      | 11               | Ice-contact system  | N48°42'  | W69°05'   |
|                   | 90       | 10.1             | Glaciofluvial delta |          |           |
| Betsiamites       | 30       | 8                | Glaciofluvial delta | N48°54'  | W68°39'   |
| Outardes          | 15       | 7.5              | Glaciofluvial delta | N49°08'  | W68°17'   |
| Manicouagan       | 15       | 7.5              | Glaciofluvial delta | N49°08'  | W68°17'   |
| Godbout           | 60       | 9.5              | Glaciofluvial delta | N49°19'  | W67°36'   |
| Pentecôte          | 103      | 10.2             | Ice-contact system  | N49°46'  | W67°11'   |
| Walker            | 103      | 11.1             | Ice-contact system  | N49°56'  | W67°02'   |
| Pasteur           | 100      | 10.9             | Ice-contact system  | N50°02'  | W66°57'   |
| Ste. Marguerite   | 50       | 8.2              | Glaciofluvial delta | N50°10'  | W66°38'   |
| Sept-Îles         | 130      | 10.8             | Ice-contact system  | N50°15'  | W66°09'   |
|                   | 42       | 7.3              | Glaciofluvial delta |          |           |
| Manitou           | 110      | 12.5             | Ice-contact system  | N50°18'  | W65°15'   |
| Riv. Au Tonnerre  | 110      | 12.5             | Ice-contact system  | N50°17'  | W64°55'   |
| Magpie            | 76       | 9.7              | Ice-contact system  | N50°20'  | W64°25'   |
| St. Jean          | 50       | 8                | Glaciofluvial delta | N50°18'  | W64°11'   |
| Romaine           | 20       | 7.5              | Glaciofluvial delta | N50°17'  | W64°26'   |
| Aguanish          | 30       | 8.5              | Glaciofluvial delta | N50°13'  | W62°07'   |
| Natashquan        | 10       | 7.5              | Glaciofluvial delta | N50°09'  | W61°46'   |

**Overfilled dammed valley.** The **Overfilled dammed valley** scenario is initially similar to the **Underfilled dammed valley** scenario, namely the development of an initial ice-contact depositional systems at the valley outlet and then of a fjord lake. However, a significant and/or protracted glaciofluvial sediment supply relative to the lake volume subsequently results in the complete infill of the lake. Sediment supply allows the fluvial system to be re-established up to the open coast through the entire valley. The afterward retreat of the LIS margin from the drainage basin forces the fluvial entrenchment and the cannibalization of ice-contact and glaciofluvial sediments by coastal processes.

In the **Overfilled dammed valley** scenario, fjord-mouth deltaic complexes show an initial outwash fan where the lower reach of its foreset slope is buried beneath glaciofluvial deltaic sediments. The elevation difference between the top surfaces of the outwash fan and the glaciofluvial delta reflects the duration of the lake infill according to the local RSL curve. The archetypal delta of this scenario is the Sault-au-Cochon deltaic complex\(^{39}\) (Fig. 2).

**Undammed fjord, early deglaciation.** In this scenario, no ice stillstand occurs at the valley mouth (absence of sedimentary deposits and/or bedrock sill?). As a consequence, the ice margin retreats inland, turning the valley into a fjord during marine invasion\(^{40}\). The glaciofluvial delta then rapidly progrades into the fjord, allowing the filling of the entire valley down to its outlet. Rapid deglaciation of the river drainage basin, owing to local high rates of ice-margin retreat and/or a restricted drainage basin area, is responsible for an early transition to paraglacial conditions that consequently occurs at a RSL well above (>60 m) the modern shoreline.

In the **Undammed fjord, early deglaciation** scenario, as no ice-contact system has been deposited at the fjord mouth, the deltaic complex is twofold, only comprised of a glaciofluvial delta overlain and reshaped by long-lasting paraglacial processes that resulted in well-developed paraglacial suites that include severely...
entrenched meander belts and stepped marine terraces. The elevation difference between marine limit and the top surface of the glaciofluvial delta relates to the duration of the in-valley deltaic progradation before expanding onto the open coast domain. Such systems are typified by the Portneuf and St. Jean River deltas (Figs 2 and 3).

Undammed fjord, late deglaciation. In this fourth and last scenario, the transition to paraglacial condition is delayed compared with the previous scenario owing to a large drainage basin and/or low rates of ice margin retreat throughout the drainage basin. Restricted paraglacial suites have hence been emplaced. Although the modern meandering river is entrenched, abandoned meander belts are not identified as the fluvial channel remained confined within the same pathway. The Sept-Îles deltaic complex, one of the largest depositional systems of the QNS, is emblematic of the undammed fjord, late deglaciation scenario. It is associated with a drainage basin extending far to the north.17,42.

Deltaic complexes as a proxy for reconstructing ice-margin retreat history

The morphostratigraphies of deltaic complexes are thus intrinsically linked to the retreat pattern of the ice margin since the latter has controlled meltwater and sediment discharges and, eventually, specific depositional scenarios (Fig. 5). Hence, combining the age constraints derived from deltaic morphostratigraphies with published records of morainic complexes (Québec North Shore, Baie Trinité, Sakami…1,3,7,8, submerged grounding zone wedges18,22 and surface exposure ages2,6, we here refine the reconstruction of LIS retreat from the coastal QNS up to more than 400 km inland (Fig. 6).

When present, ice-contact deposits lying on the QNS provide information on the time interval corresponding to LIS-margin stillstand at the valley outlet, either from altitude of the top surface (date inferred from RSL curve) or radiocarbon dates (black stars on Fig. 6). Age constraints and the occurrence of glacial stillstands are corroborated by occurrences of frontal moraines (dotted lines on Fig. 6). Furthermore, the age of the deglaciation of a given drainage basin is inferred from the morphostratigraphic deltaic record lying at its outlet by the age of the transition from a glaciofluvial delta progradation to a paraglacial setting (black dots on Fig. 6). Twenty control points have hence been obtained in the QNS hinterland as this scheme has been applied for each basin draining into the St. Lawrence. Control points with the same ages have been further linked together to draw reconstructed positions of the retreating ice margin (Fig. 6). For example, an age of 8.0 ky obtained at the head of the St. Jean drainage basin has been correlated with the 8.0 ky found at the head of the Betsiamites basin, keeping in mind that the intermediate Ste. Marguerite and Manicouagan basins partake different (younger) ages. The method permits a reconstruction of ice-margin configurations (Fig. 6). We are aware that the past extent of the drainage basins may have been different from the present-day configuration due to a differential glacio-isostatic flexure19 (ca. 1 m.km−1). We argue, however, that this error can be considered as negligible as the drainage divides lie in relatively high-relief areas.
Our reconstruction then shows linear margins from 12.5 to 9.5 ka which agrees with the overall deglaciation framework of Occhietti et al.3, although two 100s km-wide lobate ice margins are delineated for the period 8.2–7.0 ka (Fig. 6). Lobate geometries have been deciphered from the morphostratigraphic record of the Ste. Marguerite River, indicating an early deglaciation of its drainage basin relative to the two adjacent ones. Indeed, the Romaine River drainage basin, to the east, and the Péribonka 41, Betsiamites and Outardes drainage basins, to the west, were fed by meltwaters until 7.5–7.0 ka. In addition to headland deglaciation points, the proposed ice-margin reconstruction at 8.2–7.0 ka is coherent with esker distribution maps7,9,44 (Fig. 6), provided that eskers develop near and perpendicular to the retreating ice margin45. The inferred lobate ice margin is a reminiscence of mapped ice-stream lobes1, as both eastern and western lobes fit fairly well with the 8.0 ka-aged part of the Flow Set 23 reconstruction of Clark and co-authors1. In contrast, glacial lineations1,7,44 (Fig. 6) are likely to reflect older ice flow configurations prevailing either during the less-constrained 9.5–8.2 ka interval or possibly even before 12.5 ka as these landforms are essentially tangential to the inferred ice-margin positions during the 8.2–7.0 ka interval. Further, surface exposure ages6 corroborate our model of ice-margin retreat, either for the western lobe over the Manicouagan drainage basin. Our 8.2 front matches their 8.2 ± 0.4 age obtained south of the Manicouagan reservoir while their 7.7 ± 0.4 agrees with our 8.0 ice front north of the reservoir. Similarly, their ages obtained in the Churchill River in the northeastern part of the study area fit with our reconstructed ice margins (Fig. 6).

Our deglaciation model indicates low retreat rates of the older, linear ice margin from 12.5 to 9.7 ka. The older dates correspond to the Younger Dryas (YD) Cold Event dated from 12.8 to 11.7 ka, and bracketed further south by the Mars-Batiscan (12.2 to 11.5 ka) and St. Narcisse (12.8 to 11.5 ka) moraines, the latter being likely equivalent to the Québec North Shore moraine3. If related to the YD, the slow retreat of this old linear ice margin should reflect at least in part the signature of a global climatic cooling. The shift from linear ice margin to lobate features (ice-stream lobes) between 9.7 and 8.2 ka likely reflects the transition from frozen to warm basal thermal conditions of the Québec-Labrador ice sector which could be associated with a phase of development of ice streams1. This cold to warm based ice transition occurring slightly after 10 ka according to these authors. This hypothetical cold- to warm-based transition is in agreement with Tarasov and Peltier46 who suggest an abrupt increase of the proportion of warm-based ice at 8 ka. Between 9.7 and 8.2 ka, a rapid (130 m.yr⁻¹) retreat rate characterizes the Ste. Marguerite inter-lobe area that subsequently decreased down to 80 m.yr⁻¹ between 8.2 and 7.0 ka. Comparatively, retreat rates of 80 m.yr⁻¹ and 160 m.yr⁻¹ took place throughout this entire period for the

**Figure 6.** Reconstruction of the Laurentide Ice Sheet margin retreat through river drainage basins inferred from deltaic morphostratigraphies reconstructed from control points deduced from either ice-contact depositional system abandonment (stars) or onset of paraglacial suites development (melting of the ice margin out of the drainage basin, dots). See Nutz et al.41 for deglaciation pattern around Lake St. Jean. Our 8.2 ka ice margin correlates with the Sakami moraine1 and the 8.6 ka ice margin of Carlson et al.19. Surface exposure ages derive from Ullman et al.6. Esker network and glacial lineations originate from Klassen et al.7, Fulton et al.44 and Clark et al.1. See Fig. 1 for details on the background topographic map (SRTM344).
eastern and western lobes, respectively. Compared to the post-8 ka enhanced retreat (900 m yr⁻¹) corresponding to periods of enhanced melting⁶⁻¹⁰, our reconstruction shows more steady overall rates of retreat during the LIS deglaciation.

The correspondence between our morphostratigraphy-based reconstruction and other published reconstructions is a validation of the here-proposed method, which thus appear robust as far as a great number of deltaic complexes have been integrated into our model. Our reconstruction complements and strengthens previous ice-margin retreat models based on glacial landforms and surface exposure ages. However, our aim here is to provide a method for constraining retreat patterns solely based on delta morphostratigraphies which, beyond the particular case of the LIS retreat in south-eastern Québec, should be applicable to other studies of formerly glaciated regions. Particularly, the deltaic systems of eastern Hudson Bay were supplied in sediments by an extensive drainage basin formerly occupied by the northern Québec-Labrador residual ice sector almost up to its final disintegration (coastal deglaciation around 8 ka, glacial retreat after 7 ka⁸⁹). This model can also be further expanded to deltaic complexes lying in the eustatically-dominated zone (Newfoundland, Gulf of Maine) for which the morphostratigraphic record of ‘lowstand deltas’ is preserved at depth owing to the postglacial eustatic transgression⁸⁸. Our approach of reconstructing past ice-margin configurations from the delta morphostratigraphic record can provide valuable inputs to data-calibrated models to infer the general retreat pattern of the LIS⁹⁰.

References
1. Clark, C. D., Knight, J. K. & Gray, J. T. Geomorphological reconstruction of the Labrador Sector of the Laurentide Ice Sheet. Quaternary Science Reviews 19, 1343–1366 (2000).
2. Carlson, A. E., Clark, P. U., Raisbeck, G. M. & Brook, E. J. Rapid Holocene deglaciation of the Labrador sector of the Laurentide Ice Sheet. Journal of Climate 20, 5126–5133 (2007).
3. Occhietti, M., Parent, P., Lajeunesse, F., Robert, É. & Govea, M. Late Pleistocene–Early Holocene Decay of the Laurentide Ice Sheet in Québec–Labrador. Quaternary Glaciations - Extent and Chronology 15, 601–629 (2011).
4. Li, Y. X., Tornqvist, T. E., Nevitt, J. M. & Kohl, B. Synchronizing a sea-level jump, final Lake Agassiz drainage, and abrupt cooling 8200 years ago. Earth and Planetary Science Letters 315–316, 41–50 (2012).
5. Renssen, H. et al. The spatial and temporal complexity of the Holocene thermal maximum. Nature Geoscience 2, 411–414 (2009).
6. Ullman, D. J. et al. Final Laurentide ice-sheet deglaciation and Holocene climate-sea-level change. Quaternary Science Reviews 152, 49–59 (2016).
7. Klassen, R. A., Paradis, S., Bolduc, A. M. & Thompson, R. D. Glacial landforms and deposits, Labrador. Newfoundland and eastern Québec Geological Survey of Canada (1992).
8. Jansson, K.N. Map of the glacial geomorphology of north-central Québec-Labrador, Canada: Journal of Maps, 1, 46–55 (2005).
9. Storrar, R. D., Stokes, C. R. & Evans, D. J. A. Increased channelization of subglacial drainage during deglaciation of the Laurentide ice sheet. Geology 42, 239–242 (2014).
10. Briner, J. P., Axford, Y., Forman, S. L., Miller, G. H. & Wolfe, A. P. Multiple generations of interglacial lake sediment preserved beneath the Laurentide Ice Sheet. Geology 35, 887–890 (2007).
11. King, G. A. A standard method for evaluating radiocarbon dates on local deglaciation: Application to the deglacial history of central Labrador and adjacent Québec. Géographie Physique et Quaternaire 39, 163–182 (1985).
12. Dionne, J.-C. & Occhietti, S. Aperçu du Quaternaire à l’embouchure du Saguenay. Québec Géographie Physique et Quaternaire 50, 5–14 (1996).
13. Shaw, J., Gareau, P. & Courtney, R. C. Palaeogeography of Atlantic Canada 13–0 kyr. Quaternary Science Reviews 21, 1861–1878 (2002).
14. USGS (2006), Shuttle Radar Topographic Mission, 3 Arc Second scene SRTM_n47w053_n54w074, Filled Finished B 2.0, Global Land Cover Facility, University of Maryland, College Park, Maryland, February 2000.
15. Forbes, D. L. & Svyitsky, J. P. M., 1994, Paraglacial coast and coastal deltaic sedimentary systems in the northern Labrador coastal zone. Geological Society of America Bulletin, 107, 27–37 (1994).
16. Hein, C. J., FitzGerald, D. M., Buinevitch, I. V., Van Heteren, S. & Kelley, T. Evolution of paraglacial coastlines in response to changes in fluvial sediment supply. InMartini, I.P. and Wanless, H.R., eds, Sedimentary coastal zones from high to low latitudes: similarities and differences: Geological Society of London, Special Publication, 388, 247–280 (2014).
17. Normandeau, A. et al. Timing and controls on the delivery of coarse sediment to deltas and submarine fans on a formerly glaciated coast and shelf. Geological Society of America Bulletin 125, 1861–1878 (2013).
18. Lajeunesse, P. Late Wisconsinan grounding-zone wedges, northwestern Gulf of St Lawrence, eastern Canada: In Dowdeswell, J. A. et al., eds, Atlas of Submarine Glacial Landforms: Modern, Quaternary and Ancient, 1, 227–228 (2016).
19. Carlson, A. E. et al. Rapid early Holocene deglaciation of the Laurentide Ice Sheet. Nature Geoscience 1, 620–624 (2008).
20. Dietrich, P. et al. From outwash to coastal systems in the Portneuf-Forestville deltaic complex (Québec North Shore): Anatomy of a forced regressive deltaic sequence. Sedimentology 64, 1044–1078 (2017).
21. Gagnon-Poitre, A. et al. Late-Quaternary glacial to postglacial sedimentation in three adjacent fjord-lakes of the southeastern Canadian Shield, Quaternary Science Reviews, In press.
22. Lajeunesse, P., Dietrich, P. & Gienne, J.-F. Late Wisconsinan grounding zones of the Laurentide Ice Sheet margin off the Québec North Shore (NW Gulf of St. Lawrence). In Le Heron D. et al., eds., Glaciated Margins: The Sedimentary and Geophysical Archives: Geological Society of London, Special Publication (in press).
23. Russell, A. J. & Arnott, R. W. C. Hydraulic-jump and hyperconcentrated-flow deposits of a glacigenic outwash fan: Oak Ridges Moraine, Southern Ontario, Canada. Journal of Sedimentary Research 3, 887–905 (2003).
24. Talling, P. J., Masson, D. G., Sunner, E. J. & Malgessini, G. Subaqueous sediment density flows: Depositional processes and deposit types. Sedimentology 59, 1937–2003 (2012).
25. Dietrich, P., Ghieme, I.-F., Normandeau, A. & Lajeunesse, P. Upline-migrating bedforms in a proglacial sandur delta: cyclic steps from river-derived underflows? Journal of Sedimentary Research 86, 113–123 (2016).
26. Slawmaker, O. Criteria to Distinguish Between Periglacial, Proglacial and Paraglacial Environments. Quaestiones Geographicae 30, 85–94 (2011).
27. Lonne, J. Sedimentary facies and depositional architecture of ice-contact glaciomarine systems. Sedimentary Geology 98, 13–43 (1995).
28. Tarasov, L., Dyke, A. S., Neal, R. M. & Peltier, W. R. A data-calibrated distribution of deglacial chronologies for the North American ice complex from glaciological modeling. Earth Planetary Science Letters 315-316, 30–40 (2012).
29. Ritchie, B. D., Gawthorpe, R. L. & Hardy, S. Three-Dimensional Numerical Modeling of Deltaic Depositional Sequences 2: Influence of Local Controls. Journal of Sedimentary Research 74, 221–238 (2004).
30. Muto, T. & Swenson, J. B. Autogenic attainment of large-scale alluvial grade with steady sea-level fall: An analog tank-flume experiment. Geology 34, 161–164 (2006).
31. Nijhuis, A. G. et al. Fluvio-deltaic avulsions during relative sea-level fall. Geology 43, 719–722 (2015).

32. Boulton, G. S. Sedimentary and sea level changes during glacial cycles and their control on glaciomarine facies architecture. In Dowdeswell, J.A. & Scourse, J.D., eds, Glacimarine environments: Processes and Sediments: Geological Society of London, Special Publication, 53, 15–52 (1990).

33. Hansen, L. Deltic infill of a deglaciated arctic fjord, East Greenland: sedimentary facies and sequence stratigraphy. Journal of Sedimentary Research 74, 422–437 (2004).

34. Lonne, I., Nemec, W., Blikra, L. H. & Lauritzen, T. Sedimentary Architecture and Dynamic Stratigraphy of a Marine Ice-Contact System. Journal of Sedimentary Research 71, 922–943 (2001).

35. Corner, G. D. A transgressive-Regressive model of fjord-valley fill: stratigraphy, facies and depositional controls. InDalrymple, R.W., Leckie, D. & Tilman, R., eds, Incised-valley Systems in Time and Space, SEPM Special Publication, 85, 161–178 (2006).

36. Eilersten, R. S., Corner, G. D., Aasheim, O. & Hansen, L. Facies characteristics and architecture related to palaeodepth of Holocene fjord-delta sediments. Sedimentology 58, 1784–1809 (2011).

37. Lajeunesse, P. & Allard, M. Late Quaternary deglaciation, glaciomarine sedimentation and glacioisostatic recovery in the Rivière Nastapoka area, eastern Hudson Bay, Northern, Québec. Géographie Physique et Quaternaire 57, 65–83 (2003).

38. Fraser, C., Hill, P. R. & Allard, M. Morphology and facies architecture of a falling sea level strandplain, Umiujaq, Hudson Bay, Canada. Sedimentology 52, 141–160 (2005).

39. Helle, S. K. Sequence stratigraphy in a marine moraine at the head of Hardangerfjorden, western Norway: Evidence for a high-frequency relative sea-level cycle. Sedimentary Geology 164, 251–281 (2004).

40. Normandeau, A., Lajeunesse, P., Poiré, A. G. & Francus, P. Morphological expression of bedforms formed by supercritical sediment density flows on four fjord-lake deltas of the south-eastern Canadian Shield (Eastern Canada). Sedimentology 63, 2106–2129 (2016).

41. Nutz, A. et al. Forced regressive deposits of a deglaciation sequence: Example from the Late Quaternary succession in the Lake Saint-Jean basin (Québec, Canada). Sedimentology 62, 1573–1610 (2015).

42. Dietrich, P. et al. Deglacial sequences and glacio-isostatic rebound: Quaternary vs. Orдовician glaciations In Le Heron D. et al., eds., Glaciated Margins: The Sedimentary and Geophysical Archives: Geological Society of London, Special Publication (in press).

43. Peltier, W. R., Argus, D. F. & Drummond, R. Space geodesy constrains ice age terminal deglaciation: The global ICE-6G_C (VM5a) model. Journal of Geophysical Research: Solid Earth 120, 450–487 (2015).

44. Fulton, R. F. Surficial materials of Canada. Geological Survey of Canada, Map 1880A, scale1:5 000 000 (1995).

45. Boulton, G. S., Hagdorn, M., Maillot, P. B. & Zatsepin, S. Drainage beneath ice sheets: groundwater-channel coupling, and the origin of esker systems from former ice sheets. Quaternary Science Reviews 28, 621–638 (2009).

46. Tarasov, L. & Peltier, W. R. Coevolution of of continental ice cover and permafrost ice extent over the last glacial-interglacial cycle in North America. Journal of Geophysical Research 112, F2, https://doi.org/10.1029/2006JF00066 (2007).

47. Dredge, L. A. Surficial Geology of the Sept-Îles area. Canadian Journal of Earth Sciences 41, 450–487 (2015).

Acknowledgements
Field campaigns and radiocarbon dating were funded by action SYSTER and the ARTÈMIS program (LMC14) of INSU-CNRS. This work is a contribution to the ‘SeqStrat-Ice’ ANR project 12-BS06-14. Fieldwork was also supported by an NSERC Discovery grant to P.L. George Henry is thanked for his comments and corrections on this manuscript. Authors are grateful to Editorial Board Member Nick Marriner and an anonymous reviewer whose comments and suggestions led to the improvement of the quality of the manuscript.

Author Contributions
P.D., J.-F.G., A.N. and P.L. conceived the idea for the model and wrote the manuscript. P.D. drawn the figures with the support of J.-F.G., A.N. and P.L. All authors participated to field campaigns along the Québec North Shore and designed the investigation method. A.N. and P.L. realized bathymetric and seismic survey throughout the Estuary and Gulf of the St. Lawrence.

Additional Information
Competing Interests: The authors declare that they have no competing interests.

Publisher’s note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/.

© The Author(s) 2017