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Geomorphic Evidence of Postglacial Terrestrial Environments on Atlantic Canadian Continental Shelves

Indices géomorphologiques de milieux post-glacaires terrestres sur les plates-formes continentales au Canada Atlantique

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Article abstract

Changes in the geography of Atlantic Canada since the last glacial maximum (LGM) are grouped into three phases. The first phase (LGM – *ca.* 13 ka BP) commences with glaciers at the edge of the continental shelves, and ends with the glaciers having retreated to near modern coasts. In the second phase (*ca.* 13 ka BP-10 ka BP), glaciers were mainly on land; on the continental shelves there were scattered small ice caps and an outer-shelf archipelago. Early in phase three, beginning *ca.* 10 ka BP, glaciers were largely absent, and the archipelago was gradually submerging; elsewhere, falling relative sea levels caused emergence. Multibeam sonar mapping has revealed the geomorphic evidence of submerged terrestrial environments of phases II and III, including fluvial, deltaic, and coastal systems. The best-preserved fluvial systems are in Northumberland Strait and the Bras d'Or Lakes. Elsewhere, multibeam bathymetric data allow discrimination between fluvial and non-fluvial channels. Deltas were mainly preserved in the special circumstances of Newfoundland fjords. Submerged coastal systems are common in the Bras d'Or Lakes, but rare elsewhere. Landscape preservation is ascribed to special circumstances. Paleogeographic reconstructions have applications in the field of evolutionary biology and archaeology.

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GEOMORPHIC EVIDENCE OF POSTGLACIAL TERRESTRIAL ENVIRONMENTS ON ATLANTIC CANADIAN CONTINENTAL SHELVES

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ABSTRACT Changes in the geography of Atlantic Canada since the last glacial maximum (LGM) are grouped into three phases. The first phase (LGM – *ca.* 13 ka BP) commences with glaciers at the edge of the continental shelves, and ends with the glaciers having retreated to near modern coasts. In the second phase (*ca.* 13 ka BP-10 ka BP), glaciers were mainly on land; on the continental shelves there were scattered small ice caps and an outer-shelf archipelago. Early in phase three, beginning *ca.* 10 ka BP, glaciers were largely absent, and the archipelago was gradually submerging; elsewhere, falling relative sea levels caused emergence. Multibeam sonar mapping has revealed the geomorphic evidence of submerged terrestrial environments of phases II and III, including fluvial, deltaic, and coastal systems. The best-preserved fluvial systems are in Northumberland Strait and the Bras d'Or Lakes. Elsewhere, multibeam bathymetric data allow discrimination between fluvial and non-fluvial channels. Deltas were mainly preserved in the special circumstances of Newfoundland fjords. Submerged coastal systems are common in the Bras d'Or Lakes, but rare elsewhere. Landscape preservation is ascribed to special circumstances. Paleogeographic reconstructions have applications in the field of evolutionary biology and archaeology.

RÉSUMÉ *Indices géomorphologiques de milieux post-glacaires terrestres sur les plates-formes continentales au Canada Atlantique.* Les changements de la géographie du Canada atlantique depuis le dernier maximum glaciaire (DMG) sont regroupés en trois phases. La première (DMG, environ 13 ka avant le présent) débute au moment où les glaciers occupent le rebord des plates-formes continentales et se termine lorsqu'ils ont reculé jusqu'à proximité des lignes de rivage contemporaines. Pendant la deuxième phase (de 13 ka à 10 ka avant le présent), les glaciers se trouvaient principalement sur les terres; il y avait de petites calottes glaciaires éparses sur les plates-formes continentales et un archipel sur la partie extérieure des plates-formes. Au début de la troisième phase, il y a environ 10 000 ans, les glaciers étaient en grande partie absents et l'archipel s'enfonçait progressivement dans les eaux; ailleurs, les niveaux relatifs de la mer, alors à la baisse, engendraient une émergence des terres. La bathymétrie au sonar a révélé des indices géomorphologiques de milieux terrestres submergés pendant les phases II et III, incluant des systèmes fluviaux, deltaïques et côtiers. Les systèmes fluviaux les mieux conservés se situent dans le détroit de Northumberland et les lacs Bras d'Or. Ailleurs, les données bathymétriques permettent de distinguer des chenaux fluviaux d'autres chenaux non fluviaux. Les deltas ont été principalement conservés dans les cas particuliers que constituent les fjords de Terre-Neuve. Les systèmes côtiers submergés sont communs dans les lacs Bras d'Or, mais rares ailleurs. La préservation de ces paysages dépend de circonstances spéciales. Ces reconstitutions paléogéographiques ont des applications dans les domaines de la biologie évolutive et de l'archéologie.

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INTRODUCTION

Much of Atlantic Canada was ice-covered during the last glacial period, and later, when the ice was disappearing, the area experienced complex changes in relative sea level. The associated changes in paleogeography have been explored in several reconstructions (Bousefield and Thomas, 1975; Dyke and Prest, 1987a, 1987b; Dyke, 1996). Dyke and Prest's maps show ice margins at or near modern coasts from last glacial maximum (LGM) until 14 000 BP, after which retreat began. This model has been re-evaluated in recent decades (Dyke *et al.*, 2002) as new data have become available from shelf areas and as radiocarbon dates from bulk samples have been replaced by more precise accelerator mass spectrometry (AMS) dates from macrofossils. Shaw *et al.* (2002a) reconstructed geography from 13 ka BP onwards using empirical data, and more recently the history of glaciation has been re-evaluated (Shaw *et al.,* 2006).

The goal of this paper is to present recent geomorphic evidence obtained through regional-scale multibeam sonar mapping on the continental shelves of Atlantic Canada, and to demonstrate that this evidence broadly supports the ideas set forth in Shaw *et al.* (2002a) and Shaw *et al.* (2006). The author will propose that the changes in geography can be grouped into three phases, characterized by progressively decreasing extent of glacier ice. The author will focus on the third phase, during which changing relative sea level became the dominant control on geographic change. The new data reveal landforms that were submerged by the postglacial transgression; for descriptive ease they are grouped under three headings, namely: (1) fluvial systems, (2) deltas and (3) coastal systems.

METHODS

Geomorphic evidence of former terrestrial environments comes from the growing body of multibeam bathymetric survey data collected by the Geological Survey of Canada and the Canadian Hydrographic Service. These data allow us to delineate geomorphic features that were previously impossible or difficult to recognize with geophysical techniques such as sub-bottom profiling. Analyses of backscatter strength derived from the raw multibeam data (Courtney and Shaw, 2000), together with ground-truthing using the more traditional suite of tools (sub-bottom profiling, sidescan sonar, cores, grab samples and seabed photographs, etc.), supplement the multibeam terrain imagery and facilitate its interpretation. The paleogeographic maps, originally published by Shaw *et al.* (2002a), are based on a digital elevation model (Shaw and Courtney, 2004) that was adjusted to take account of relative sea-level changes. Chronology referred to in the text is in radiocarbon years unless otherwise noted.

STUDY AREA

The continental shelves in the study area (Fig. 1) are dissected by glacially over-deepened channels (King *et al.*, 1974). The Laurentian Channel is more than 500 m deep in some areas, and shallows at the shelf edge to a depth of 410 m. Off the northeast coast of Newfoundland, the continental shelf and the offshore banks (Funk Island Bank, 220-300 m) are deeper than elsewhere. Trinity Trough and Notre Dame Channel (Warren, 1976) extend to the shelf edge. Off Nova Scotia, Emerald Basin and LaHave Basin are the largest of a series of irregular basins on the shelf. In the Gulf of Maine, over-deepened basins converge into the Northeast Channel that shallows to a shelf-edge depth of 200 m. The deepest water landward of the shelf edges is not in the basins noted above, but in the fiords that radiate from the interior of Newfoundland (Shaw, 2003). Those on the west coast are moderately deep (≤230 m), the southwest coast fiords range up to 770 m depth, and maximum depths in northeast coast fjords commonly exceed 600 m. Flemish Cap, an isolated offshore bank located east of the Grand Banks of Newfoundland, has a minimum depth of 126 m and is separated from the Grand Banks by Flemish Pass, which has a depth of more a thousand metres.

CHANGING GEOGRAPHY FROM LGM ONWARDS

Geographic changes are divided into three phases: (1) an early phase during which glaciers reached near the edges of continental shelves, and then retreated by deepwater calving; (2) a second phase that started with ice margins located near modern coasts, and ended with the disappearance of glaciers; (3) a third phase during which glaciers were absent from Atlantic Canada. Complex relative sea-level changes due to isostatic and eustatic processes were occurring during all three phases, but in the third phase, large-scale changes in geography were primarily driven by relative sea-level changes alone. This phase continues today, albeit at slow rates. In this paper Phases I and II are briefly summarized – a complete description is contained in Shaw *et al.* (2006) – and the emphasis is on the terrains that were emergent in phase III, and that were later submerged. Geographic change from 13 ka BP onwards (not showing the glaciers) can be viewed on line at <http://gsca.nrcan.gc.ca/COASTWEB/sealevel/progression_e.php>

PHASE I: LGM TO 13 KA BP

Shaw *et al.* (2006) argue that the margin depicted in Figure 2 existed before the classic LGM, perhaps as early as 25 ka BP (see also Piper and Campbell, in press). Major divides separated catchment areas that were, periodically or intermittently, drained by ice streams. The margin was composed of two principal types: (1) places where ice streams in shelf-crossing troughs calved into the ocean; and (2) relatively inactive ice, grounded to depths of 450-500 m on the Scotian shelf (Mosher *et al.* 1989; Bonifay and Piper, 1988).

Deglaciation proceeded by the calving of grounded ice in deep water (Shaw *et al.*, 2006), beginning off northeastern Newfoundland, and continuing in the Gulf of Maine. Off Nova Scotia the removal of grounded ice was underway in the Emerald Basin by 18 ka BP. The calving ice margin at the terminus of the ice stream in the Laurentian Channel maintained its position at the edge of the continental shelf until just after 14.5 ka BP (Piper and MacDonald, 2002). Subsequent rapid retreat along the Laurentian Channel (Josenhans and Lehman, 1999) marooned ice on the adjacent banks (King

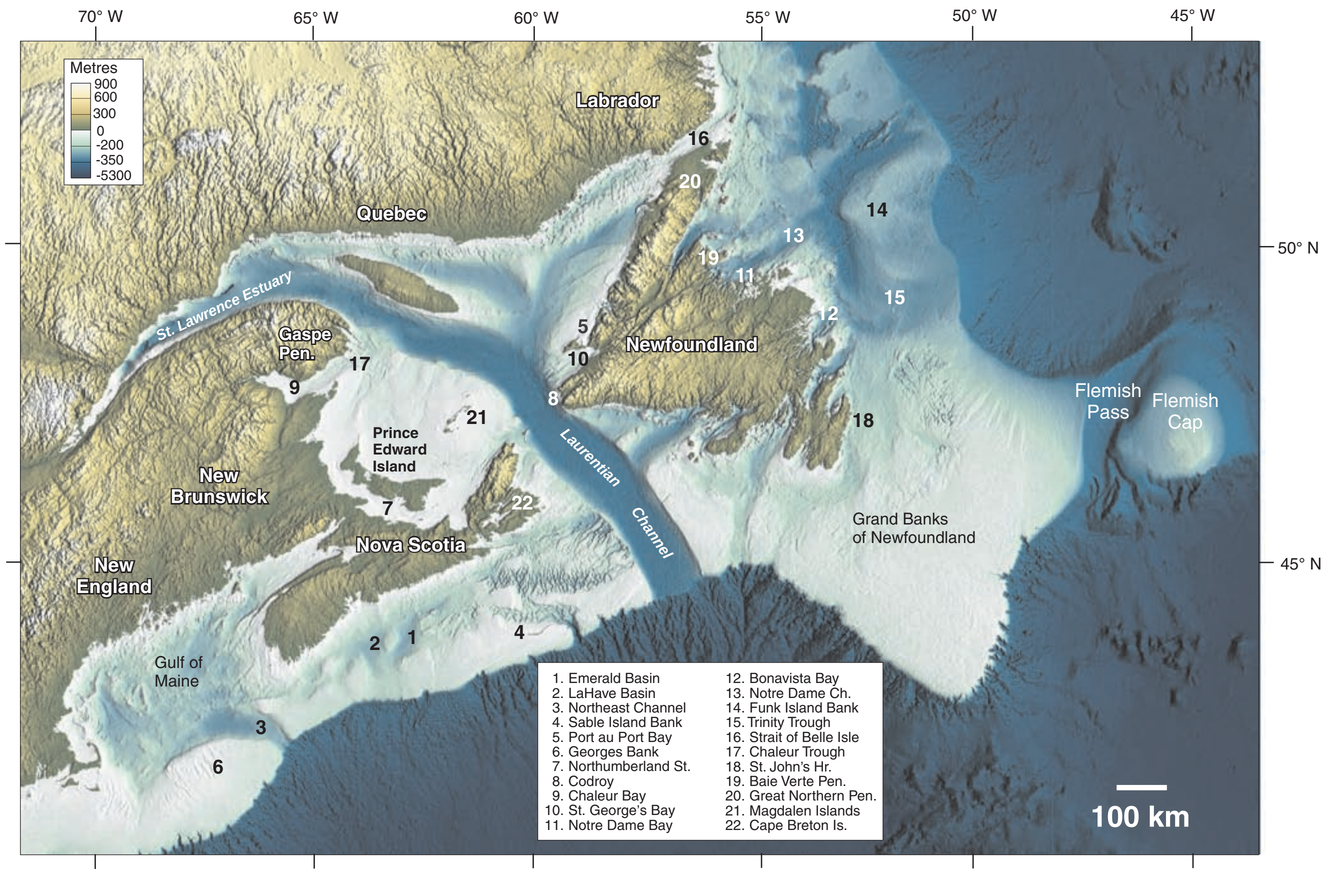

FIGURE 1. Shaded relief image of Atlantic Canada and the adjacent continental shelves.

Image en relief du Canada atlantique et des plates-formes continentales adjacentes.

and Fader, 1990). The embayment rapidly retreated into the Gulf of St. Lawrence (Rodrigues *et al.*, 1993), reaching the head of the St. Lawrence Estuary by 13.5 ka BP (Locat, 1977).

By 14 ka BP rapidly calving ice margins had reached the south and southwest coasts of Newfoundland (Shaw *et al.*, 2000; Shaw, 2003). In St. George's Bay, calving ice created a tidewater margin (Bell *et al.*, 2001); on the south coast it was grounded at fiord mouths from 14.2 ka BP onwards. The calving removed ice from deep channels on the shelves elsewhere around Newfoundland (Cumming *et al.*, 1992 ; Shaw, 2003), thereby isolating ice caps on the Grand Banks.

PHASE II: 13 KA BP TO 10 KA BP

At the onset of the second phase of landscape evolution (Fig. 3), glacier margins were on land in many regions, so that ablation proceeded by melting and sublimation alone (rather than by calving as in phase I). In the Gulf of St. Lawrence the calving margin had migrated far up the St. Lawrence Estuary and lay near the Strait of Belle Isle in the northeast. Along the west coast of Newfoundland, ice retreated inland. Along the south coast, ice margins had retreated to fjord heads by 12.5 ka BP (Shaw *et al.*, 2000). In northeast Newfoundland a major lobe was mostly on land and was slowly ablating and a tidewater margin extended along the east side of the Great Northern Peninsula.

Because of lowered relative sea level – a combined effect here, as elsewhere in the study area, of globally-lowered eustatic sea level combined with local isostatic effects – parts of the offshore banks were emergent, forming an archipelago extending from the Grand Banks to offshore New England. The largest island, on the modern Grand Banks (Fig. 3), had a maximum elevation of 60 m at 13 ka BP. Off Nova Scotia the islands had a maximum elevation of 101 m in the vicinity of modern Sable Island and 13 m on modern Georges Bank. By contrast, in New England and New Brunswick there was significant submergence of coastal regions (due to strong crustal depression) and marine embayments penetrated far inland along modern river valleys.

CHANGES AFTER 10 KA BP

After an expansion of ice coincident with the Younger Dryas (Stea and Mott, 1989), Nova Scotia was ice-free by 10 ka BP and the interior of Newfoundland was ice-free soon after. Subsequent changes in geography were largely due to eustasy and isostasy alone, rather than to variations in glacier extent. By 9 ka BP the large island on the Grand Banks (Fig. 4) was smaller than at 13 ka BP, with a maximum relief of ~23 m.

At 9 ka BP, the islands in the vicinity of Sable Island Bank were smaller in extent, or had broken into several parts, due to relative sea-level rise. Maximum relief of these islands was

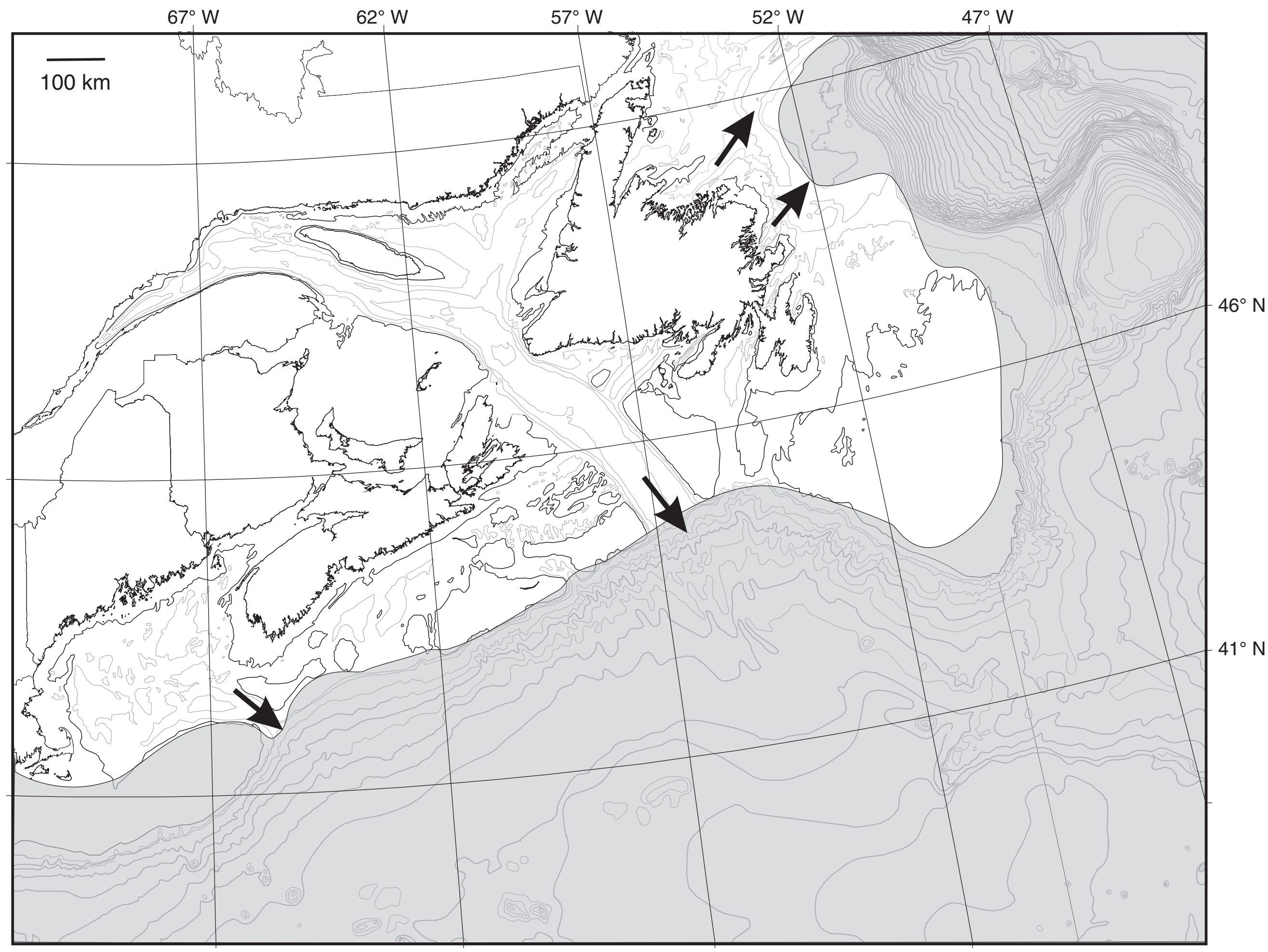

FIGURE 2. Maximum glacier extent during the Late Wisconsinan glaciation. Arrows show inferred locations of major ice streams.

Étendue maximale des glaces durant la glaciation du Wisconsinien tardif. Les flèches montrent l'emplacement des principaux courants glaciaires.

~45 m. Georges Bank was similarly reduced in extent with a maximum relief of ~17 m. The emergent areas around Prince Edward Island, the Magdalen Islands, and Cape Breton Island had reached their greatest areal extent. A wide peninsula extended northeast into the Gulf of St. Lawrence from western Prince Edward Island, and a similar peninsula extended from northeastern New Brunswick. In Newfoundland there were small areas of emergence in the St. George's Bay area. The northern tip of the Great Northern Peninsula remained submerged, except for a large island. The coastal fringe of the mainland (south Labrador and Québec) was also submerged.

Relative sea-level rise became pervasive after 9 ka BP in most southern areas. The islands on the continental shelves were greatly reduced in size by 8 ka BP and disappeared soon after. A major change took place *ca.* 6 ka BP when inundation of Northumberland Strait (Fig. 1) created modern Prince Edward Island. In Cape Breton Island (Fig. 1), the ocean flooded across a sill 25 m below modern sea level at *ca.* 6 ka BP, and created the Bras d'Or Lakes inland sea. As relative sea level rose, deltas at the heads of fjords in southwest, south, and east Newfoundland were submerged (Shaw and Forbes, 1995).

PRESERVATION OF GEOMORPHIC EVIDENCE

The geomorphic evidence of submerged terrain is grouped within three classes, namely fluvial systems (primarily river channels), deltas, and coastal systems (beaches, barriers, spits, etc.). Before describing some of the evidence, it is worthwhile considering the factors that ensure the creation and preservation of landscape elements. For fluvial systems, incision is most rapid when the eroded material is drift rather than resistant bedrock, so local conditions play a role. There are several requirements for the formation and preservation of (Gilbert-style) deltas, the most important of which is the existence of a sediment source. Shaw and Forbes (1995) demonstrated that at the heads of Newfoundland fjords, raised glaciomarine deltas were incised by streams to form lowstand deltas that were subsequently submerged; deltas did not form in fjords where raised glaciomarine deltas were absent.

Once the process of submergence begins, morphologic elements of all three classes are subject to wave and current action, and the scouring effects of sea ice. Coastal-evolution models for glaciated coasts catalog the modification of littoral

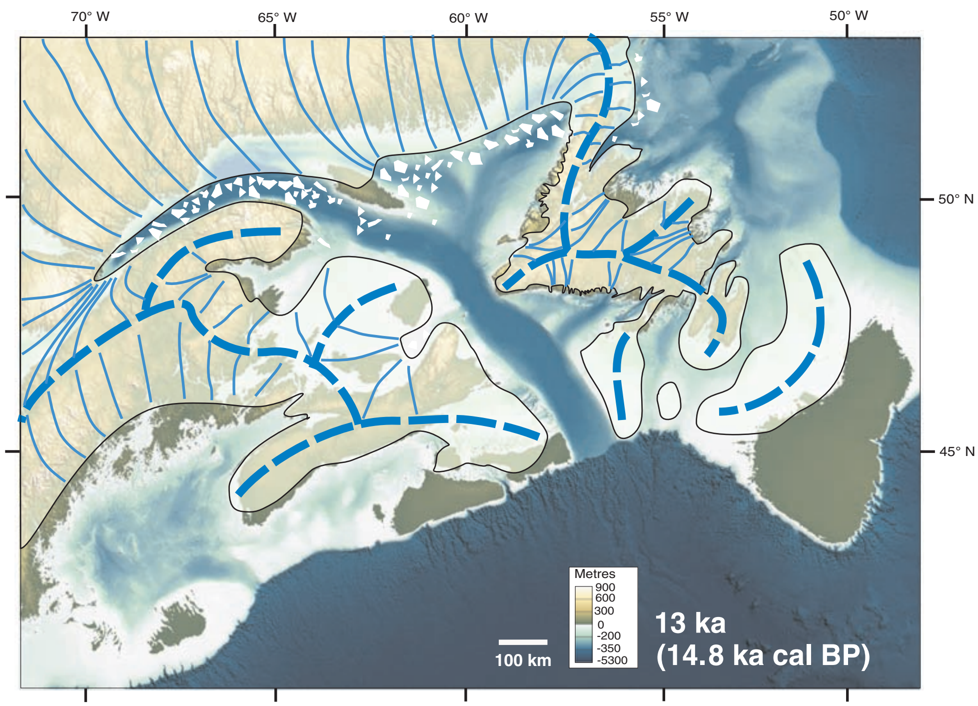

FIGURE 3. 13 ka BP paleogeography. Emergent areas are shown in green.

Paléogéographie de 13 000 ans. Les régions émergentes sont représentées en vert.

systems as sea level rises (Boyd *et al.*, 1987; Carter *et al.*, 1987), and emphasize the depletion of (glacial) sediment supplies and the migration and destruction of spits and barriers. The result is that the seaward remains of the migrating coastal systems comprise scattered drumlin 'scars' and sheets of transgressive sand and gravel. Analyses of cores through the latter sediments have revealed well-preserved estuarine deposits that, when dated, help define the relative sea-level history for the Atlantic coastal region near Halifax (Forbes *et al.*, 1991). Submerged erosional terraces have been mapped in Atlantic Canada, notably by Kranck (1972) who described five terrace levels in Northumberland Strait (Fig. 1).

With all three categories of geomorphic terrain (fluvial-channel, deltaic and marine systems), time is important. For fluvial systems, time is required for incision, so prolonged lowstands favour the formation of drainage networks. A sustained sea-level lowstand would also facilitate the formation of erosional terraces, large regressive coastal systems, and deltas.

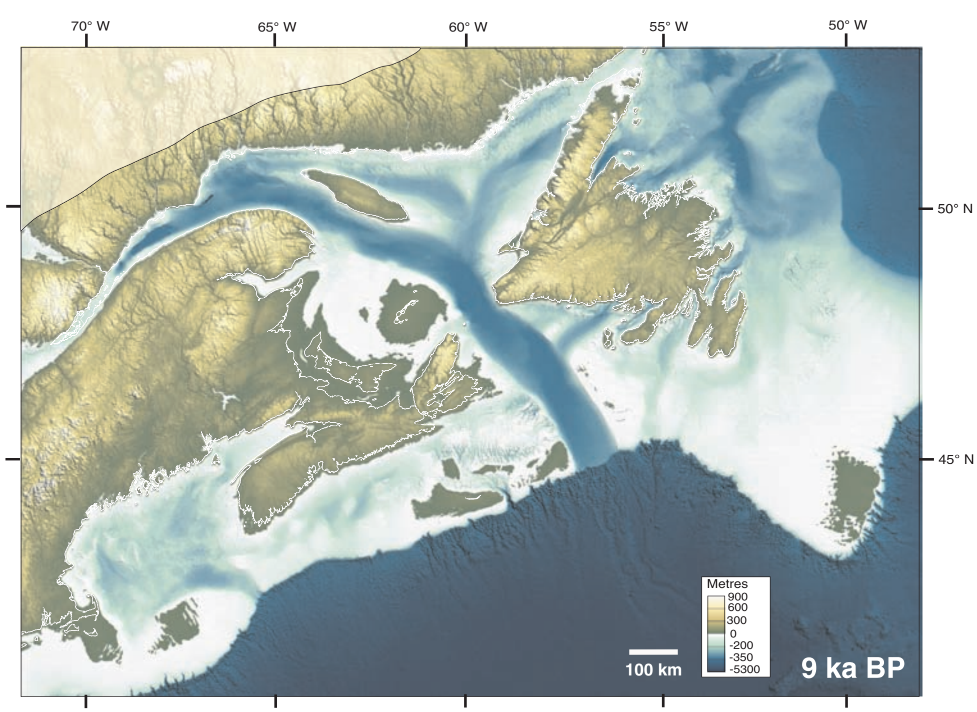

FIGURE 4. 9 ka BP paleogeography. White lines indicate modern coastlines.

Paléogéographie de 9000 ans. Les lignes blanches représentent les côtes contemporaines.

However, most sea-level curves in the region reveal a brief lowstand, between a fall and a subsequent rise. This pattern can be seen, for example, in the sea-level curve for St. George's Bay, Newfoundland (Bell *et al.*, 2003, this issue). Figure 5 shows shoreline positions for various times. The shorelines were constantly migrating, especially in the extensive emergent areas on the gently-sloping continental shelf. Even today in these areas the sea floor is affected by waves and tidal currents, and consists of sheets of mobile gravel and sand or large bedforms such as the barchan dune fields on Browns Bank (Todd, 2005). These mobile sediments obscure any underlying geomorphic evidence. In the following section the author will emphasize the special conditions that have facilitated the preservation of submerged geomorphic terrain.

SUBMERGED FLUVIAL SYSTEMS

Although fluvial landscapes probably existed in formerly emergent areas, most of the geomorphic evidence on the offshore banks has been destroyed by high wave energy during the postglacial transgression (Fader, 1989; King and Fader, 1986). Although only small parts of the offshore banks have been mapped with multibeam systems, evidence of fluvial activity is identifiable. For example, multibeam imagery of Georges Bank reveals complex networks of northward-draining fluvial channels (B.J. Todd, pers. comm., 2004). (The location of the bank is shown on Figure 1; the channels cannot be seen on this figure, which is based on a 1 km grid of bathymetric data). More evidence has been preserved close to modern coasts, although even in this setting the geomorphic evidence is often minimal. Thus, acoustic methods have been used to identify and retrieve datable evidence of submerged estuarine deposits off Nova Scotia (Forbes *et al.*, 1991).

Submerged features identified by multibeam sonar surveys includes early-Holocene incised and braided river channels in several parts of the Bras d'Or Lakes, on Cape Breton Island (Fig. 1), Nova Scotia. These lakes were freshwater until rising relative sea level flooded the -25 m sill and converted them into brackish arms of the ocean. Shaw *et al.* (2002b) thought this happened at 4-5 ka BP, but work in progress suggests that the marine incursion dates to *ca.* 6 ka BP. Locations of fluvial systems that were identified using multibeam sonars are shown on Figure 6.

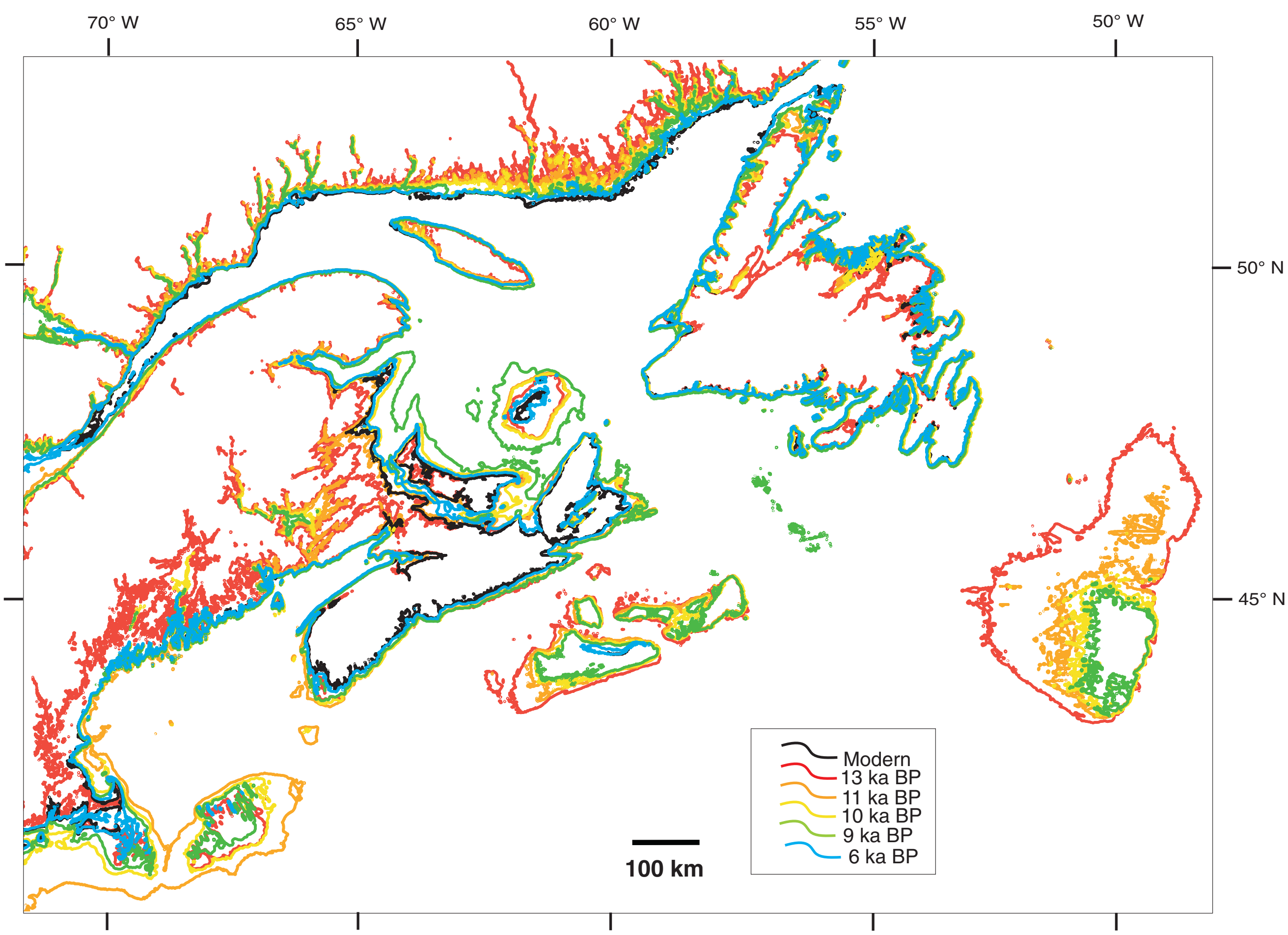

FIGURE 5. Shoreline positions in Atlantic Canada at 13, 11, 10, 9, and 6 ka BP.

Localisation des lignes de rivage au Canada atlantique il y a 13 000, 11 000, 10 000, 9000 et 6000 ans.

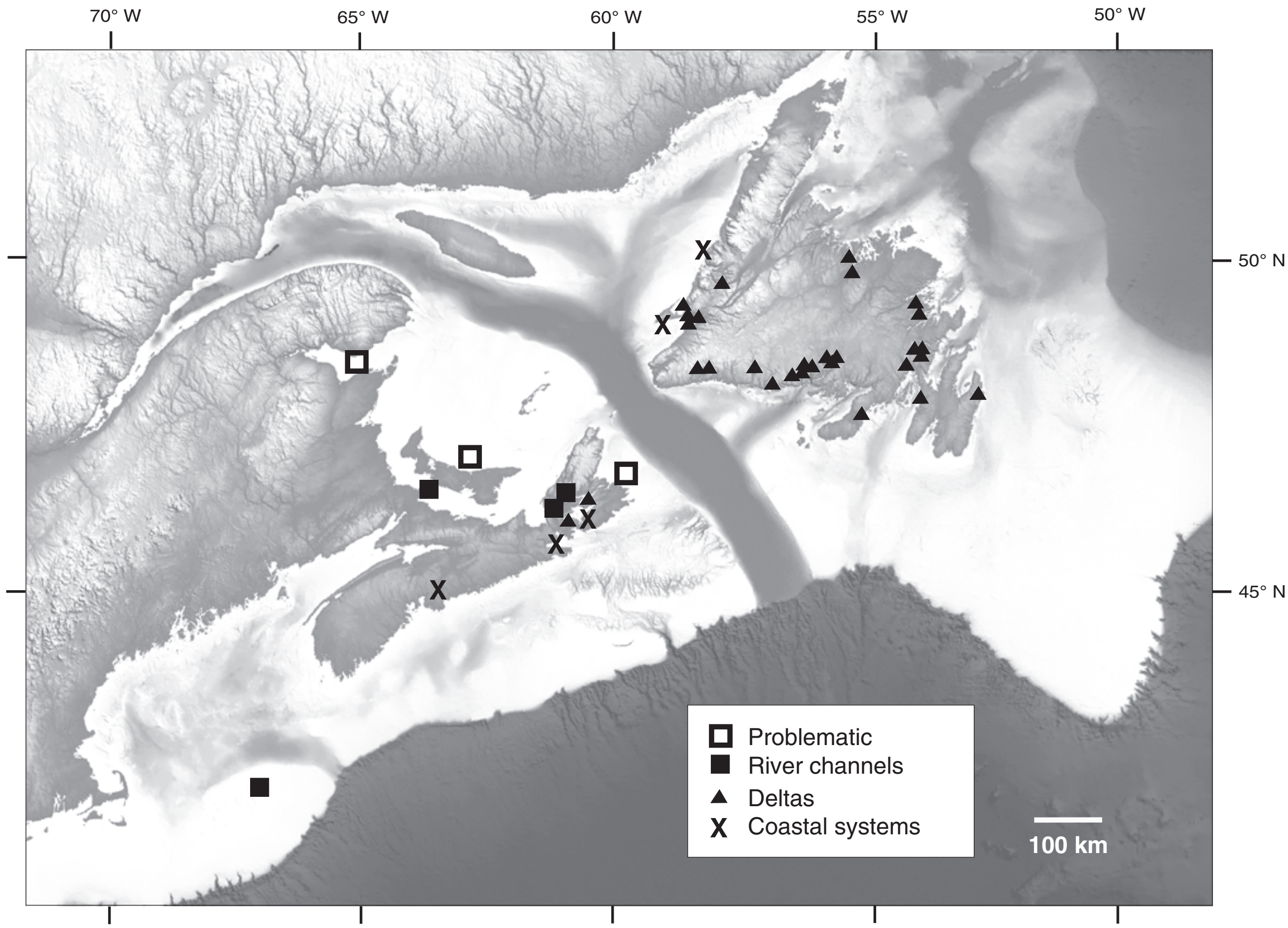

FIGURE 6. Map of submerged geomorphic features.

Carte des entités géomorphologiques submergées.

DISCRIMINATING BETWEEN FLUVIAL AND NON-FLUVIAL CHANNELS

Figure 6 also shows the locations of 'problematic' fluvial features, either erroneously identified as fluvial in origin, or that may have formed under glaciers. An example of the former from Chaleur Bay, Gulf of St. Lawrence, highlights the contribution to understanding that multibeam bathymetry mapping has made in recent years. Syvitski (1992) published sub-bottom profiler data showing channels incised into glaciomarine mud in the bay. They were either sediment-free, partly filled with acoustically transparent postglacial mud, or buried by the same material. The data strongly supported the contention that the channels had been formed by fluvial action during a sea-level lowering of ~90 m. However, Shaw *et al.* (2002a) noted that, when compiling relative sea-level data to create paleogeographic maps, this -90 m lowering appeared to be an outlier, and that geomorphic evidence supported a much shallower postglacial sea-level lowering. A multibeam sonar survey was undertaken to examine the supposed fluvial channels.

The imagery reveals that the sea floor is covered in parallel 'v'-shaped furrows up to 8 m deep and averaging 10 m wide (Fig. 7). These features are interpreted as having formed at the sole of relatively thin grounded ice that re-advanced down the bay towards the northeast, and have analogs in the Skaggerack, Norway (O. Longva, pers. comm., 2003). Other linear features observed on the image depicted in Figure 7, but not formed by extensive grounded ice, include iceberg furrows in parabolic patterns (A), iceberg furrows (B), and sedimentary furrows formed by modern currents (C and D).

DISCRIMINATING BETWEEN FLUVIAL AND SUB-ICE CHANNELS

Multibeam bathymetric surveys have yielded imagery of channels that may have formed beneath grounded glaciers. A good example is located offshore of Cape Breton Island (Fig. 1) where the sea floor consists of planated, folded Carboniferous rocks with a micro-relief of several metres between ridges and swales. Paleogeographic maps (Shaw *et al.*, 2002a) show relative sea level was low from at least 13 ka BP onwards; a wide part of the inner shelf around eastern Cape Breton Island was subaerially exposed. The extent of the exposed area was much smaller by *ca.* 6 ka BP.

The multibeam sonar imagery (Fig. 8) shows a series of channels incising bedrock ridges and extending to a depth of

~50 m, at which point they are obscured by overlying sediments (Shaw *et al.,* 2002b). The channels are not present close to the modern coast, do not align with any channels on land, and do not appear to be part of a dendritic network. They are interpreted as having formed under glacial ice. Further support for the presence of sub-glacial channels in this region comes from adjacent Bras d'Or Lakes. Channels in the lakes cut across contours, are in deep, enclosed basins, and are thus unlikely to have formed subaerially. Similar subglacial channels may occur off Prince Edward Island (McCulloch *et al.,* 2002).

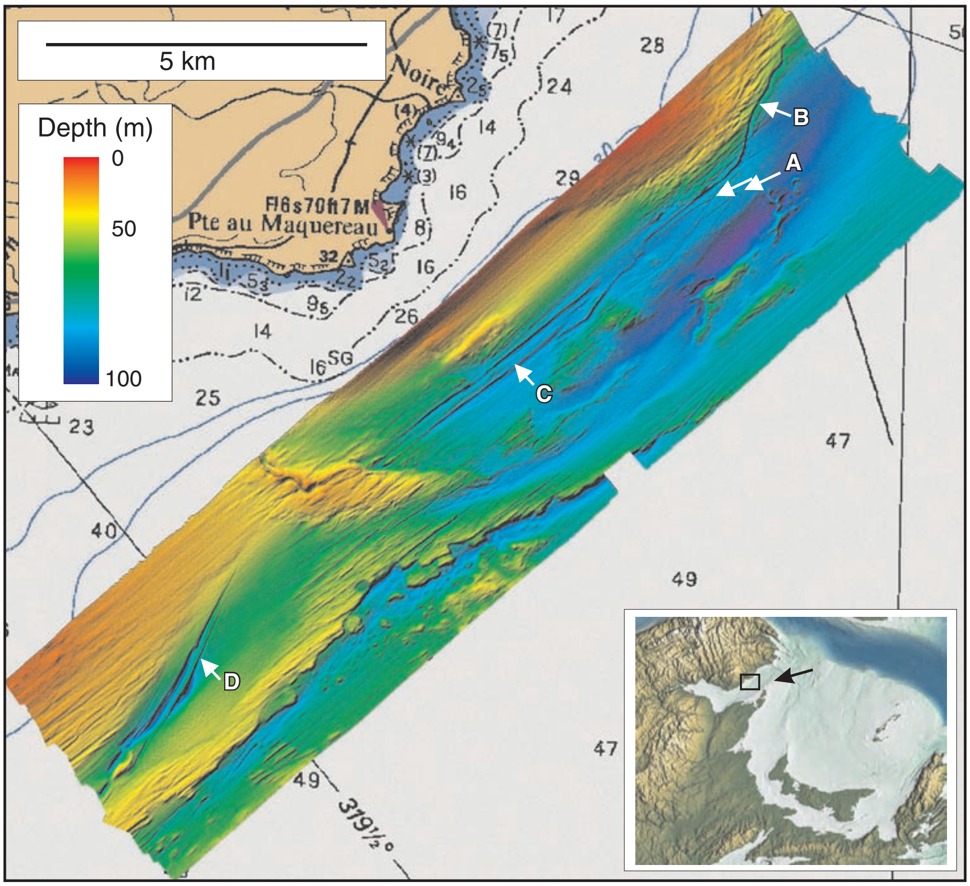

FIGURE 7. Furrows on the sea floor in Chaleur Bay. The main set of furrows developed beneath grounded ice that advanced down the bay, overriding glaciomarine sediments. Other linear features include iceberg furrows and sedimentary furrows. See text for interpretation of lettering.

Sillons dans le fond marin de la baie des Chaleurs. La partie principale des sillons s'est formée sous la glace échouée qui s'avançait dans la baie en chevauchant les sédiments glaciomarins. Parmi les autres entités linéaires, on observe des sillons d'icebergs et des sillons sédimentaires. Les lettres apparaissant sur la carte sont expliquées dans le texte.

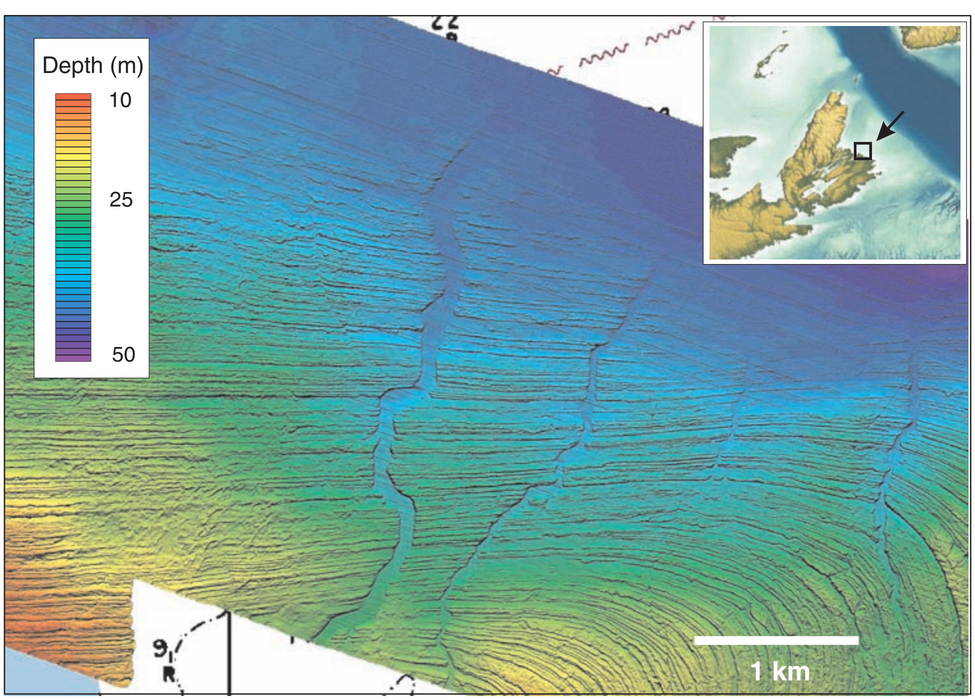

FIGURE 8. Channels off Cape Breton Island.

Chenaux au large de l'île du Cap-Breton.

WELL PRESERVED FLUVIAL SYSTEMS

A clear example of a submerged fluvial landscape comes from western Northumberland Strait (Fig. 1), which separates Prince Edward Island from the mainland. In this region relative sea level rapidly dropped from the early postglacial high stand, and fell below the modern level *ca*. 12 ka BP (McCulloch *et al*., 2002). Paleogeographic maps (Shaw *et al*., 2002a) show that Prince Edward Island was connected to the mainland by 10 ka BP, and that Northumberland Strait was subaerially exposed by that time. From the paleo-relief it can be inferred that a river system occupied the emerged area, with the principal river draining towards the east, fed by tributaries from both Prince Edward Island and the mainland. Kranck (1972) showed the various elements of such a drainage system. The maximum emergence in the region occurred at 9 ka BP, when the river mouth was probably located offshore from the modern coast of Cape Breton Island (Fig. 1).

The multibeam imagery (Fig. 9) shows a major stream draining eastwards, fed by tributaries draining from both north and south. The terrain was irregular, with numerous closed basins, so that many small lakes existed, in addition to those connected by the principal river. The configuration of this drainage network agrees well with the network proposed by Kranck (1972), although the multibeam imagery shows the drainage divide farther west than on her map. The preservation of the drainage system, despite strong currents (Fader and Pecore, 1989) and impact by sea-ice pressure-ridge keels, is probably because the valleys are incised into Upper Carboniferous to Permian bedrock. Kranck (1972) discussed the age of the Northumberland Strait channel system, and decided that it was in part 'pre-Wisconsin' in age, probably post-Tertiary, and had a 'multiple age'.

River channels are also found to a depth of 50 m off the mouth of the Codroy River, in southwestern Newfoundland (Fig. 1) and in the Bras d'Or Lakes, Cape Breton Island (Fig. 1) which contain some of the best preserved terrestrial landscapes of all three types described here. The lakes were freshwater for more than 5000 years, in which time river valleys, deltas, and coastal systems were formed. The relatively small fetches, and hence small depths to wave base, combined with the rapid onset of transgression, facilitated preservation. (Based on a new sea-level curve in preparation, it is estimated that just before 6000 BP the lakes were instantly exposed to a rate of sea-level rise of >70 cm/century).

A river system was present in what is now St. Patrick's Channel (Fig. 10). A former meandering channel occurs in the west of the figure, below a blanket of postglacial mud. Analyses of sediment cores in this area reveal beds of freshwater peat

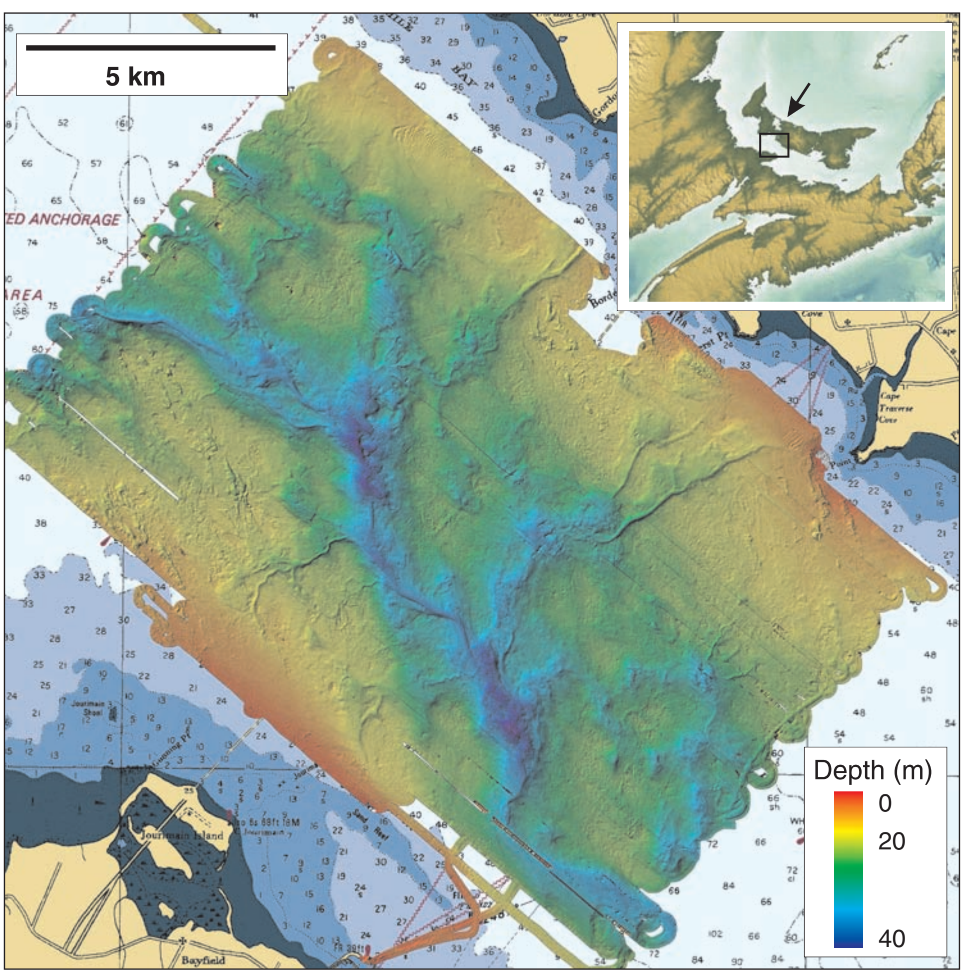

FIGURE 9. Submerged fluvial channels in Northumberland Strait, between Prince Edward Island (top right) and New Brunswick (bottom left). Inset shows location.

Chenaux fluviaux submergés dans le détroit de Northumberland entre l'île du Prince-Édouard (en haut à droite) et le Nouveau-Brunswick (en bas à gauche). L'encadré montre la localisation.

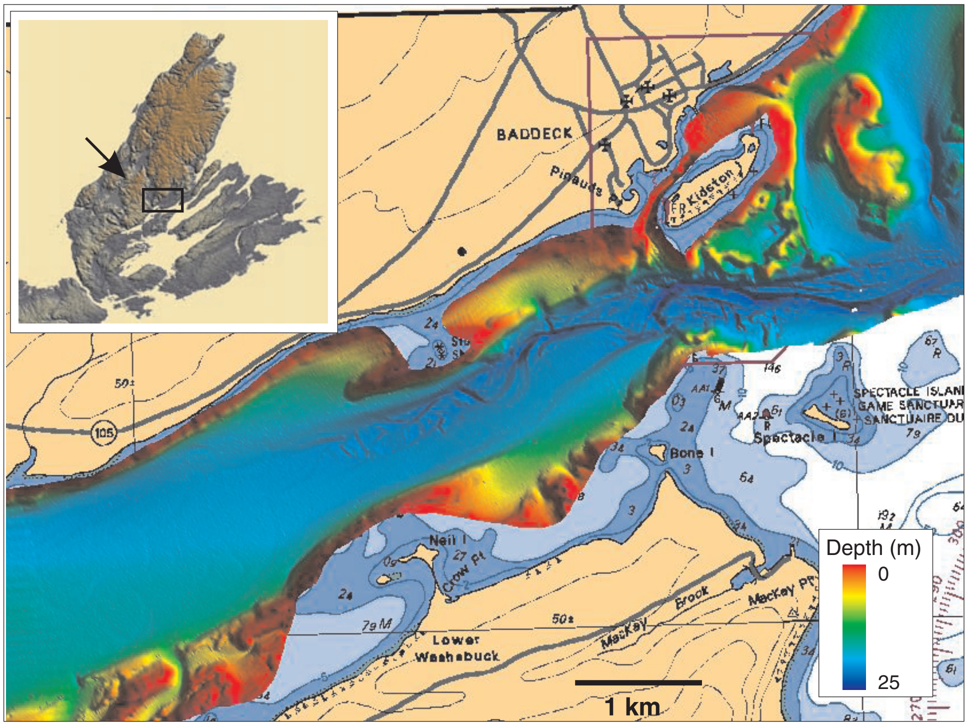

FIGURE 10. Fluvial channels in the Baddeck area, Bras d'Or Lakes, Nova Scotia. Inset shows location.

Chenaux fluviaux dans la région de Baddeck, aux lacs Bras d'Or (Nouvelle-Écosse). L'encadré montre la localisation.

and macrofossils indicative of poorly-drained, swampy environments. The channel becomes confined between bluffs in the Baddeck area, where the channel floor shows well-preserved gravel bars. A few kilometres east of the image the channel system terminated in a delta graded to the -25 m former lake level. A similar channel system in Denys Basin, a shallow arm of the lake south of Grand Narrows, also terminates in a wide, flat delta.

SUBMERGED DELTAS

The preservation of deltas has occurred mainly in locations sheltered from wave action, primarily the fjords of southwest and south Newfoundland. The primary factor determining the presence of submerged deltas is sediment supply. Shaw and Forbes (1995) described the process whereby, in the early postglacial period, streams incised glacial deltas and outwash deposits at fiord heads, creating Gilbert-style deltas at depths accordant with the local postglacial lowstand depth. Fjords without glacial deposits at their heads lacked the sediment supply to form low stand deltas. As shown in Figure 6, the known deltas are distributed around the Newfoundland coasts, except where relative sea level never dropped below the modern level. The submerged deltas in St. George's Bay, western Newfoundland (Fig. 1; Shaw and Forbes, 1995; Shaw and Courtney, 1997) and nearby Port au Port Bay (Fig. 1; Forbes *et al.*, 1993) formed in sheltered bodies of water barely connected to the ocean during the postglacial low stand. Some of those in St. George's Bay do not appear on multibeam imagery because they have been enveloped in late Holocene barrier-platform deposits (Shaw and Forbes, 1995).

Figure 11 shows a submerged delta (A) at the head of Bay of Exploits, on the south coast of the island. This delta is graded to a former sea level of -16 m and has been radiocarbon dated (foreset beds) to *ca.* 8.5 ka BP (Shaw and Forbes, 1995). Geophysical data indicate that the submerged terrace (B) at the west side of the bay is an erosional feature, cut into glaciomarine sediments and at the same elevation as the -16 m postglacial sea-level lowstand.

Other deltas occur in former lakes, now marine. For example, unpublished multibeam imagery shows a large delta in St. John's Harbour, Newfoundland, graded to -14, the depth of the sill at the harbour mouth. As noted above, large deltas occur in the Bras d'Or Lakes, Nova Scotia, graded to the early Holocene lake level of -25 m and connected to the stream systems also visible on multibeam imagery.

SUBMERGED COASTLINES

As noted above, the very high rates of mid-Holocene coastal change that pertained in the mid-Holocene in particular (Shaw *et al.*, 1993) do not appear suitable to generating or preserving large coastal systems. Nevertheless, in some settings, ancient coastal systems have been well preserved. The most favourable setting appears to be in coastal embayments that existed as lakes in the early Holocene, and that were flooded by the Holocene transgression. The example of the Bras d'Or Lakes, already mentioned with respect to fluvial systems and deltas, is highly instructive. Multibeam imagery and seismic data reveal that the southern lake contains fields of drumlins that provided sediment to form lacustrine coastal systems (unlike the ocean coasts, there were no tides, so the back-barrier lagoons were not infilled by estuarine sediments). Multibeam imagery (Fig. 12) clearly reveals spits, barrier beaches and lagoons that have analogs on the modern lake coasts. The features identified in Figure 12 have

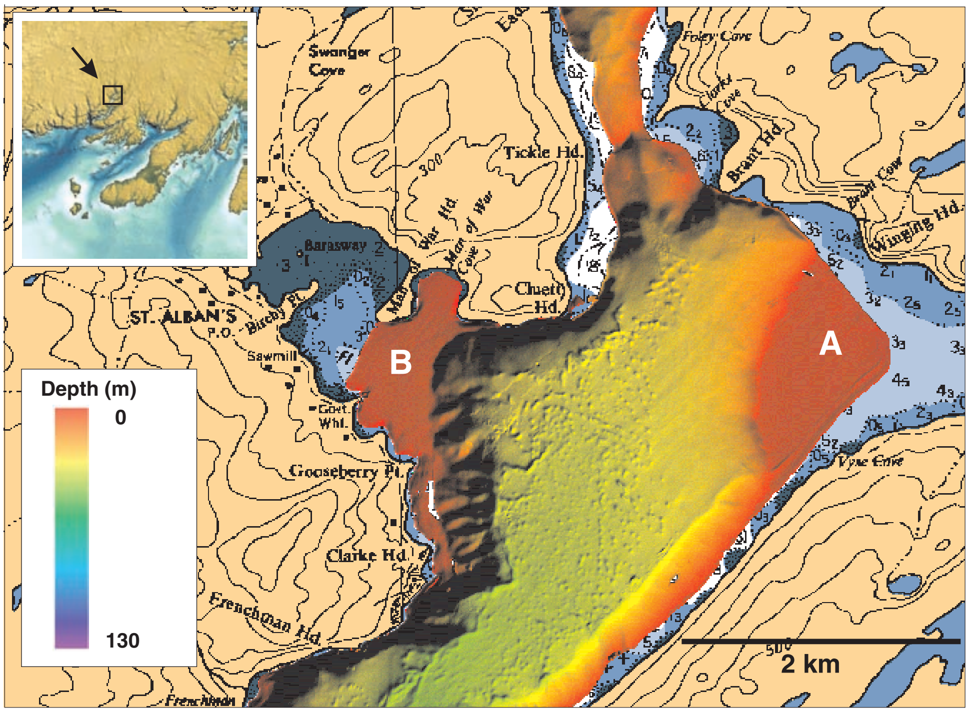

FIGURE 11. Submerged delta in Bay d'Espoir, Newfoundland (A). The terrace at B is interpreted as an erosional feature cut into glaciomarine sediments. Inset shows location.

Delta submergé de la baie d'Espoir à Terre-Neuve (A). La terrasse en B serait une entité d'érosion découpée dans les sédiments glaciomarins. L'encadré montre la localisation.

high backscatter and are composed of fine to medium gravel. The preservation of these coastal features is attributed to: (1) the almost immediate onset of transgression, so that the lake was subject to the high rate of sea-level rise in the adjacent ocean (see Shaw *et al.,* 1993); and (2) the relatively restricted fetch in the lakes. (The rate of sea-level rise at the onset of the transgression in the Bras d'Or Lakes was about 79 cm/century; the modern rate of sea-level rise in the region is 37 cm/century).

DISCUSSION

Emery and Uchupi (1972: p. 56) noted, many years before the advent of multibeam sonar systems, that "a general law can be formulated which states that contours on charts are more irregular and complex in direct proportion to the density of soundings". This has been the case in Atlantic Canada and, despite the limited area of coverage, the high-resolution multibeam sonar imagery of the sea floor has revealed great complexity and provided great insights in the Quaternary geology of the region.

DOES THE GEOMORPHIC EVIDENCE SUPPORT THE MODEL?

The imagery examined so far tends to support the paleogeographic maps contained in Shaw *et al.* (2002a), maps that were largely created using independent evidence (empirical sea-level curves). It is evident, however, that landscapes have been heavily modified during the postglacial transgression, or that channel systems are buried beneath sediment, so that well-preserved fluvial systems are rather rarely observed on multibeam imagery. With regard to submerged deltas, most examples observed on multibeam data were created and preserved in rather special settings, either in Newfoundland fjords or in coastal basins that were formerly freshwater. Coastal systems, as is known from modern process research, tend to migrate during a transgression, leaving little geomorphic evidence on multibeam sonar imagery. Again, unique conditions favor their preservation, namely low wave energy and the rapid onset of marine transgression in former lakes.

RESEARCH APPLICATIONS

At a time when research activities of the Geological Survey of Canada are tuned to societal needs, it is pertinent to note that the changes of geography described here are increasingly of interest outside the narrow field of Quaternary geology. One important area of interest is in archaeology, and a good example concerns the controversial view held by some, *e.g.* Bradley and Stanford (2004), that the earliest peopling of North America may have been from south-western Europe during the last glacial maximum. Atlantic Canada lay on the presumed migration route. The paleogeography of the region described by Shaw *et al.* (2002, 2006), and supported by data in this paper, is highly relevant. For example, Bradley and Stanford's figure 4 shows ice sheets confined to coastal Newfoundland and southwestern Nova Scotia at LGM, with the continental shelf outside this limit entirely emergent. This depiction can be contrasted with our Figure 2. On the other hand, any migrations at later dates would have encountered the geographies depicted in our Figure 3 (13 ka BP) and Figure 4 (9 ka BP).

The Bras d'Or Lakes featured largely in this paper, mainly because they contain well-preserved submerged river channels, deltas and coastal systems. It can be argued that part of

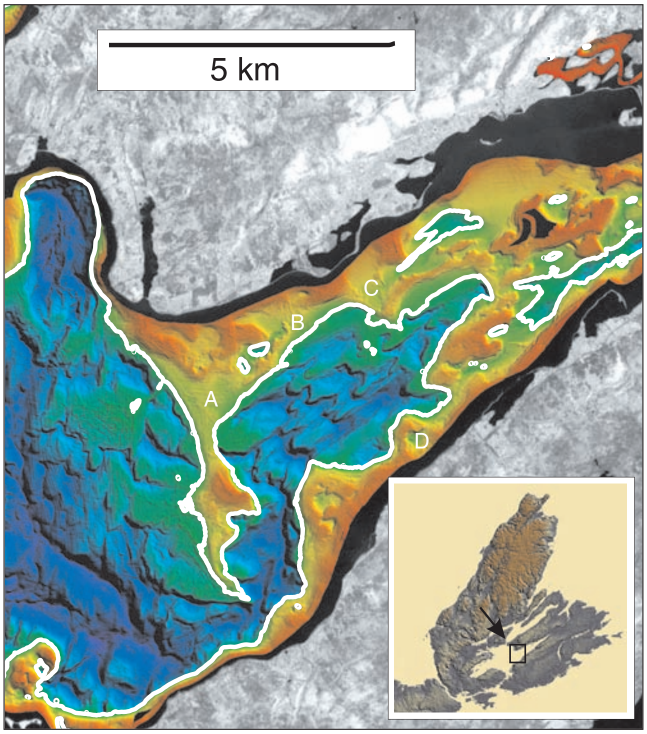

FIGURE 12. Multibeam imagery of the Bras d'Or Lakes, Nova Scotia, an inland sea that was inundated by the ocean *ca.* 6 ka BP. The main shoreline in the southern lake was ~-24 m (white line). Coastal features that have been preserved during the transgression include a tombolo (A), spits (B), a barrier beach (C), and spit-lagoon complexes (D). The drumlins (E) lie below the -25 m early-Holocene lake level. The histogram of bathymetry (insert, bottom right) shows a primary peak at -22 m and a secondary peak at -25 m, the main lowstand depth for the lakes.

Imagerie multifaisceaux des lacs Bras d'Or (Nouvelle-Écosse), une mer intérieure envahie par l'océan il y a 6000 ans. La ligne de rivage principale du lac méridional se situait à environ -24 m (ligne blanche). Parmi les entités côtières qui ont été conservées pendant la transgression, on remarque un tombolo (A), des épis (B), un cordon littoral (C) et des complexes d'épis et de lagunes (D). Les drumlins (E) se situent à -25 m, le niveau du lac à l'Holocène précoce.

the missing archaeological record of human occupation during the Archaic Period in Nova Scotia (9000 to 2500 years ago) might be found on the submerged coastlines in this area. Ultimately it is to be hoped that archaeological hypotheses and problems can be tested and resolved through improved access to paleogeographic reconstructions.

A second area of interest is biological. Resolving the question of the postglacial immigration routes of freshwater and marine fish, for example, depends on understanding paleogeography (Verspoor *et al.,* 2005). With the advent of DNA analysis, biologists are interested in determining how paleogeography influenced the development of genetically distinct populations. An instructive example concerns the possibility that the Flemish Cap (Shaw, 2005) provided a glacial refugium for Atlantic cod (*Gadus morhua)*. de Cárdenas (2004) indicated that there is a separated cod population on Flemish Cap, without connections with neighboring cod populations. Similarly, analyses of whole-mitochondrial-geonome DNA sequences have led Marshall *et al.* (2004) to state that the Flemish Cap cod population is distinct, that the fish had persisted independently for a long time, and that Flemish Cap may have been a refugium during the last ice age.

In phase I of the deglacial history, when glacier ice lay on the Grand Banks of Newfoundland, the Flemish Cap seamount was ice-free and not subaerially exposed (Shaw, in press). Based on the ICE-5G (Peltier, 2004) relative sea-level history, the maximum lowering of relative sea level was -115.8 m at 20 ka BP. The shallowest part of Flemish Cap (-126 m today) was thus ~10 m below sea level. Relative sea level was rising slowly at 13 ka BP, when the shallowest part was at an approximate depth of 16 m, and was rising rapidly at 10 ka BP when the shallowest part lay at a depth of 50 m. So, Flemish Cap was submerged (and ice free) from LGM onwards, thereby providing one of the few locations in Atlantic Canada where Atlantic Cod may have persisted, and facilitating the development of a genetically distinct population.

CONCLUSIONS

1- The evolution of geography since LGM in Atlantic Canada is divided into three phases: (1) an early phase during which ice was retreating on the continental shelves through deep-water calving; (2) a second phase during which the ice lay near modern coasts, and was retreating inland by melting; (3) a third phase during which glaciers were mostly absent in Atlantic Canada. Complex relative sea-level changes due to isostatic and eustatic processes were occurring during all three phases, but in the third phase, large-scale changes in geography were primarily driven by relative sea-level changes alone.

2- The geomorphic evidence for terrestrial environments that were submerged in the third phase includes relict fluvial features, deltas, and coastlines. The available evidence agrees with the paleogeographic reconstructions of Shaw *et al*. (2000).

3- The rapidity of sea-level change, high wave and current levels in exposed areas, and the brevity of lowstands, tended to reduce the probability that terrestrial landscapes would be preserved during the postglacial transgression.

4- The preservation of terrestrial landscapes is dependent on special conditions, including those pertaining in the Newfoundland fjords (preserved deltas) and in former lakes that are now marine, particularly the Bras d'Or Lakes (fluvial features, deltas and coastlines).

5- Results of paleogeographic research in Atlantic Canada have applicability in several fields, including archaeology and evolutionary biology.

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