



Deglaciation of Anticosti Island (eastern Canada) and its implications on climate-driven dynamics of the Laurentide Ice Sheet margin[☆]

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ABSTRACT

Reconstructing the dynamical retreat pattern of former ice margins is essential to better understand the long-term evolution of ice-sheets and their sensitivity to climate change. Here we present a geomorphological map of ice-marginal landforms from Anticosti Island together with 31 cosmogenic nuclide surface exposure and 24 radiocarbon ages, that suggest close ties between regional deglaciation patterns and climate. These results reveal that the Laurentide Ice Sheet stabilized on Anticosti Island between ~15.5 and ~14.4 ka, before subsequently resuming its retreat toward the Québec North Shore and into the Gulf of St. Lawrence. Moraine ages highlight a strong sensitivity of the LIS to temperature changes in the Northern Hemisphere, as the documented ice-margin stabilizations coincide with the end of Heinrich Stadial 1, a period after the Last Glacial Maximum characterized by cold winters but warming summers. In turn, ice sheet recession in the area coincided with the onset of the Bølling-Allerød (~14.6 ka), marked by relatively warmer atmosphere temperature year-round across the Northern Hemisphere. These results provide evidence for the synchronicity of the ice margin along the south-eastern Laurentide Ice Sheet in response to abrupt cold periods and allow further discussion of the regional implications for deglaciation of the Laurentian Channel in the context of a large calving bay formation in the former Gulf of St. Lawrence.

1. Introduction

The former ice sheets that once covered the Northern Hemisphere played an undeniable role on global climate change and landscape evolution (e.g., Alley and Clark, 1999; Clark et al., 2001; Denton et al., 2022). Their growth and disintegration since their maximum extension around 24 000 years ago have been closely linked to changes in atmospheric/oceanic circulation and global sea-level fluctuations (Alley and Clark, 1999; Clark et al., 2000; Carlson et al., 2008; Briner et al., 2020; Toucanne et al., 2026). The maximum extent of the Laurentide Ice Sheet (LIS) in Atlantic Canada during the Last Glacial Maximum (LGM) has long been debated (e.g., Coleman, 1920; Flint, 1943; Prest and Grant, 1969; Ives, 1978; Piper and Macdonald, 2001; Olejczyk and Gray, 2007). Although it is accepted that ice reached its maximal position near the continental shelf edge (Shaw et al., 2006; Roger et al., 2013; Dalton

et al., 2020, 2023), the details and chronology of the deglaciation that followed the LGM remain unclear and poorly documented in the Gulf of St. Lawrence (Josenhans and Lehman, 1999; Rémillard et al., 2016). This lack of detail is particularly relevant considering the presence of regional ice caps, such as the Appalachian Glacier Complex, which must have coalesced with the LIS that flowed into the southern Gulf of St. Lawrence via the Laurentian Channel (Stea et al., 1998, 2011; Shaw et al., 2006). These retreat patterns are even more difficult to determine when deglaciation occurs in a marine environment, where (1) the behaviour of the ice margin is subject to instabilities due to various rates of iceberg calving, changes in the subglacial topography, ocean temperature and the presence or absence of a floating ice shelf (e.g., Jamieson et al., 2014; Carr et al., 2015) and (2) the difficulties of acquiring geochronological data complicate the establishment of a reliable chronology.

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Episodes of ice-margin stabilization and re-advance punctuating the general retreat of ice sheets are recorded by moraine systems that, in many cases, extend laterally over several hundred kilometers (e.g., Dubois and Dionne, 1985; Occhietti et al., 2011; Lajeunesse et al., 2019; Couette et al., 2023). These episodes left their imprints both on land and offshore, providing key geomorphological markers for reconstructing ice margins across the successive stages of deglaciation. Reconstructing and dating the evolution of former ice margin positions at the transition between marine and terrestrial environments is therefore essential to: (1) better understand the long-term history of ice-sheet evolution and their sensitivity to climate change; (2) identify ice-margin instabilities, reflected by episodes of readvances and/or rapid retreat; and (3) document the genesis of landforms left by the retreating ice sheet, both on the continent and on islands, which provide key information about

the intermediate stages of deglaciation in eastern Canada.

Located at the confluence of ice flows from the Québec North Shore, the Laurentian Channel and Newfoundland (Stea et al., 1998; Shaw et al., 2006), Anticosti Island occupies a strategic position in the center of the Gulf of St. Lawrence as it is a pivotal area for reconstructing the deglaciation of the continental shelf of eastern Canada. Due to the remote location of the island and its limited access, its glacial history is mainly based on a few studies carried out in recent decades and concentrated in its western and northern sectors (Gratton et al., 1984; Painchaud et al., 1984; St-Pierre et al., 1987; Goslin et al., 2023). These studies relied mostly on a radiocarbon-based chronology near the coastline, and below the marine limit, which relies on the availability of shells and organic materials and provides only a minimum age to constrain deglaciation. The development of cosmogenic nuclide dating

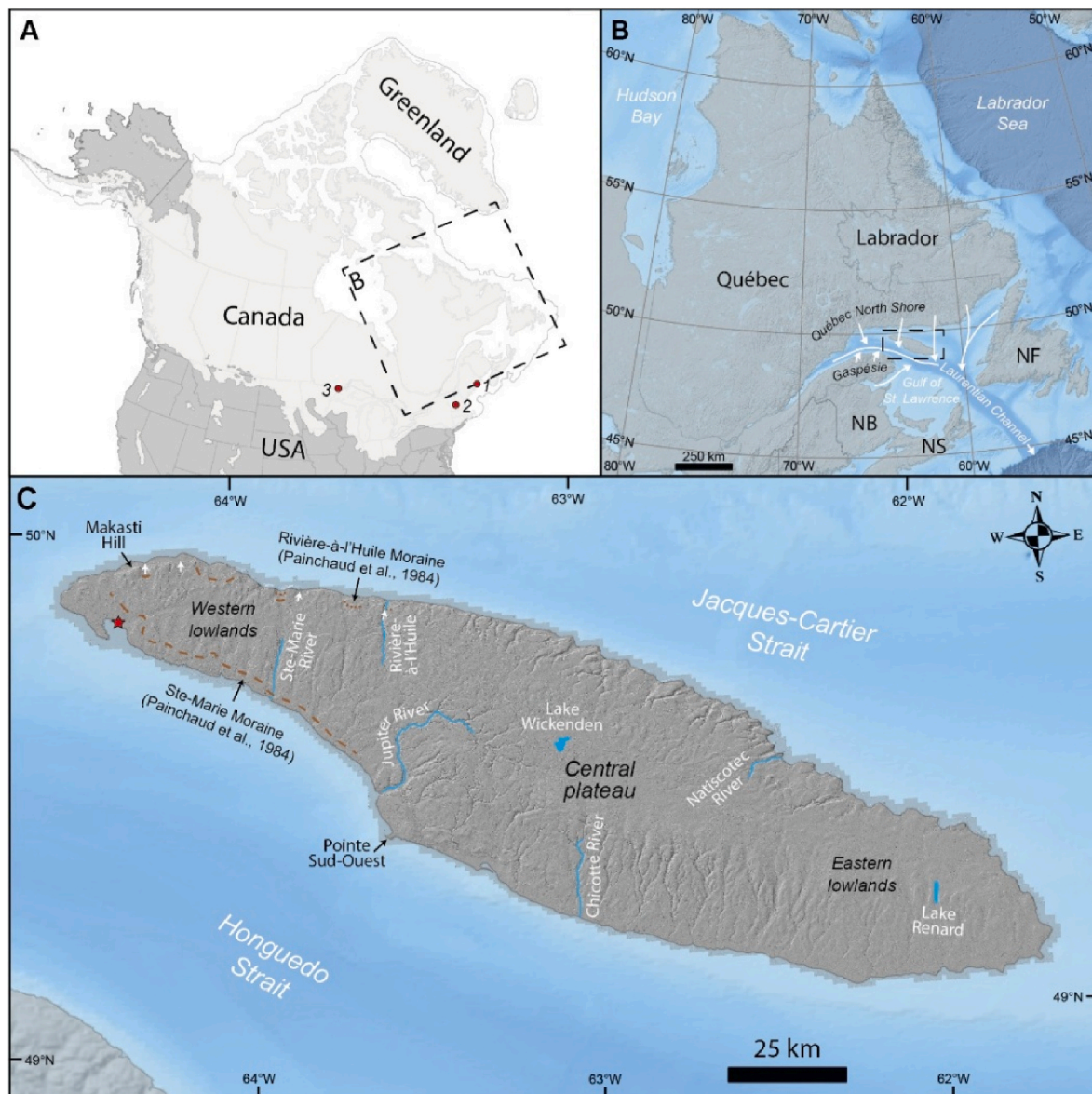


Fig. 1. Location of the study area. A) Extent of the ice cover in North America during the Last Glacial Maximum, modified from Dalton et al. (2020). Numbers refer to the location of studies cited in this paper: (1) Pineo Ridge moraine complex (Hall et al., 2017; Koester et al., 2017), (2) North Charlestown Moraine (Balco et al., 2009; Ridge et al., 2012), and (3) Eagle-Finlayson Moraine (Lowell et al., 2021). B) Location of Anticosti Island within eastern Canada. NL: Newfoundland; NS: Nova Scotia; NB: New Brunswick. White arrows represent generalized ice flow directions associated with a St. Lawrence Ice Stream in the Laurentian Channel (modified from Shaw et al., 2006; Eyles and Putkinen, 2014). C) Anticosti Island and the location of elements discussed in the text. The dashed line represents the Sainte-Marie Moraine and dotted line represents the Rivière-à-l'Huile Moraine, according to Painchaud et al. (1984). White arrows indicate the location and flow direction of the glaciofluvial outwash deposits (Painchaud et al., 1984). The red star represents the village of Port-Menier. Bathymetry data and digital elevation model are from the GEBCO grid (gebco.net). High-resolution LiDAR-derived DEM of Anticosti Island is from the Government of Québec (foretouverte.gouv.qc.ca).

methods enabling direct dating of glacial deposits has clarified the timing of deglaciation in several areas of North America (e.g., Marsella et al., 2000; Briner et al., 2005, 2007; Balco et al., 2009; Bromley et al., 2015; Davis et al., 2015; Ullman et al., 2016; Margreth et al., 2017; Lowell et al., 2021; Young et al., 2021; Couette et al., 2023; Hall et al., 2025). Additionally, the recent availability of 1-m resolution Digital Elevation Models (DEMs) derived from LiDAR data in southern Québec has allowed for the identification of new glacial landforms necessary for paleogeographical reconstructions of deglaciation (Dietrich et al., 2017, 2020; Nutz et al., 2020; Trottier et al., 2021; Héту et al., 2023). The integration of these chronological data and geomorphological mapping provide a framework to refine our understanding of deglaciation patterns and late Quaternary evolution of Anticosti Island and its adjacent areas.

In this paper, we report on the deglaciation history of Anticosti Island by using geomorphological mapping, cosmogenic ^{10}Be and ^{36}Cl exposure dating of boulders and glacially-inherited surfaces, as well as radiocarbon dating of organic samples. More specifically, this paper aims to (1) constrain the position of the ice margin during its overall retreat; (2) define the dynamical behaviour of the LIS and Anticosti Ice Cap in order to identify time intervals of important changes; and (3) identify the potential controls for ice margin stabilization and their implications in the regional climate system to provide a revised deglacial chronological framework for Anticosti Island and, by extension, for the Gulf of St. Lawrence.

2. Regional setting

Anticosti Island covers an area of approximately 8000 km² (240 km-long and 60 km-wide) and is located in the Gulf of St. Lawrence, eastern Canada (Fig. 1). It belongs to the St. Lawrence Lowlands geological province, bordered to the north by the Canadian Shield and to the south by the Appalachian Mountains (Pétryk, 1981). Anticosti Island is formed by a series of cuestas composed of carbonate rocks of Upper Ordovician to Lower Silurian age (Copper and Long, 1989; Desrochers and Gauthier, 2009). These structures are gently inclined to the south-southwest, exhibit only minor deformations (Copper and Long, 1989), and extend laterally on the Gulf of St. Lawrence seafloor (Lajeunesse et al., 2019). The bedrock is marked by a network of diaclasses dominated by north-south and east-west axes (Bordet et al., 2010). The island is characterized by a low-relief and incised central plateau (200–300 m above sea level, masl) flanked by lowland plains (<150 masl) at the western and eastern extremities.

Surficial materials on Anticosti Island are scarce and generally consist of thin (<1m) discontinuous till (Dubois et al., 1990). Nonetheless, two moraine systems have been previously identified and described in the literature: the Sainte-Marie and Rivière-à-l'Huile moraines (Fig. 1c). Painchaud et al. (1984) were the first to recognize and map the extent of the Sainte-Marie Moraine between Jupiter River and Makasti Hill, in the southwestern part of the island, indicating a southwesterly and southerly ice flow (Painchaud et al., 1984; St-Pierre et al., 1987). In most of these valleys, series of 5–20 individual De Geer moraines were identified directly beyond the Sainte-Marie Moraine (Painchaud et al., 1984). In the northwestern part of the island, small discontinuous ridges and fluvio-glacial outwash were associated to the Sainte-Marie Moraine, suggesting a predominantly northward flow (Painchaud et al., 1984). In turn, a series of small and discontinuous ridges located at the mouth of several valleys –north of the Sainte-Marie Moraine– were associated to the Rivière-à-l'Huile Moraine (Painchaud et al., 1984). This moraine lies, for the most part, below the marine limit and is buried underneath glaciomarine and coastal deposits (Dubois et al., 1990). Analysis of LiDAR data has recently revealed a series of elongated ridges in the south-central region of the island and were interpreted as ice stream lateral moraines (Héту et al., 2023).

Early workers proposed that Anticosti Island was covered by the LIS during the late Wisconsinan glaciation (Coleman, 1920; Bolton and Lee,

1960). Till fabric analyses indicate a predominant southwesterly ice flow across the entire island, consistent with the orientation of measured glacial erosion marks (St-Pierre et al., 1987). This ice flow is also confirmed by the presence of rock drumlins and megagrooves, interpreted as the onset zone of the Laurentian Channel Ice Stream (Eyles and Putkinen, 2014). The Sainte-Marie Moraine was associated –based on flow indicators and the geochemistry of tills suggesting a local origin– with a readvance of a residual ice mass ~14.5 cal ka BP, which was abandoned following the retreat of the LIS (Gratton et al., 1984; Painchaud et al., 1984). More recently, work focusing on paleo-beach ridges has demonstrated that the northern shore was likely deglaciated by ~14.5 cal ka BP, according to radiocarbon dating of the marine limit in the Rivière-à-l'Huile and Naticotec River sectors (Goslin et al., 2023). Based on sediment supply rates, they also suggested that a local ice cap remained anchored on the central plateau of Anticosti Island for nearly a millennial following the retreat of the LIS. In turn, radiocarbon dating from marine cores suggest deglaciation of the Jacques-Cartier Strait, northeast of Anticosti Island, as early as 15.8 ± 0.4 cal ka BP (Josenhans and Lehman, 1999), potentially supporting the isolation of an ice cap on the island. Héту et al. (2023) associated the series of ice stream lateral moraines with a readvance of fast-flowing ice streams from this local ice cap. They also observed glaciotectionic deformations on the central plateau suggesting ice flows towards the north and northeast, as well as a southwesterly flow suggesting an ice divide on the high central plateau of Anticosti Island. Their work, however, did not allow establishing a connection between these ice flows and the glacial re-advance at the origin of the Sainte-Marie Moraine. Finally, radiocarbon ages obtained continuously on a beach ridge complex near Rivière-à-l'Huile, from the marine limit (14.5 ± 0.3 cal ka BP) to the current coastline (8.3 ± 0.2 cal ka BP), confirm the problem raised by Painchaud et al. (1984) concerning an age of 10.5 cal ka BP previously obtained from a shell embedded within the Rivière-à-l'Huile Moraine (Goslin et al., 2023).

3. Material and methods

3.1. Field mapping and sampling

Ice marginal landforms were mapped to spatially constrain the ice retreat pattern across Anticosti Island during deglaciation. Our mapping builds upon previous investigations and compilation across the study area (Painchaud et al., 1984; St-Pierre et al., 1987; Dubois et al., 1990; Héту et al., 2023). High-resolution LiDAR-derived DEM (1-m) from the Government of Québec (foretouverte.gouv.qc.ca) allowed refining and extending previous maps of glacial deposits. The dataset was first visualized in the ESRI ArcGIS Pro software for geomorphological mapping and interpretation, using a hillshaded DEM with an altitude of 045° and azimuth of N315°. Mapping of surficial units was completed during field campaigns, where sites of interest were investigated for validation of ice marginal landforms and to collect samples for geochronological constraints on deglaciation of the island (Fig. 2).

During fieldwork, marine shells were collected from the highest raised-beach ridges at several locations around Anticosti Island. They were all collected from trenches shoveled into ridge slopes and from already accessible outcrops (coastal cliffs, river banks). Shells from littoral species (mainly mussels) were targeted to obtain accurate dates for beach-ridge deposition. Shells from glaciomarine deposits (mainly *Hiattella arctica*, *Mya truncata*) were also collected to obtain minimum ages for deglaciation. Additionally, samples of ~1 kg of rock were collected for cosmogenic exposure dating from boulders located on ice marginal landforms and outcropping bedrock surfaces. The samples were collected from the upper exposed surface of boulder and bedrock using a handheld rocksaw, a hammer and a chisel. The flat top of stable boulders embedded in the moraine or till matrix were usually targeted to minimize the possibility of overturning, post-deposition exhumation and extreme weathering. Where available, quartz veins or quartz-rich material were extracted from the boulders. All samples were thoroughly

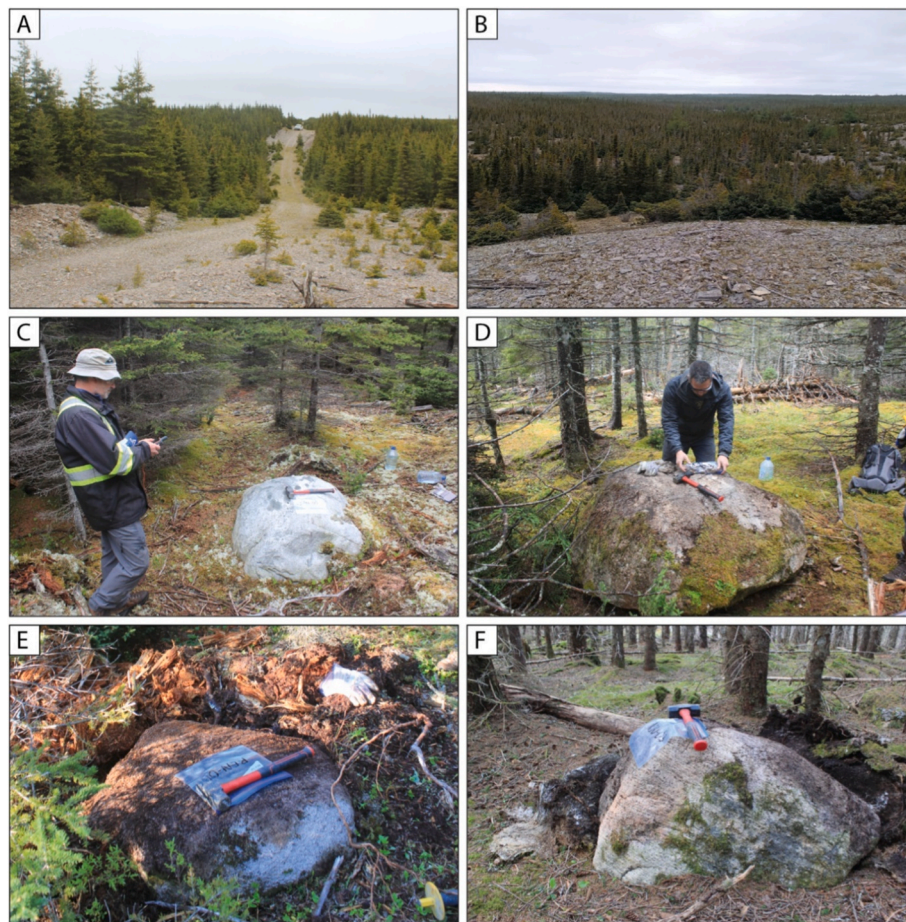


Fig. 2. Photographs of cosmogenic sample sites. A) View of the Sainte-Marie Moraine near the sampling site (note the pick up truck for scale). B) Location of Lake Wickenden site showing highly weathered and frost-shattered bedrock. View looking south of the central plateau showing a typical landscape of Anticosti Island. C) Sample SMA-05 collected from the Sainte-Marie Moraine (14.5 ± 0.6 ka). D) Sample RAH-04 collected from the Rivière-à-l'Huile Moraine (14.2 ± 0.5 ka). E) Sample REN-05 collected near Lake Renard (13.6 ± 0.5 ka). F) Sample AQU-03 collected from the Aquila Moraine (14.1 ± 0.5 ka).

documented in the field, including site description, coordinates and elevation obtained using a handheld GPS.

3.2. Radiocarbon dating

Accelerator Mass Spectrometry (AMS) radiocarbon dating was carried-out at the Keck Carbon Cycle AMS Laboratory (University of California) on 24 marine shells collected from Anticosti Island. The obtained AMS ^{14}C ages were calibrated within the age-depth modelling process and converted to calendar years using the online software Calib 8.2 (Stuiver and Reimer, 1993; <http://calib.org/>) with the Marine20 radiocarbon age calibration curve (Heaton et al., 2020). A local reservoir correction (ΔR) of -2 ± 78 was used to account for the regional offset of the world ocean ^{14}C age (McNeely et al., 2006). Additionally, an increased marine reservoir correction of 390 yrs was used to obtain values representing a high-depletion scenario for polar regions (Heaton et al., 2023). All individual radiocarbon ages from both scenarios are presented as the mean of the calibrated age range with 2σ uncertainty (Table 1). For simplification, only the high-depletion scenario is presented throughout the manuscript, therefore representing a minimum age for the deposits. These radiocarbon ages were complemented by previously published ^{14}C ages that have been recalibrated using the aforementioned parameters (Supplementary Table 1). The calibration method used in this paper provide slightly different results (3%) than those from recent geochronological compilations (Dalton et al., 2020, 2023). Using any of those two calibration methods would not significantly affect the resulting ages presented in this paper and therefore not

change the final interpretation. For comparison, resulting calibrated ages using the same calibration methods from both studies, alongside the Holocene-based and high-depletion scenarios, are presented in Supplementary Table 2.

3.3. Cosmogenic exposure dating

Samples for cosmogenic ^{10}Be ($n = 18$) and ^{36}Cl ($n = 15$) analyses were collected from 29 moraine boulders and four glacially-modified bedrock surfaces (Fig. 2). Sample preparation was performed at the “Laboratoire National des Nucléides Cosmogéniques” (LN2C) at CER-EGE (Aix-en-Provence, France). Granitic rocks were crushed, pulverized and sieved to isolate the 250–710 μm fraction. For limestone samples, a grain size range of 250–500 μm was used.

^{10}Be sample preparation, analysis and age calculation.

Chemical preparation for ^{10}Be analysis was performed on 18 samples following a protocol modified from Kohl and Nishiizumi (1992) and Child et al. (2000). Quartz isolation was achieved using a Frantz magnetic separator and froth-floatation mineral-separation techniques. Samples were subsequently treated by successive leaching cycles with diluted HF and HNO_3 ($\sim 2\%$ each) solution to purify the quartz. A commercial ^9Be carrier (~ 0.45 mg) was added to the samples before dissolving the pure quartz in concentrated HF (48%). Beryllium was then isolated using precipitation through anion and cation exchange columns. The obtained beryllium hydroxide was dried and converted to BeO at 900°C . The resulting BeO was then combined with Nb powder for target preparation. $^{10}\text{Be}/^9\text{Be}$ ratios were measured at ASTER, the

Table 1
Radiocarbon and calibrated radiocarbon ages from material collected on Anticosti Island.

Laboratory ID	Latitude (DD)	Longitude (DD)	Location	Environment	Dated material	¹⁴ C a BP	Holocene-based ΔR Cal a BP (2σ)	GS scenario ΔR Cal a BP (2σ)
South Shore								
ULA-10386	49.1039	−61.9969	Rivière de la Petite Loutre	Littoral	Mixed shells	12 765 ± 30	14 320 (14 020–14 760)	13 750 (13 500–14 010)
ULA-8299	49.1885	−62.7678	Ruisseau Martin	Littoral	Mixed shells	12 970 ± 25	14 680 (14 290–15 020)	14 020 (13 740–14 340)
ULA-7691	49.2066	−62.9861	Caps-des-Caps	Glaciomarine	<i>Macoma calcarea</i>	13 295 ± 30	15 170 (14 880–15 470)	14 570 (14 180–14 930)
ULA-8446	49.2450	−63.0865	Rivière Chicotte	Littoral/Marine limit	Mixed shells	13 515 ± 25	15 450 (15 160–15 740)	14 940 (14 560–15 230)
ULA-7399	49.2517	−63.0922	Rivière Chicotte	Littoral/Marine limit	Mixed shells	13 465 ± 30	15 390 (15 100–15 680)	14 860 (14 470–15 170)
ULA-8435	49.2897	−63.2199	Rivière Galiote	Glaciomarine	Mixed shells	13 245 ± 30	15 100 (14 810–15 410)	14 480 (14 110–14 850)
ULA-7533	49.2898	−63.2194	Rivière Galiote	Glaciomarine	Mixed shells	13 530 ± 25	15 470 (15 170–15 770)	14 960 (14 590–15 260)
ULA-7519	49.2831	−63.2172	Rivière Galiote	Glaciomarine	Mixed shells	13 520 ± 25	15 460 (15 160–15 750)	14 950 (14 570–15 240)
ULA-7419	49.2779	−63.2283	Rivière Galiote	Glaciomarine	<i>Mya truncata</i>	13 395 ± 30	15 300 (15 010–15 600)	14 740 (14 340–15 070)
ULA-8302	49.3505	−63.3939	Rivière du Brick	Glaciomarine	<i>Mya truncata</i>	13 440 ± 25	15 350 (15 070–15 650)	14 820 (14 430–15 140)
ULA-8442	49.3487	−63.3942	Rivière du Brick	Glaciomarine	<i>Mya arenaria</i>	13 455 ± 30	15 370 (15 080–15 670)	14 840 (14 450–15 160)
ULA-10389	49.4054	−63.5741	Pointe Sud-Ouest	Glaciomarine	<i>Hiatella arctica</i>	14 195 ± 25	16 340 (16 040–16 650)	15 830 (15 540–16 140)
ULA-10392	49.4116	−63.5761	Pointe Sud-Ouest	Glaciomarine	<i>Hiatella arctica</i>	14 090 ± 25	16 200 (15 900–16 510)	15 700 (15 390–16 000)
ULA-7708	49.4794	−63.6051	Rivière Jupiter	Glaciomarine	<i>Hiatella arctica</i>	13 615 ± 30	15 580 (15 270–15 890)	15 070 (14 780–15 390)
ULA-8470	49.6688	−63.8810	Rivière Cailloux	Littoral/Marine limit	Mixed shells	13 640 ± 30	15 620 (15 310–15 930)	15 110 (14 820–15 410)
ULA-8309	49.8494	−64.2350	Port-Menier	Littoral/Marine limit	Mixed shells	13 375 ± 25	15 270 (14 990–15 570)	14 700 (14 300–15 040)
ULA-8408	49.8097	−64.2988	Port-Menier	Littoral/Marine limit	Mixed shells	13 605 ± 30	15 570 (15 260–15 880)	15 060 (14 770–15 380)
ULA-8439	49.8494	−64.3151	Port-Menier	Littoral	Mixed shells	13 465 ± 25	15 390 (15 100–15 680)	14 860 (14 470–15 170)
ULA-8436	49.8375	−64.3399	Port-Menier	Littoral	Mixed shells	13 415 ± 25	15 320 (15 040–15 620)	14 770 (14 380–15 100)
ULA-8444	49.8290	−64.3549	Port-Menier	Littoral	Mixed shells	13 460 ± 25	15 380 (15 090–15 670)	14 850 (14 470–15 160)
North Shore								
ULA-7463	49.2954	−61.8292	Baie du Renard	Littoral	Mixed shells	13 390 ± 25	15 290 (15 010–15 590)	14 730 (14 340–15 060)
ULA-10400	49.2687	−61.8828	Baie du Renard	Littoral/Marine limit	Mixed shells	12 945 ± 25	14 640 (14 250–14 980)	13 980 (13 710–14 300)
ULA-8315	49.8556	−63.8055	Rivière Kakawis	Littoral/Marine limit	Mixed shells	12 865 ± 25	14 500 (14 130–14 870)	13 880 (13 600–14 130)
ULA-8299	49.9064	−64.3407	Baie du Petit Maskati	Littoral/Marine limit	Mixed shells	12 985 ± 30	14 700 (14 310–15 040)	14 040 (13 750–14 380)

The AMS ¹⁴C ages were calibrated with the age-depth modelling process, using the online software Calib 8.2 with the Marine20 (Heaton et al., 2020) radiocarbon age calibration curve. A local Holocene-based reservoir correction (ΔR) of −2 ± 78 was used to account for the regional offset of the world ocean ¹⁴C age, as determined by McNeely et al. (2006). The glacial (GS) scenario was determined by adding 390 years to the Holocene-based reservoir correction (Heaton et al., 2023).

Table 2
Sample characteristics, AMS measurement results and ¹⁰Be ages.

Sample no.	Latitude (DD)	Longitude (DD)	Altitude (m)	Thickness (cm)	Quartz (g)	Carrier (mg)	¹⁰ Be/ ⁹ Be (10 ⁻¹⁴)	Blank ¹⁰ Be/ ⁹ Be (10 ⁻¹⁴)	¹⁰ Be conc. (atoms g ⁻¹)	¹⁰ Be age (a)
Sainte-Marie Moraine										
SMA-01	49.7281	-63.9602	82	2.0	30.1882	0.4512	7.19 ± 0.26	0.29 ± 0.04	68 739 ± 2582	14 410 ± 670 (960)
SMA-02	49.7274	-63.9615	74	2.1	30.2765	0.4537	5.98 ± 0.21	0.29 ± 0.04	56 742 ± 2148	15 529 ± 586
SMA-03	49.7274	-63.9616	75	2.1	30.0047	0.4529	6.34 ± 0.21	0.29 ± 0.04	60 854 ± 2109	12 946 ± 492*
SMA-04	49.7274	-63.9619	75	2.0	26.9426	0.4530	5.74 ± 0.22	0.29 ± 0.04	61 022 ± 2497	13 869 ± 482
SMA-05	49.7283	-63.9628	75	1.8	30.0724	0.4524	6.64 ± 0.28	0.29 ± 0.04	63 608 ± 2820	13 897 ± 571
										14 459 ± 643
Rivière-à-l'Huile Moraine										
RAH-04	49.8317	-63.7690	128	2.0	30.2320	0.4523	6.92 ± 0.23	0.29 ± 0.04	66 060 ± 2324	14 220 ± 370 (680)
RAH-05	49.8317	-63.7715	123	1.5	30.2156	0.4529	6.88 ± 0.28	0.29 ± 0.04	65 807 ± 2865	14 236 ± 503
										14 195 ± 620
Aquila Moraine										
AQU-01	49.2918	-62.0057	60	2.1	30.0995	0.4536	6.46 ± 0.28	0.29 ± 0.04	61 927 ± 2797	13 690 ± 680 (950)
AQU-02	49.2919	-62.0061	62	2.0	30.1058	0.4527	6.42 ± 0.27	0.29 ± 0.04	61 347 ± 2728	12 815 ± 520
AQU-03	49.2922	-62.0061	65	2.0	30.3451	0.4547	6.11 ± 0.24	0.29 ± 0.04	58 056 ± 2428	13 276 ± 556
AQU-04	49.2925	-62.0064	66	2.0	30.4916	0.4522	6.47 ± 0.23	0.29 ± 0.04	61 043 ± 2277	14 059 ± 532
AQU-05	49.2924	-62.0067	65	2.2	30.0244	0.4520	5.81 ± 0.22	0.29 ± 0.04	55 346 ± 2239	13 525 ± 544
AQU-06	49.2922	-62.0057	67	2.0	30.4704	0.4537	6.09 ± 0.24	0.29 ± 0.04	57 507 ± 2400	11 980 ± 562*
										14 804 ± 549
Lake Renard										
REN-02	49.2042	-62.0240	96	1.9	30.4955	0.4563	6.45 ± 0.23	0.32 ± 0.04	61 074 ± 2302	13 490 ± 340 (730)
REN-03	49.2041	-62.0239	97	2.0	25.3301	0.4553	5.24 ± 0.19	0.32 ± 0.04	58 826 ± 2357	13 803 ± 626
REN-04	49.2041	-62.0239	96	1.8	26.0816	0.4587	4.76 ± 0.20	0.32 ± 0.04	52 009 ± 2432	13 672 ± 610
REN-05	49.2043	-62.0241	96	2.0	30.4550	0.4589	6.75 ± 0.23	0.32 ± 0.04	64 481 ± 2382	12 932 ± 543
										13 618 ± 510
Chicotte Moraine										
CHI-02	49.2678	-62.9909	99	1.9	6.5213	0.4587	1.26 ± 0.11	0.32 ± 0.04	43 739 ± 5305	N/A
										9723 ± 1182*

The ¹⁰Be ages were calculated with the “Lm” scaling scheme (Lal, 1991; Stone, 2000), using the CRONUS-Earth online calculator version 3.0 (Balco et al., 2008; <http://hess.ess.washington.edu/>) and the production rate calculated with the NENA calibration data set of Balco et al. (2009). The ¹⁰Be AMS standard applied was the ASTER in-house STD-11 with a ¹⁰Be/⁹Be ratio of 1.19 × 10⁻¹¹ (Braucher et al., 2015) and a ¹⁰Be half-life of 1.387 ± 0.012 Ma (Chmeleff et al., 2010; Korschinek et al., 2010). A rock density of 2.7 g cm⁻³ was applied for all samples and a standard atmosphere was used. No erosion and no topographic shielding were accounted for in our calculations. Snow cover correction were not applied. The asterisks (*) mark the samples that are considered as outliers and were not included in the mean age calculations (in bold).

Table 3
Sample characteristics, AMS measurement results and ³⁶Cl ages on silicate rocks.

Sample no.	Latitude (DD)	Longitude (DD)	Altitude (m)	Thickness (cm)	Sample weight (g)	Carrier (mg)	Cl (ppm)	³⁶ Cl/ ³⁵ Cl (10 ⁻¹⁴)	³⁵ Cl/ ³⁷ Cl	³⁶ Cl conc. (atoms g ⁻¹)	³⁶ Cl age (a)
Rivière-à-l'Huile Moraine											N/A
RAH-01	49.8445	-63.8462	106	2.2	51.96	2.0268	18.47 ± 1.21	7.09 ± 0.45	10.29 ± 0.18	67 430 ± 4437	9883 ± 876*
RAH-02	49.8444	-63.8479	102	2.0	49.68	2.0274	13.42 ± 0.76	20.82 ± 0.93	14.74 ± 0.26	176 633 ± 8412	34 429 ± 2762*
RAH-03	49.8449	-63.8485	104	2.0	49.94	2.0220	10.10 ± 0.58	19.72 ± 0.92	18.08 ± 0.33	163 870 ± 7744	25 592 ± 1996*
Makasti Hill											N/A
MAS-01	49.9138	-64.2995	119	2.0	51.36	2.0292	9.79 ± 0.55	15.02 ± 0.75	18.17 ± 0.31	121 699 ± 6166	24 217 ± 1984*
MAS-02	49.9142	-64.3003	126	2.0	50.26	2.0280	9.09 ± 0.52	9.94 ± 0.61	19.17 ± 0.36	81 083 ± 5019	16 775 ± 1494*
MAS-03	49.9142	-64.3005	126	2.1	51.81	2.0244	0.36 ± 0.05	7.44 ± 0.52	119.04 ± 2.12	50 680 ± 3532	11 360 ± 1090*
Chicotte Moraine											14 190 ± 800 (1050)
CHI-01	49.2681	-62.9905	100	2.1	51.08	2.0352	1.98 ± 0.14	10.54 ± 0.59	57.49 ± 1.00	75 368 ± 4225	15 347 ± 1327
CHI-03	49.3247	-63.0824	163	2.0	41.89	2.0244	29.98 ± 1.71	8.86 ± 0.54	9.51 ± 0.17	108 307 ± 6924	17 179 ± 1471*
CHI-05	49.3246	-63.0828	155	2.2	49.13	2.0214	12.85 ± 0.73	8.56 ± 0.53	15.31 ± 0.28	75 140 ± 4746	13 790 ± 1228
CHI-06	49.3249	-63.0847	157	2.2	50.39	2.0316	11.96 ± 0.69	8.26 ± 0.50	15.90 ± 0.30	70 364 ± 4351	13 553 ± 1205

The ³⁶Cl ages were calculated with the time-invariant scaling method by [Stone \(2000\)](#), using the Excel® spreadsheet of [Schimmelpfennig et al. \(2009\)](#). AMS ratios were normalized with the ASTER in-house standard SM-CL-12 with an assigned ³⁶Cl/³⁵Cl value of (1.428 ± 0.015) × 10⁻¹² ([Merchel et al., 2011](#)) and assuming a natural ³⁵Cl/³⁷Cl ratio of 3.127. A rock density of 2.7 g cm⁻³ was applied for all samples. No erosion and no topographic shielding were accounted for in our calculations. Snow cover correction were not applied. The asterisks (*) mark the samples that are considered as outliers and were not included in the mean age calculations.

Table 4
Sample characteristics, AMS measurement results and ³⁶Cl ages for carbonate rocks.

Sample no.	Latitude (DD)	Longitude (DD)	Altitude (m)	Thickness (cm)	Sample weight (g)	Carrier (mg)	CaO (%)	Cl (ppm)	³⁶ Cl/ ³⁵ Cl (10 ⁻¹³)	³⁵ Cl/ ³⁷ Cl	³⁶ Cl conc. (atoms g ⁻¹)	³⁶ Cl age (a)
Rivière-à-l'Huile Moraine												N/A
RAH-06	49.8445	-63.8481	106	1.3	50.09	2.0124	52.03	130.01 ± 9.88	4.10 ± 0.29	4.58 ± 0.08	220 836 ± 18 591	7255 ± 754*
Lake Wickenden												9890 ± 80 (480)
WIC-01	49.5824	-63.1426	215	1.7	43.73	2.0142	52.66	111.52 ± 7.79	6.95 ± 0.33	4.90 ± 0.09	322 016 ± 19 561	9816 ± 828
WIC-02	49.5629	-63.1393	215	1.6	51.40	2.0070	53.47	140.39 ± 11.51	6.00 ± 0.27	4.32 ± 0.07	348 865 ± 23 390	9966 ± 901
Safari												14 260 ± 430 (810)
SAF-01	49.3674	-62.5412	146	2.1	48.07	2.0064	53.90	159.85 ± 13.27	3.25 ± 0.21	4.21 ± 0.07	215 066 ± 18 214	13 849 ± 1456
SAF-02	49.3674	-62.5411	146	2.0	51.28	2.0088	52.21	165.21 ± 14.30	3.33 ± 0.21	4.11 ± 0.07	227 423 ± 19 084	14 702 ± 1539

The ³⁶Cl ages were calculated with the time-invariant scaling method by [Stone \(2000\)](#), using the Excel® spreadsheet of [Schimmelpfennig et al. \(2009\)](#). AMS ratios were normalized with the ASTER in-house standard SM-CL-12 with an assigned ³⁶Cl/³⁵Cl value of $(1.428 \pm 0.015) \times 10^{-12}$ ([Merchel et al., 2011](#)) and assuming a natural ³⁵Cl/³⁷Cl ratio of 3.127. A rock density of 2.7 g cm⁻³ was applied for all samples. No erosion and no topographic shielding were accounted for in our calculations. Snow cover correction were not applied. The asterisks (*) mark the samples that are considered as outliers and were not included in the mean age calculations.

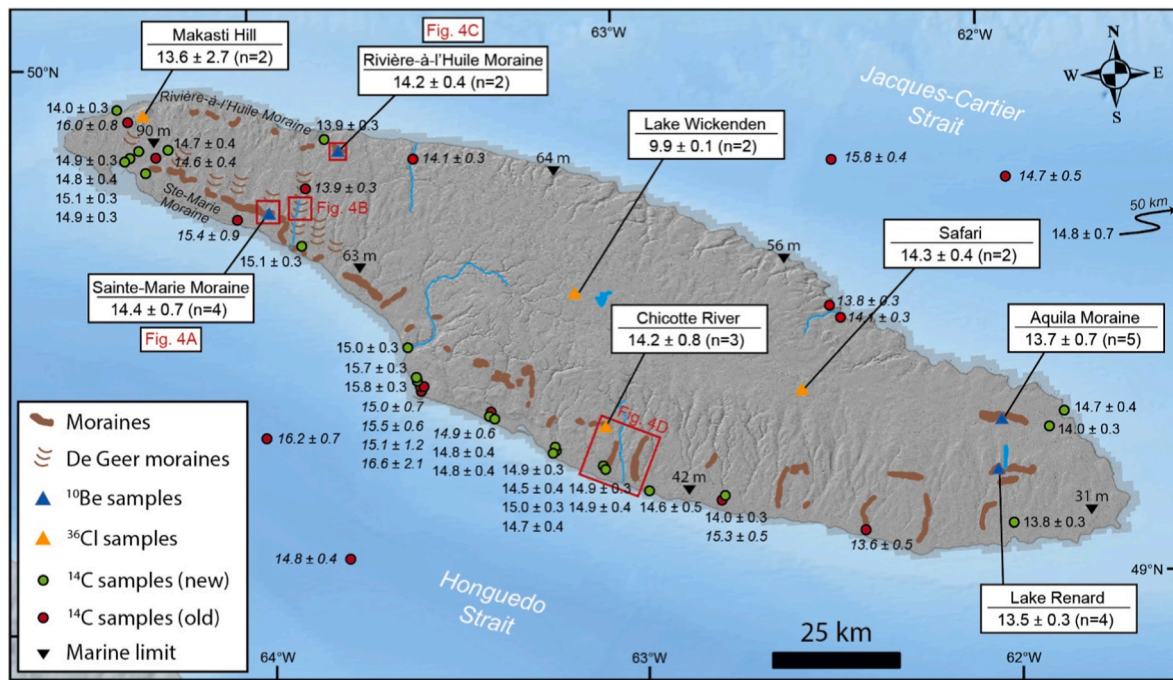


Fig. 3. Ice-marginal landform mapping, as well as location of cosmogenic ^{10}Be dating (blue triangles), cosmogenic ^{36}Cl dating (orange triangles) and radiocarbon ^{14}C dating (green and red dots) around Anticosti Island. All ages are reported in thousand years (ka); Ages from the literature are represented in *italics*. Bathymetry data is from the GEBCO grid (gebcoset.org). High-resolution LiDAR-derived DEM of Anticosti Island is from the Government of Québec (foretouverte.gouv.qc.ca).

French Accelerator Mass Spectrometry (AMS) at CEREGE. The measurements of samples were normalized against an in-house CEREGE standard STD11, with an assumed $^{10}\text{Be}/^9\text{Be}$ ratio of $(1.191 \pm 0.013) \times 10^{-11}$ (Braucher et al., 2015) and a ^{10}Be half-life of 1.387 ± 0.012 Ma (Chmeleff et al., 2010; Korschinek et al., 2010). A procedural blank was processed with each batch of samples to evaluate ^{10}Be contamination during laboratory procedures. Blanks BKPO-03 and BKPO-04 have $^{10}\text{Be}/^9\text{Be}$ ratios of $2.93 \pm 0.41 \times 10^{-15}$ and $3.24 \pm 0.42 \times 10^{-15}$, respectively.

^{10}Be ages were calculated using the online exposure age calculator formerly known as the CRONUS-Earth online exposure age calculator version 3.0 (Balco et al., 2008; <https://hess.ess.washington.edu/>). Calibration was done using the northeastern North America (NENA) ^{10}Be production rate of 4.04 ± 0.27 atoms/g/a (Balco et al., 2009) and the nuclide- and time-dependent Lm scaling scheme (Lal, 1991; Stone, 2000). All ^{10}Be exposure ages are presented and discussed with 1σ analytical uncertainty (Table 2). Outliers were identified using the CRONUS-Earth online calculator and defined as ^{10}Be ages that are $>2\sigma$ older or younger from the mean of the remaining ^{10}Be ages. Landform ages were defined as the error-weighted mean of the sample population and uncertainties were quantified as the standard error of ages, excluding outliers. Production rate uncertainty was included in quadrature to the analytical uncertainty when comparing and discussing landform ages with independent climate records and radiocarbon ages. Post-glacial isostatic uplift corrections were neglected in the final results, as the effects of glacio-isostatic rebound on cosmogenic nuclides production are not well constrained and would likely introduce additional uncertainties on the age calculations (Staiger et al., 2007; Balco et al., 2009). The effects of postglacial erosion, topographic shielding and snow cover were not accounted for in the final calculations.

^{36}Cl sample preparation, analysis and age calculation.

Chemical preparation for ^{36}Cl analysis was performed on 15 samples following the procedure described in Schimmelpfennig et al. (2011). Samples were first treated by water and acid leaching to remove atmospheric ^{36}Cl contamination. An in-house ^{35}Cl carrier (~ 2 mg) was added to the samples before dissolving in HNO_3 (10%) for carbonate

rocks, and in concentrated HF (48%) and HNO_3 (10%) for silicate rocks. After total dissolution, the sulfur was removed by adding 1 ml of $\text{Ba}(\text{NO}_3)_2$ and allowing $\text{BaCO}_3/\text{BaSO}_4$ to precipitate. ^{36}Cl was finally concentrated as a AgCl precipitate for AMS analysis. $^{35}\text{Cl}/^{37}\text{Cl}$ and $^{36}\text{Cl}/^{35}\text{Cl}$ ratios were measured by AMS at the 5 MV accelerator ASTER at CEREGE. Use of an isotopically enriched carrier allows simultaneous determination of the ^{36}Cl and the natural Cl concentrations of the dissolved samples. For normalisation of the $^{36}\text{Cl}/^{35}\text{Cl}$ ratios, an in-house standard with a given $^{36}\text{Cl}/^{35}\text{Cl}$ value of $1.42 \pm 0.02 \times 10^{-12}$ was used (Merchel et al., 2011). Blank corrections were performed by subtracting the number of atoms of ^{36}Cl and Cl in the blanks from those in the samples. For carbonate rocks, Ca concentrations were measured by inductively coupled plasma atomic emission spectrometry (ICP-AES) at CEREGE. For silicate rocks, bulk rock and chemically treated sample fractions (~ 2 g each) were sent to the Service d'Analyse des Roches et des Minéraux (SARM) in Nancy (France) for chemical composition analyses (Supplementary Tables 3 and 4).

^{36}Cl concentrations and ages were calculated with the Excel spreadsheet of Schimmelpfennig et al. (2009), using the time-invariant scaling method from Stone (2000) and employing the following ^{36}Cl production rates, referenced to sea level and high latitude: 42.2 ± 4.8 atoms ^{36}Cl (g Ca) $^{-1}$ yr $^{-1}$ for spallation of Ca (Schimmelpfennig et al., 2011), 148.1 ± 7.8 atoms ^{36}Cl (g K) $^{-1}$ yr $^{-1}$ for spallation of K (Schimmelpfennig et al., 2014), 13.0 ± 3.0 atoms ^{36}Cl (g Ti) $^{-1}$ yr $^{-1}$ for spallation of Ti (Fink et al., 2000), 1.9 ± 0.2 atoms ^{36}Cl (g Fe) $^{-1}$ yr $^{-1}$ for spallation of Fe (Stone et al., 1996), and 696 ± 185 neutrons (g air) $^{-1}$ yr $^{-1}$ for the production rate of epithermal neutrons from fast neutrons in the atmosphere at the land/atmosphere interface (Marrero et al., 2016). A high-energy neutron attenuation length of 160 g cm $^{-2}$ was used. All ^{36}Cl exposure ages are presented and discussed with 1σ analytical uncertainty (Tables 3 and 4). As for the ^{10}Be ages, outliers were defined as ^{36}Cl ages that are $>2\sigma$ older or younger from the mean of the remaining ^{36}Cl ages. Landform ages were defined as the error-weighted mean of the sample population and uncertainties were quantified as the standard error of ages, excluding outliers. Production rate uncertainty was included in quadrature when comparing and discussing landform ages

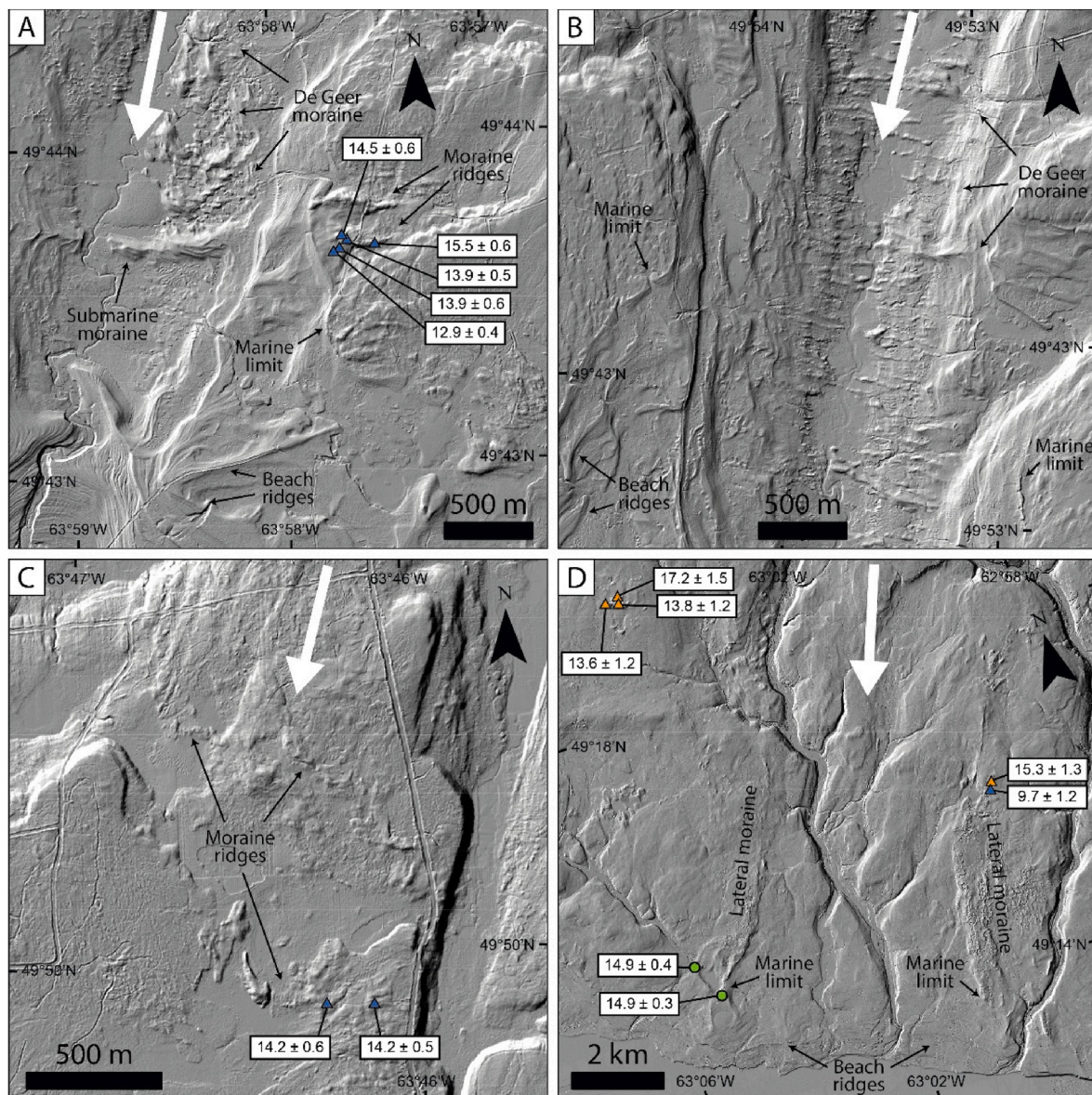


Fig. 4. Examples of ice-marginal landforms on the LiDAR-derived DEM from Anticosti Island. A) The Sainte-Marie Moraine and location of the sampling sites for the cosmogenic ^{10}Be exposure dating is shown by the blue triangles. Note the beach-ridges overprinting the moraine in the valley. B) Series of De Geer moraines near the Sainte-Marie River. C) The Rivière-à-l'Huile Moraine and location of the sampling sites for cosmogenic ^{10}Be exposure dating is shown by the blue triangles. D) Lateral moraines overprinted by beach-ridges near Chicotte River. The location of radiocarbon-dated samples collected from the marine limit is shown by green circles and sampling sites for the cosmogenic ^{10}Be and ^{36}Cl exposure dating are shown by the blue and orange triangles, respectively. All ages are reported in thousand years (ka). White arrows represent the general ice flow directions. Figure locations are shown in Fig. 3.

with independent climate records and radiocarbon ages. The effects of postglacial erosion, topographic shielding and snow cover were not accounted for in the final calculations.

4. Results

4.1. Ice marginal landforms

Anticosti Island is generally characterized by a thin and discontinuous till cover. Nonetheless, LiDAR data allowed identifying ice marginal landforms, which are grouped into several geomorphological systems and briefly described below. The resulting mapping of ice marginal landforms from Anticosti Island is presented in Fig. 3.

The Sainte-Marie Moraine was mapped almost continuously for nearly 70 km between the Jupiter River, in the south, and the westernmost tip of the island. It mostly consists of single or few relatively

large ridges, generally reaching <15 m high (Fig. 4a). Due to the relatively low altitude of the eastern lowlands (<100 m), this moraine can extend as outwash and subaquatic ice-marginal deposits in the axis of valleys. The ridges composing the Sainte-Marie Moraine are occasionally overprinted by littoral deposits, including beach-ridges recording the marine limit.

In most valleys of the western part of the island, a series of cross-valley De Geer moraines are identified and are located directly beyond the Sainte-Marie Moraine. They are generally observed in small groups as closely spaced ridges and are on average ~75 m apart (Fig. 4b). Valleys usually contain between 10 and 30 individual moraines, except for the Sainte-Marie River valley where nearly 200 of such features are observed and extend to the northern part of the island.

The Rivière-à-l'Huile Moraine consists of small ridges located at the head of some valleys, in the northwesternmost part of the island. This moraine is generally discontinuous and lies, for the most part, below the

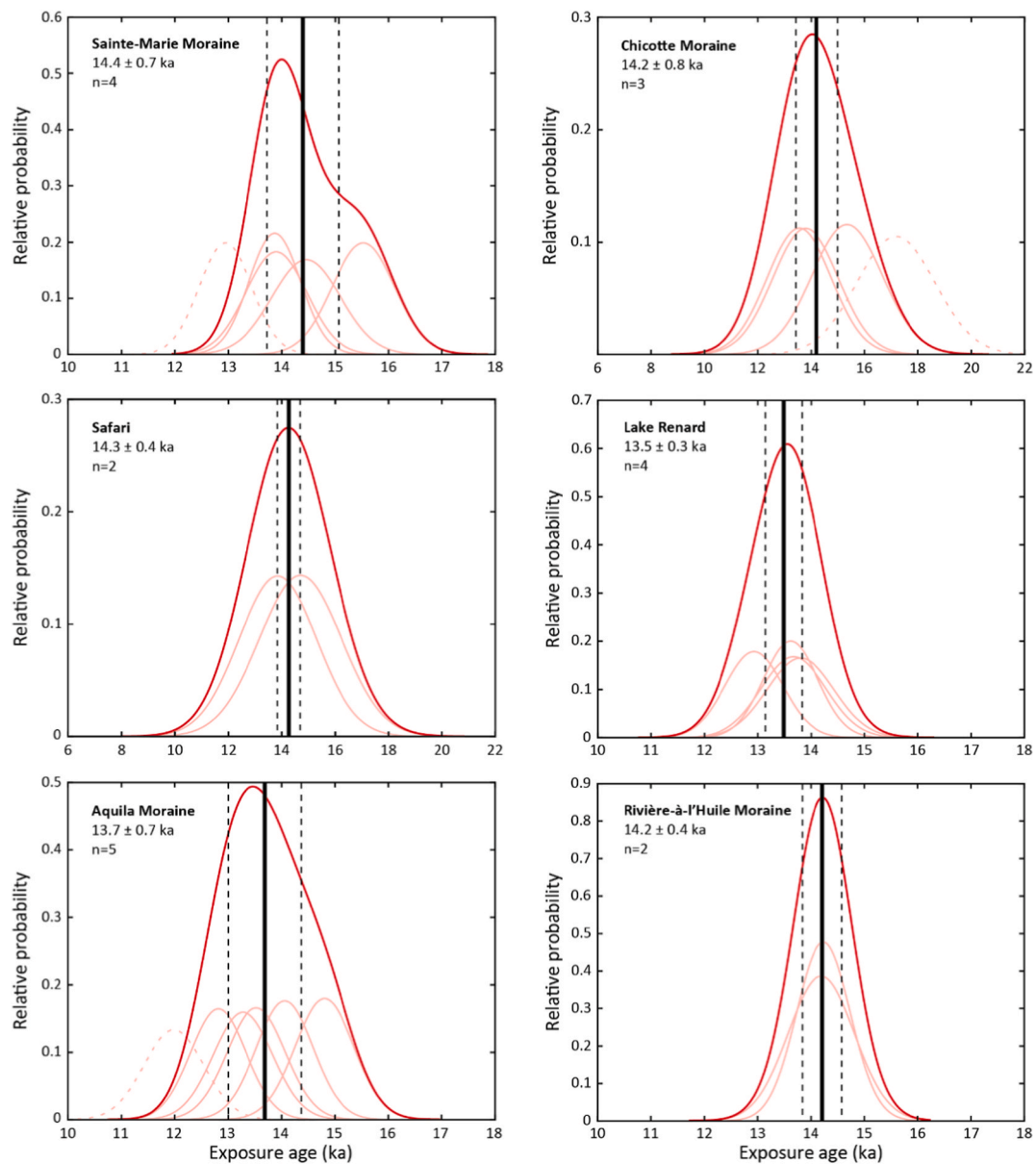


Fig. 5. Probability distribution function (PDF) plots of ^{10}Be and ^{36}Cl ages for moraine systems and landforms on Anticosti Island. PDF plots were generated using the iceTEA (Tools for Exposure Ages from ice margins; <http://ice-tea.org/en/>) “Import and plot ages” tool (Jones et al., 2019). Thick and dashed black lines represent the weighted average and the 1σ interval. Thin red lines represent individual sample ages with internal uncertainties, and thick red lines show summed probability distributions. Dashed red lines are individual ages identified as outliers and are not included in the calculation of the mean landform ages.

marine limit. The ridges are therefore buried underneath thick sequence of glaciomarine and littoral deposits and are mostly inaccessible. However, some segments of the Rivière-à-l’Huile Moraine were deposited above the marine limit and generally consist of ridges ranging between 5 and 10 m in height (Fig. 4c). The configuration of the ridges sampled for cosmogenic exposure dating suggest deposition by a southerly ice flow (i.e., by the LIS).

A series of lateral moraines is observed south of the central plateau. These landforms consist of elongated and arcuate ridges up to 10 km in length that are oriented parallel to the inferred ice flow (Fig. 4d). They usually range between 10 m and 30 m in height, and between 50 and 500 m in width. These landforms are generally observed in pairs and are located on both sides of major rivers or valleys, suggesting passageways for small ice streams, or faster flowing glacier outlets. Since they often extend near the present coastline, their southernmost part is usually overprinted by littoral deposits.

Additionally, minor ice-marginal landforms were also observed and

mapped at various locations in the eastern part of the island. Based on their overall orientation, they are assumed to record the recession of the LIS across the island. However, their connection to other moraines on Anticosti Island could not be established since they are sparsely distributed.

4.2. Radiocarbon ages

Shell samples were collected from the highest raised beach and glaciomarine deposits at several locations around Anticosti Island (Fig. 3). The environment from which these shells were collected indicates that they were deposited shortly after the withdrawal of the ice margin.

On the south shore of the island, samples generally yield tightly clustered ages (Table 1). Samples obtained from raised beach deposits in the southwestern part of the island range between 14.7 ± 0.4 and 15.1 ± 0.3 cal ka BP. Two additional samples, collected from beach ridges

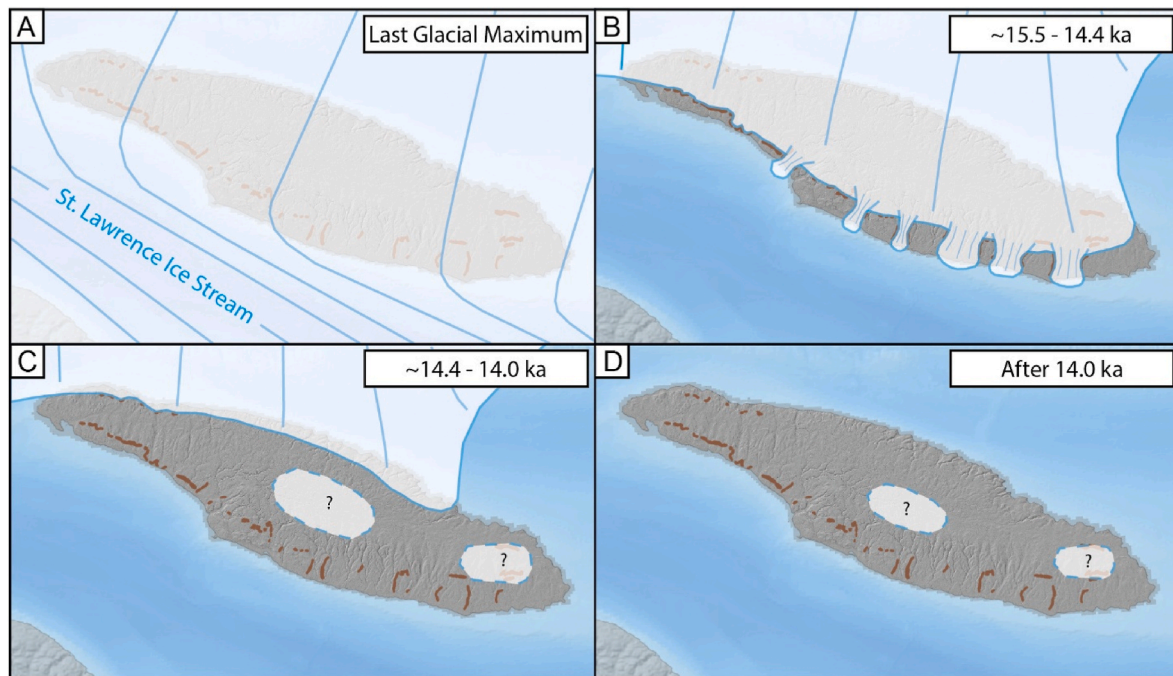


Fig. 6. Paleogeographical reconstruction of the deglaciation of Anticosti Island. (A) Fully glaciated at the Last Glacial Maximum. (B) Deglaciation of the southern part of the island and deposition of the Sainte-Marie Moraine at the end of HS-1. (C) Retreat of the LIS during the early Bølling-Allerød and deposition of the Rivière-à-l'Huile Moraine along the north shore. (D) Retreat of the LIS into the Jacques-Cartier Strait.

directly overlying a moraine ridge near Chicotte River, in the south of the island, yielded similar ages of 14.9 ± 0.3 cal ka BP. Two samples collected from littoral deposits in the eastern part of the island yielded slightly younger ages of 13.8 ± 0.3 and 14.0 ± 0.3 cal ka BP. Similarly, multiple samples obtained in glaciomarine deposits across the entire south shore gave consistent ages ranging between 14.5 ± 0.4 and 15.0 ± 0.3 cal ka BP. However, two samples yielded older ages of 15.7 ± 0.3 and 15.8 ± 0.3 cal ka BP near Pointe Sud-Ouest, suggesting an earlier deglaciation for this site.

On the north shore, three samples yielded consistent ages of 13.9 ± 0.3 and 14.0 ± 0.3 cal ka BP on littoral sediment from the marine limit and one sample on the eastern end of the island yielded an age of 14.7 ± 0.4 cal ka BP (Table 1). Altogether, the radiocarbon ages provide minimum limiting ages for ice retreat from the coasts of Anticosti Island.

4.3. Cosmogenic exposure dating

Several sites were visited for cosmogenic exposure dating across Anticosti Island, including major and subordinate moraine ridges, glacially polished surfaces, as well as erratic boulders (Fig. 3). The resulting cosmogenic exposure ages from the sampled boulders and surfaces are provided for each of these sites.

Five boulders (SMA samples) were collected within a ~ 100 m radius on one of the outermost ridges of the Sainte-Marie Moraine. Four samples yielded consistent ^{10}Be ages ranging from 13.9 ± 0.5 and 15.5 ± 0.6 ka, with an outlier at 12.9 ± 0.5 ka (Table 2). The samples collected from the Sainte-Marie Moraine have a resulting weighted average of 14.4 ± 0.7 ka (Table 2; Fig. 5).

Six samples were also collected from two distinct sites, located nearly 20 km apart, on a moraine ridge near Rivière-à-l'Huile (RAH samples). Four boulders, located within 150 m of each other, were sampled from the crest of a first moraine ridge and yielded ^{36}Cl exposure ages ranging from 7.1 ± 0.7 to 34.4 ± 2.8 ka (Tables 3 and 4). Two boulders, located ~ 200 m apart, were sampled from the crest of a second moraine ridge and yielded nearly identical ^{10}Be ages of 14.2 ± 0.5 ka and 14.2 ± 0.6 ka (Table 2). Since all ^{36}Cl samples are erroneously too old or too young for

the last deglaciation, we favour the ^{10}Be samples as representative of the Rivière-à-l'Huile Moraine with a weighted average of 14.2 ± 0.4 ka (Fig. 5). Additionally, three samples were also collected within a 50 m radius from erratic boulders at a nearby site on Makasti Hill (MAS samples). The samples yielded disparate ^{36}Cl ages of 11.4 ± 1.1 , 16.8 ± 1.5 and 24.2 ± 2.0 ka (Table 3).

Five boulders (CHI samples) were also sampled from two sites associated with the lateral moraine system near Chicotte River. Two samples were collected at the first site, from the crest of a lateral moraine ridge. The first sample yielded a ^{10}Be age of 9.7 ± 1.2 ka (Table 2) and the second sample yielded a ^{36}Cl age of 15.2 ± 1.2 ka (Table 3). Three samples were collected at the second site –consisting of a small ridge connected to the lateral moraine– and yielded ^{36}Cl ages ranging from 13.6 ± 1.2 to 17.2 ± 1.5 ka (Table 3). Considering the ^{10}Be sample from the first site as an outlier, the remaining samples from the Chicotte River moraine ridges have a weighted average of 14.9 ± 1.5 ka. Although the oldest sample (CHI-03; 17.2 ± 1.5 ka) fits into the criterion established for identifying outliers, the rather large uncertainties of the ^{36}Cl favour the inclusion of a wide range of ages. Excluding this sample would, however, yield a younger age of 14.2 ± 0.8 ka (Fig. 5) for the deglaciation of the south-central part of the island.

Four samples were collected from two different sites on the central plateau of the island. At the first site, two bedrock surface samples (Lake Wickenden – WIC samples) were collected within ~ 200 m from each other at the top of a highly weathered ridge. The samples yielded similar ^{36}Cl ages of 9.8 ± 0.8 ka and 10.0 ± 0.9 ka, and a resulting weighted average of 9.9 ± 0.1 ka (Table 4). At the second site, two bedrock surface samples (Safari – SAF samples) –collected under a 70 cm till cover and less than 5 m apart– yielded ^{36}Cl ages of 13.8 ± 1.5 ka and 14.7 ± 1.5 ka, and a weighted average of 14.3 ± 0.4 ka (Table 4; Fig. 5).

Additionally, minor moraine ridges were also sampled in the eastern part of the island. Four samples (REN samples) were collected from a thin till deposit located on top of a hill, south of Lake Renard. These boulders were located within a radius of 100 m and yielded consistent ^{10}Be ages ranging between 12.9 ± 0.5 and 13.8 ± 0.6 ka, and a resulting weighted average of 13.5 ± 0.3 ka (Table 2; Fig. 5). Six boulders (AQU

samples) were also sampled at another site north of Lake Renard. The samples were located on the crest of a small moraine and yielded five ^{10}Be ages ranging from 12.8 ± 0.5 to 14.8 ± 0.5 ka, with one outlier at 12.0 ± 0.5 ka (Table 2). The samples collected north of Lake Renard have a ^{10}Be weighted average of 13.7 ± 0.7 ka (Fig. 5).

5. Deglaciation chronology on Anticosti Island

The geochronological data collected on Anticosti Island allow refining its deglaciation history and identifying the timing of ice margin activity. In general, both radiocarbon and cosmogenic ages agree well on the timing of ice retreat and a step-by-step glaciological reconstruction is presented in Fig. 6.

5.1. Retreat of the LIS onto Anticosti Island

Previous work has demonstrated that Anticosti Island was completely glaciated by the LIS during the Late Wisconsinan (St-Pierre et al., 1987). Recent ice sheet reconstructions position the maximum ice extent further east during the LGM, near the continental shelf break (Fig. 6a; Dyke et al., 2003; Shaw et al., 2006; Dalton et al., 2023). The relatively small spread of available ages, for both the cosmogenic and radiocarbon dating methods, suggest that deglaciation of the island was rapid. This rapid deglaciation was likely favoured by an ice stream in the Laurentian Channel draining the LIS interior (Shaw et al., 2006; Margold et al., 2018) and by the formation of calving embayments both to the north and south of Anticosti Island during late glacial times (Rodrigues et al., 1993; Josenhans and Lehman, 1999; Dalton et al., 2020, 2023).

Radiocarbon samples collected from raised beach-ridges and glaciomarine sediments generally support a deglaciation of the southern shore of Anticosti Island between 15.1 and 14.5 cal ka BP. However, several samples suggest that the coastline of the Pointe Sud-Ouest may have been ice-free as early as 15.8 cal ka BP. These results are generally in line with those from previous studies, apart from two shells dated at 16.6 ± 2.0 cal ka BP near Pointe Sud-Ouest (Gratton et al., 1984) and 16.0 ± 0.8 cal ka BP at the western tip of the island (Dubois et al., 1988). These older ages could point toward an earlier deglaciation of the island, but their large uncertainties should also be considered as they overlap with the remaining data. The radiocarbon ages from the southern shore of Anticosti Island are generally consistent with an age obtained from proximal glaciomarine sediments from the Honguedo Strait, indicating a deglaciation by 16.2 ± 0.7 cal ka BP (Rodrigues et al., 1993). Considering the consistency of the radiocarbon ages along the entire coast of the island, it is likely that the ice margin retreat onto Anticosti Island was laterally synchronous. However, the older radiocarbon age at the easternmost tip of the island suggest that it could have been deglaciated together with the south shore (Fig. 6b). This configuration is supported by radiocarbon-dated marine sediments in the eastern Jacques-Cartier Strait (Dalton et al., 2020), that suggest the formation of a calving bay in the area.

5.2. Ice margin readvances, moraine formation and deglaciation of Anticosti Island

The timing of deposition of the Sainte-Marie Moraine –identified as the result of an ice margin readvance (Painchaud et al., 1984)– is supported by a moraine ^{10}Be age of 14.4 ± 0.7 ka. Additionally, a series of lateral moraine systems –sampled at two locations near Chicotte River– possibly consist of its eastern extension. While the physical connection between the two moraine systems could not be established, the ^{36}Cl age of 14.2 ± 0.8 ka from the Chicotte River moraine ridges is similar to the Sainte-Marie Moraine. Both moraine systems likely represent an important phase of the Sainte-Marie readvance. Near the coastline, the overprinting of some moraines by raised beach-ridges suggests that the Sainte-Marie readvance occurred prior to the deposition of littoral deposits (i.e., marine limit). In some valleys, littoral deposits may not

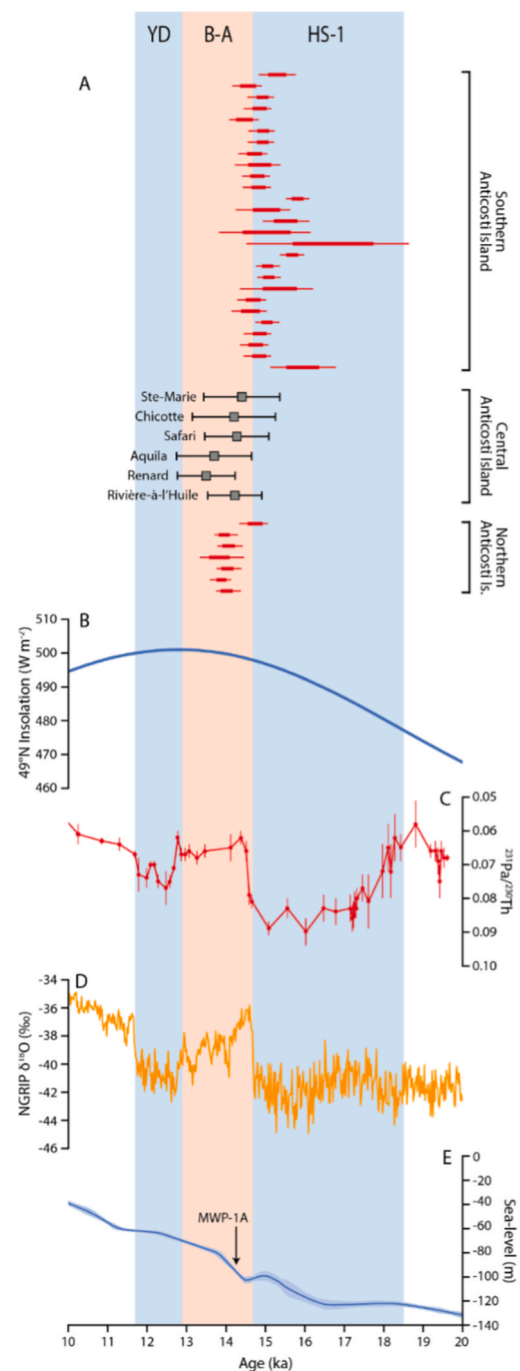


Fig. 7. (A) Radiocarbon ages (red) from this study (Table 1) and the literature (Supplementary Table 1 and references therein) constraining the deglaciation of Anticosti Island. Shown are the 1σ (thick line) and 2σ (thin line) calibrated age range. Cosmogenic ages (grey) constraining ice margin stabilizations on Anticosti Island. Shown are the error-weighted mean (square) and standard error (line) for each site. (B) 49°N June insolation curve (Laskar et al., 2004). (C) North Atlantic sediment $^{231}\text{Pa}/^{230}\text{Th}$, a proxy for Atlantic Meridional Overturning Circulation strength (McManus et al., 2004). (D) $\delta^{18}\text{O}$ record from NGRIP project (orange; Rasmussen et al., 2014). (E) Ice volume equivalent sea-level (blue - $\pm 1\sigma$; Lambeck et al., 2014). Vertical bars represent cold and warm intervals discussed in the text. YD: Younger Dryas; B-A: Bölling-Allerød; HS-1: Heinrich Stadial 1; MWP-1A: Meltwater Pulse 1A.

reflect the true marine limit, as the marine incursion was obstructed by a glacial front near the present coastline. Nonetheless, radiocarbon dating of coastal deposits overlying the moraine ridges dated by the cosmogenic method provide ages varying between 14.5 and 15.1 cal ka BP. These results indicate a minimum age for a glacial readvance, which could have reached or even exceeded the modern coastline, and may represent the maximum extent of the Saint-Marie readvance. The mean exposure age may therefore be more representative of the ice margin retreat from the position of the moraine and indicate a minimum age of deposition. We also note that the oldest boulder from both the Sainte-Marie Moraine (SMA-02; 15.5 ± 0.6 ka) and Chicotte River moraine ridges (CHI-01; 15.3 ± 1.3 ka) have a comparable age. The oldest-exposure-age has in some cases been used to estimate the true age of moraines, as they minimize the variability introduced by soil erosion, boulder weathering and gradual exposure of boulders at the surface (e.g., Zreda et al., 1994; Hallet and Putkonen, 1994; Putkonen and Swanson, 2003). However, an ice margin readvance – as it is the case for the Sainte-Marie Moraine – would undoubtedly incorporate older material and bring additional variability and uncertainty into the age of a landform. We therefore suggest that the Sainte-Marie Moraine was deposited by a readvance of the ice margin which occurred between 15.5 and 14.7 ka – shortly before the deposition of beach-ridges – and the ice margin retreated from this position at ~ 14.4 ka (Fig. 6b). The large spread of ages could also point toward multiple ice margin readvances over the southern coast of Anticosti Island. Such dynamical behaviour of the ice margin could also explain the presence of older shells at the western tip of the island and near Pointe Sud-Ouest (Gratton et al., 1984; Dubois et al., 1988).

Deglaciation of the inner part of Anticosti Island is constrained almost exclusively by cosmogenic exposure dating. On the central plateau, two sites were ^{36}Cl -dated at 9.9 ± 0.1 ka (Lake Wickenden) and 14.3 ± 0.4 ka (Safari). Due to the highly weathered nature of the first site (Fig. 2b), it is probably not representative of the deglaciation of the island. The second site located at the eastern end of the central plateau, however, provides a plausible age for deglaciation of the central part of Anticosti Island. Similarly, the results of the cosmogenic dating on the moraine ridges near Rivière-à-l'Huile suggest that the ice margin stabilized on the northern part of the island at ~ 14.2 ka. In the eastern part of the island, two minor moraine ridges are ^{10}Be -dated at 13.5 ± 0.3 ka (Lake Renard) and 13.7 ± 0.7 ka (Aquila Moraine). The ages of the distinct sites almost all overlap with each other and are statistically undistinguishable from one another. In turn, the oldest boulder sampled in the eastern part of the island (14.8 ± 0.5 ka; AQU-06) is closer in age with other sites on the island. It may therefore be more representative of the landform true age as discussed above. Along the north shore of the island, most radiocarbon ages are coherent with a deglaciation of the coast by 14 ka, except for the easternmost part at 14.7 ka. Altogether, these ages indicate a relatively rapid retreat of the ice across Anticosti Island that lasted only a few centuries, most likely between 14.4 and 14.0 ka (Fig. 6c). The presence of De Geer moraines in some valleys suggests, however, that the retreat pace was rather gradual (~ 75 m/yr).

Considering the results from the cosmogenic exposure dating on Anticosti Island, as well as the radiocarbon ages along the northern shore, we can confidently state that the LIS had completely withdrawn from the island by ~ 14 ka (Fig. 6d). This timing is further supported by radiocarbon ages from the literature also suggesting ice free conditions on the northern shore of the island around ~ 14 ka (Goslin et al., 2023). These ages conflict with a sample collected in a marine sediment core, suggesting a deglaciation as early as 15.8 ± 0.7 cal ka BP (Josenhans and Lehman, 1999). This timing could point toward an earlier retreat of the ice margin along the axis of the strait, favoured by enhanced calving at the marine-terminating ice margin. However, this age is ~ 1000 yrs older than two other samples retrieved from the Jacques-Cartier Strait (Dalton et al., 2020) and should therefore be considered with caution.

5.3. The Anticosti Ice Cap

One of the long-standing questions regarding the glacial history of Anticosti Island was whether there was a local ice cap during the last deglaciation. Early work invoked a residual ice cap to explain the Sainte-Marie Moraine in the western part of the island (Painchaud et al., 1984), while more recent studies have proposed ice cap development restricted to the central and eastern parts of the island (Goslin et al., 2023; Héту et al., 2023). The chronological data presented here does not provide clear evidence for the presence of an independent ice cap on Anticosti Island, as exposure ages are statistically similar across the island, including the central plateau (14.3 ± 0.4 ka). Slightly younger exposure ages in the eastern part of the island (13.5 ± 0.3 and 13.7 ± 0.7 ka) could, however, reflect delayed deglaciation of localized areas, potentially due to short-lived residual ice masses. While the geomorphological signature of the landforms sampled suggest an ice margin generally retreating towards the north, it does not rule out the presence of a residual ice mass during the late stages of deglaciation. It is also possible that the hypothesized local ice cap on Anticosti Island was, in fact, characterized by isolated and individualized ice masses. Enhanced calving in the deeper part of the Jacques-Cartier Strait could have favoured the isolation of these ice masses in the eastern and central parts of the island. The preservation of independent ice masses is not unusual, with several examples of low-elevation and wet-based ice caps occurring throughout the last deglaciation in Atlantic Canada (Catto, 1998; Shaw et al., 2006; Stea et al., 2011).

The possibility of a local ice cap is therefore included in our deglaciation scenario. Residual ice masses could have been restricted to the higher central plateau and, possibly, to certain depressions in the east. However, it seems unlikely that the Sainte-Marie Moraine was deposited by a local ice cap in the western part of the island due to: (i) the absence of a radial ice flow; and (ii) the presence of a series of recessional moraines across most valleys indicating a SW-NE oriented ice retreat. These local ice masses preserved on Anticosti Island could have formed between ~ 14.4 and ~ 14.0 ka following the retreat of the LIS margin (Fig. 6c). Based on the youngest cosmogenic ages in the eastern part of the island, they likely had completely disappeared by ~ 13.5 ka (Fig. 6d). These results are closely comparable to the timing of 14.5–13.8 ka reconstructed from meltwater supplies to beach-ridges (Goslin et al., 2023). However, a more thorough analysis of geomorphological and sedimentological evidence, as well as a larger chronological dataset, would be necessary for precisely constraining the extent and timing of such ice masses on Anticosti Island, as well as its potential interaction with the retreating LIS margin.

6. Implications on LIS margin dynamics

6.1. Controls on ice margin behaviour

Chronological controls on the Sainte-Marie Moraine indicate that the LIS margin stabilized on Anticosti Island towards the end of Heinrich Stadial 1 (HS-1; 20–14.6 ka; Hodel et al., 2017). Although Greenland ice cores recorded generally cold atmosphere temperatures during HS-1 (Fig. 7; Rasmussen et al., 2014), ice sheets of the Northern Hemisphere witnessed extensive retreat across many regions (e.g., Alley and Clark, 1999; Rinterknecht et al., 2006; Lowell et al., 2021; Halsted et al., 2024). Denton et al. (2005) suggested that the cooling recorded in ice cores was mainly a winter phenomenon associated with extensive sea ice in the North Atlantic and that summers continued to warm due to rising insolation (Fig. 7; Laskar et al., 2004) and greenhouse gases, which could have driven an increasingly negative ice surface mass balance over a large portion of the ice sheet surface and favour overall ice retreat. This seasonality has been termed 'Heinrich Summers' and is associated with a series of feedback processes driven by enhanced meltwater fluxes to the North Atlantic Ocean, thus increasing the continentality in the Northern Hemisphere (Denton et al., 2022; Toucanne et al., 2026). Similarly,

numerical modelling suggests that climate variability and seasonality of temperatures is highly underestimated in Greenland ice cores during cold glacial conditions, such as HS-1 (He et al., 2021). Relatively colder peaks of temperature are therefore sometimes completely absent or appear highly attenuated in the ice core-derived $\delta^{18}\text{O}$ record. Nonetheless, centennial-scale events are still recorded in Greenland ice cores and cold temperature peaks occurred toward the end of HS-1 (Fig. 7; Rasmussen et al., 2014). Such cooling could be the results of –or accentuated by– oceanic processes, such as the strength of northward heat transport by the Atlantic Meridional Overturning Circulation (AMOC) (Alley and Clark, 1999; Clark et al., 2001; McManus et al., 2004; Weijer et al., 2019). North Atlantic sediment $^{231}\text{Pa}/^{230}\text{Th}$ (Fig. 7; McManus et al., 2004) suggests a variation in the strength of northward heat transport by the AMOC around 15 ka. This weakening of the AMOC is thought to be linked to meltwater events from receding Northern Hemisphere ice sheets (Clark et al., 2001; McManus et al., 2004; Carlson and Clark, 2012; Hodell et al., 2017). It is, however, difficult to assess whether this weakening at the end of HS-1 is related to a continuous flow of freshwater input from the receding ice sheets gradually weakening AMOC (Carlson and Clark, 2012; Denton et al., 2022) –in line with the ‘Heinrich Summers’ theory– or a single large-scale freshwater event causing an abrupt reduction in AMOC (Clark et al., 2001; Thornalley et al., 2010). The combination of increased seasonality and abrupt oceanic processes in the North Atlantic likely provoked cooler and/or wetter climatic conditions, triggering resurgence of the ice sheets in the Northern Hemisphere and, consequently, lead to the readvance of the ice margin on Anticosti Island.

Ice recession from the Sainte-Marie Moraine –and Anticosti Island– coincides with the beginning of the Bølling-Allerød interstadial at 14.6 ka (Fig. 7; Rasmussen et al., 2014). The onset of the Bølling-Allerød was accompanied by an abrupt and substantial increase in temperature to interglacial values, reflecting the effects of rising insolation, higher greenhouse gas concentrations, and a resurgence in the strength of the AMOC (Clark et al., 2001; McManus et al., 2004; Liu et al., 2009). Consequently, it is likely that the LIS retreated from Anticosti Island during this interval in response to hemispheric warming and enhanced ice-sheet ablation. In contrast, a local Anticosti Ice Cap may have persisted during the early Bølling-Allerød, despite climatic conditions generally unfavorable for glacier growth (Alley and Clark, 1999; Rasmussen et al., 2014). It could therefore explain its relatively short-lived presence on the island before completely disappearing (Goslin et al., 2023), although local climatic conditions may have been different shortly after deglaciation and helped maintain such ice caps (Stea et al., 2011).

The location of Anticosti Island along the northern slope edge of the Laurentian Channel likely played a key role on the LIS dynamics, acting as a pinning point for the ice margin to stabilize during its overall retreat and favouring the formation of a calving bay in the Jacques-Cartier Strait. First, the ice margin seemingly anchored and stabilized on the topographic high represented by the island. This vertical pinning point drastically increased basal drag which, in turn, decreased mass flow to the ocean through iceberg calving (Jamieson et al., 2014; Carr et al., 2015). Coupled with the cold peaks of temperature at the end of HS-1, it created an ideal setting for the stabilization of the LIS across Anticosti Island. Therefore, it is highly likely that the Sainte-Marie readvance was climatically induced by colder atmosphere temperature and topographically controlled by the presence of the island in the Gulf of St. Lawrence. In contrast, deeper water in the Jacques-Cartier Strait likely favoured the acceleration of ice retreat, leading to the early deglaciation of the easternmost tip.

6.2. Synchronicity of ice margin stabilization in the SE sector of the LIS

Coeval stabilizations and/or readvances of the ice margin have been identified along the southeastern sector of the LIS (Balco et al., 2009; Ridge et al., 2012; Hall et al., 2017; Koester et al., 2017; Lowell et al.,

2021; Halsted et al., 2024). Cosmogenic exposure dating of the Pineo Ridge moraine complex (Fig. 1a) by two independent studies allowed identifying the timing of ice margin stabilization in eastern Maine between 15.3 and 14.5 ka. Hall et al. (2017) published a dataset of nine samples, producing a mean age of 15.0 ± 0.8 ka and a peak age of 15.3 ka. In turn, Koester et al. (2017) published a dataset comprising seven boulders, yielding a mean exposure age of 14.5 ± 0.7 ka. While there is a slight discrepancy between the results of both studies, the datasets are statistically indistinguishable as the uncertainties overlap. Furthermore, the Pineo Ridge moraine complex can, allegedly, be traced at least 40–50 km into New Brunswick as a series of kames, ice-contact deltas and moraines (Hall et al., 2017), constraining the position of the ice margin over nearly 200 km in the region at that time. More recently, a larger dataset of 45 samples was used to constrain the deglaciation of eastern Maine at 15.3 ± 0.5 ka (Hall et al., 2025), supporting the previous studies in the area. In New Hampshire, the North Charlestown Moraine (Fig. 1a) was dated between 14.7 and 14.6 ka based on the North American Varve Chronology (NAVC) from the Connecticut Valley (Ridge et al., 2012). The authors suggest that the moraine represents a phase of ice margin stabilization during an overall fast retreat, as there is no evidence of a major readvance. Although only one sample was retained in the final version, this moraine was also used as a calibration site for cosmogenic ^{10}Be production rates in northeastern North America (Balco et al., 2009). The lone sample yielded a concordant cosmogenic exposure age of 14.8 ± 0.5 ka, supporting the age derived from the varve chronology. This age was further corroborated in a recent compilation of geochronological data in the northeastern United States, indicating a stabilization of the receding ice margin slightly prior to 14.6 ka (Halsted et al., 2024). Finally, cosmogenic exposure dating of 11 samples constrain the timing of deposition of the Eagle-Finlayson Moraine (Fig. 1a) between 16.3 ± 1.1 ka and 13.3 ± 0.9 ka in Western Ontario (Lowell et al., 2021). Using a Bayesian modelling approach, they suggested that ice retreated from the position of the moraine at 14.7 ± 0.7 ka. According to their model, the Eagle-Finlayson Moraine is part of a series of moraines that represent a hiatus (i.e., stabilizations of the ice margin) of 620 years in the deglaciation chronology of the Lake Superior region.

Considering the respective uncertainties of these chronologies, stabilization ages from different sectors of eastern North America have a similar timing as the Sainte-Marie readvance and stabilization on Anticosti Island, dated between 15.3 and 14.4 ka. The synchronicity of the ice margin over thousands of kilometers (>2500 km) in the southeastern sector of the LIS therefore implies an external control on its behaviour. Altogether, these results suggest an ice-sheet-wide response to HS-1 cooling and strengthen our interpretation on climate forcings as the main driver of ice margin readvance on Anticosti Island. Coeval stabilization and/or readvance of the ice margin also occurred further north on Baffin Island (Margreth et al., 2017; Jenner et al., 2018) and in western Canada (Norris et al., 2022), emphasising once again the external forcing on the behaviour of the LIS at the end of HS-1.

6.3. Implications on the dynamics of the St. Lawrence Ice Stream

The geochronological data and deglaciation scenario presented for Anticosti Island provide a comprehensive and direct dating chronology for the deglaciation of the Gulf of St. Lawrence. This scenario includes a phase of ice margin stabilization at the end of HS-1 and retreat at the beginning of the Bølling-Allerød that is likely to be similar for the Laurentian Channel. This timing is further supported by comparable deglaciation ages from radiocarbon dating of marine shells in Gaspésie, located directly to the south of the Honguedo Strait, suggesting that ice retreated from its coast and into the valleys between 14.5 and 14.0 cal ka BP (Hétu and Gray, 2000; Olejczyk and Gray, 2007). The implication of this deep-water trough terminating at the Atlantic continental shelf edge is of utmost importance for the regional deglaciation as it was one of the major pathways for ice drainage within the southeastern sector of the

LIS during the last glacial episode, draining ice flowing from Québec-Labrador, Nova Scotia, New Brunswick and Newfoundland (Shaw et al., 2006; Stea et al., 2011). The Laurentian Channel is widely interpreted to have hosted a fast-flowing ice stream (namely the St. Lawrence Ice Stream) during the LGM and subsequent deglaciation (Thomas, 1977; Parent and Occhietti, 1999; Hulbe et al., 2004). Glaciological models further suggest that Anticosti Island was located at the onset zone of fast-flowing ice sourced from the Québec North Shore and resulted from the funneling of ice into the overdeepened Laurentian Channel (Shaw et al., 2006; Stokes and Tarasov, 2010; Eyles and Putkinen, 2014). While the complete retreat history of the St. Lawrence Ice Stream remains mostly unresolved, our results provide chronological constraints on its late-stage separation from ice sourced on the Québec North Shore and serve as a benchmark for the retreat of the ice stream into the Laurentian Channel.

The retreat of the ice margin from Anticosti Island closely aligns with the rapid global sea-level rise of ~20 m associated with Meltwater Pulse 1A (~14.65–14.3 ka; Fig. 7; Lin et al., 2021). This event reflects catastrophic ice wastage globally (Fairbanks, 1989; Lambeck et al., 2014; Harrison et al., 2019; Lin et al., 2021; Couette et al., 2022; Li et al., 2023; Coonin et al., 2025) and may be connected to the rapid retreat of the ice margin along the Laurentian Channel (Shaw et al., 2006). Whether the St. Lawrence Ice Stream significantly contributed to global sea-level rise during Meltwater Pulse 1A is, however, beyond the scope of this paper. Nonetheless, the impact of the St. Lawrence Ice Stream demise should be further investigated, as deglaciation of the LIS was likely a major contributor to Meltwater Pulse 1A sea-level rise (Carlson and Clark, 2012; Clark and Tarasov, 2014; Lin et al., 2021; Coonin et al., 2025).

7. Conclusion

The cosmogenic and radiocarbon ages, together with a map of major moraine systems presented in this paper, allow establishing a new chronological framework for the deglaciation of Anticosti Island. These results highlight the complex interplay of climatic factors in controlling the behaviour of the LIS margin at the end of HS-1 and at the onset of the Bølling-Allerød interstadial. The combination of increased seasonality, abrupt oceanic processes, and weakening of the AMOC during HS-1 likely provoked the re-advance and stabilization of the ice margin on Anticosti Island, while a subsequent rapid warming at the beginning of the Bølling-Allerød led to its retreat. The synchronous ice margin stabilization in the southeastern sector of the LIS supports the interpretation of a widespread, climate-driven control on ice-sheet dynamics during this interval (e.g., Ridge et al., 2012; Hall et al., 2017, 2025; Koester et al., 2017; Lowell et al., 2021). These results suggest that ice retreat in the Laurentian Channel, which served as a significant ice drainage pathway for the LIS, was temporally consistent with the onset of Meltwater Pulse 1A. They also highlight the potential role of the St. Lawrence Ice Stream in contributing to rapid sea-level rise during deglaciation. These findings therefore offer key constraints for numerical models evaluating LIS contributions to past and future sea-level change and provide a valuable analogue for the vulnerability of modern marine-based ice-sheet margins, ice shelves and calving bays in Antarctica and Greenland. Future work in the Gulf of St. Lawrence should focus on constraining the precise timing and spatial patterns of the last deglaciation, as well as identifying both its glaciological and climatic consequences, including the development of a major calving bay, which may serve as an analogue for the possible future collapse of marine-terminating ice sheets.

Author contributions

POC and PB conceived and designed the study in cooperation with VR and PL. PB, BH and JD collected samples for radiocarbon dating. POC, PB and VR collected samples for cosmogenic exposure dating. POC performed ^{10}Be and ^{36}Cl sample preparation and data analysis under the

supervision of VR. ASTER team oversaw measurement of cosmogenic nuclides via AMS and LN2C national facility. POC drafted the initial manuscript and performed initial data reduction and statistical analysis. All authors were involved in the discussion of the data and contributed to the final version of this manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.quascirev.2026.109904>.

Data availability

All data and/or code is contained within the submission.

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