UNIVERSITÉ DU QUÉBEC À MONTRÉAL

RECONSTRUCTION DU LAC GLACIAIRE CAMBRIEN ET DE L'INCURSION MARINE À PARTIR DES ENREGISTREMENTS GÉOMORPHOLOGIQUES ET SÉDIMENTAIRES DU CENTRE-SUD DE L'UNGAVA-LABRADOR (CANADA)

MÉMOIRE

PRÉSENTÉ

COMME EXIGENCE PARTIELLE

DE LA MAÎTRISE EN SCIENCES DE LA TERRE

PAR

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^{10}Be : Béryllium 10

^{14}C : Carbone 14

^{9}Be : Béryllium 9

AMOC : *Atlantic meridional overturning circulation* / Circulation méridienne de retournement de l'Atlantique

BP : *Before present* / Avant aujourd'hui

cal a BP : Années calibrées avant aujourd'hui (1950)

CDEM : *Canadian Digital Elevation Model* / Modèle numérique d'élévation canadien

DGPS : *Differential global positioning system* / Système mondial de positionnement différentiel

GIA : *Glacio-isostatic adjustment* / Ajustement glacio-isostatique

GPS : *Global positioning system* / Système mondial de positionnement

HCl : Acide chlorhydrique

HClO4 : Acide perchlorique

HF : Acide fluorhydrique

HIZ : *Horseshoe Intersection Zone* / Zone d'intersection du *Horseshoe*

LDEO : Lamonth-Doherty Earth Observatory

LIS : *Laurentide Ice Sheet* / Inlandsis laurentidien

MNT : Modèle numérique de terrain

SIG: Système d'information géographique

SNRC : Système national de référence cartographique

RÉSUMÉ

Le retrait de la calotte Laurentidienne dans le nord du Québec et du Labrador (Canada) a mené à la formation de plusieurs grands lacs de barrage glaciaire. Le drainage de ces lacs glaciaires pourrait potentiellement avoir affecté la circulation océanique de l'Atlantique Nord et le climat au cours de la déglaciation. L'évaluation de l'impact de ces décharges répétées d'eau de fonte sur le système océan-climat est cependant limitée par le manque de données sur la configuration (étendue et volume) et la chronologie de ces lacs glaciaires, de même que sur la position de la marge glaciaire qui a contrôlé leur évolution. De plus, l'incursion des eaux marines postglaciaires sur le territoire complexifie l'interprétation de certaines séquences de rivages qui enregistrent ces événements, notamment dans la région centre-sud de l'Ungava. La compréhension des processus géomorphologiques qui ont façonné le territoire est également d'intérêt pour les recherches archéologiques qui ont révélé la présence de plusieurs sites pré-contact témoignant de l'occupation du territoire (campements, routes migratoires, etc.) par des groupes autochtones.

Ce projet de maîtrise se penche sur les enregistrements géomorphologiques et sédimentaires de la région englobant les vallées des rivières Caniapiscau et Koksoak, au sud de Kuujjuaq (Nunavik). La cartographie des eskers, moraines et chenaux d'eau de fonte, effectuée à partir d'images satellitaires et de modèles d'élévation numérique, a permis de reconstruire le patron de déglaciation régional. L'étude des paléo-rivages glaciolacustres et glaciomarins, deltas et terrasses a quant à elle permis d'établir la configuration respective de ces deux étendues d'eau. Les observations cartographiques ont été validées par des travaux de terrain qui ont également permis la prise de mesures d'élévation de haute précision (± 1 m) des formes clés le long d'un transect nord-sud de 190 km. La reconstruction des plans d'eau est basée sur un système d'information géographique (SIG) qui inclus l'utilisation de paléosurfaces illustrant la physiographie régionale approximative au moment de leur existence (~7 ka BP).

Les résultats indiquent que les rivages présents dans les vallées des rivières Caniapiscau et Koksoak et dans le bassin du lac Cambrien sont majoritairement d'origine glaciomarine. La combinaison du patron du retrait glaciaire déterminé à partir des données cartographiques et des modélisations indique qu'un lac glaciaire s'est développé dans le sud du lac Cambrien et dans les bassins adjacents à l'est, avec une étendue d'environ 2500 km^2 et un volume de 105 km^3. De plus, l'application de la datation par isotopes cosmogéniques à des blocs présents sur des rivages de différentes élévations a donnée 14 âges ^{10}Be qui indiquent que le drainage du Lac glaciaire Cambrien et l'incursion marine concomitante se sont produits aux alentours de 7200 ans ± 200 ans BP. L'exondation progressive du territoire causée par le rebond post-glaciaire a culminé avec le retrait des eaux marines de la zone d'étude vers 4400 ans ± 200 ans BP.

Ensemble, ces résultats renforcent le schéma et le timing du retrait glaciaire dans la région pendant la dernière déglaciation, en plus de fournir un cadre chronologique à la migration et l'établissement humain dans le centre-nord de l'Ungava par les ancêtres des Naskapi. Les nouvelles datations cosmogéniques affinent également les reconstructions paléogéographiques du sud de la baie d'Ungava, en plus de préciser la magnitude des décharges d'eau de fonte de cette région au début de l'Holocène.

Mots-clés : déglaciation, lacs glaciaires, cartographie quaternaire, datation par nucléides cosmogéniques, archéologie

INTRODUCTION

La période du Quaternaire est caractérisée par le développement cyclique de masses de glace d’envergure continentale qui ont recouvert de grandes superficies de l’Hémisphère Nord (Hewitt, 2000). Au cours du dernier million d’années, ces cycles glaciaires étaient marqués par une lente croissance de ces inlandsis, laquelle était suivi d’une déglaciation rapide (Imbrie et al., 1993; Lisiecki and Raymo, 2005). Cette dynamique a donné lieu à une série d'interactions entre les différentes composantes du système climatique, en plus de produire une vaste gamme d’enregistrements sédimentaires et géomorphologiques sur les territoires anciennement englacés (Prest et al. 1968; Fulton, 1995). L’étude de ces archives morpho-sédimentaires permet en partie de reconstituer l’histoire glaciaire et post-glaciaire des régions septentrionales. Dans le nord du Québec, la présence de dépôts et formes de terrain d’origine glaciolacustres (deltas, rivages, terrasses) témoignent de l’existence de plusieurs lacs d’obturation glaciaire dans les vallées d’importantes rivières du centre de l’Ungava (Ives, 1960; Barnet, 1963; Dubé-Loubert et Roy, 2017). Ces lacs glaciaires se sont développés lors de la dernière déglaciation, alors que la marge glaciaire en retrait a endigué les voies d’écoulement naturel de ces rivières vers la baie d’Ungava (Gray et al., 1993). La production massive d’eau de fonte concomitante au retrait glaciaire a contribué à l'agrandissement de ces bassins glaciolacustres (Teller, 1995).

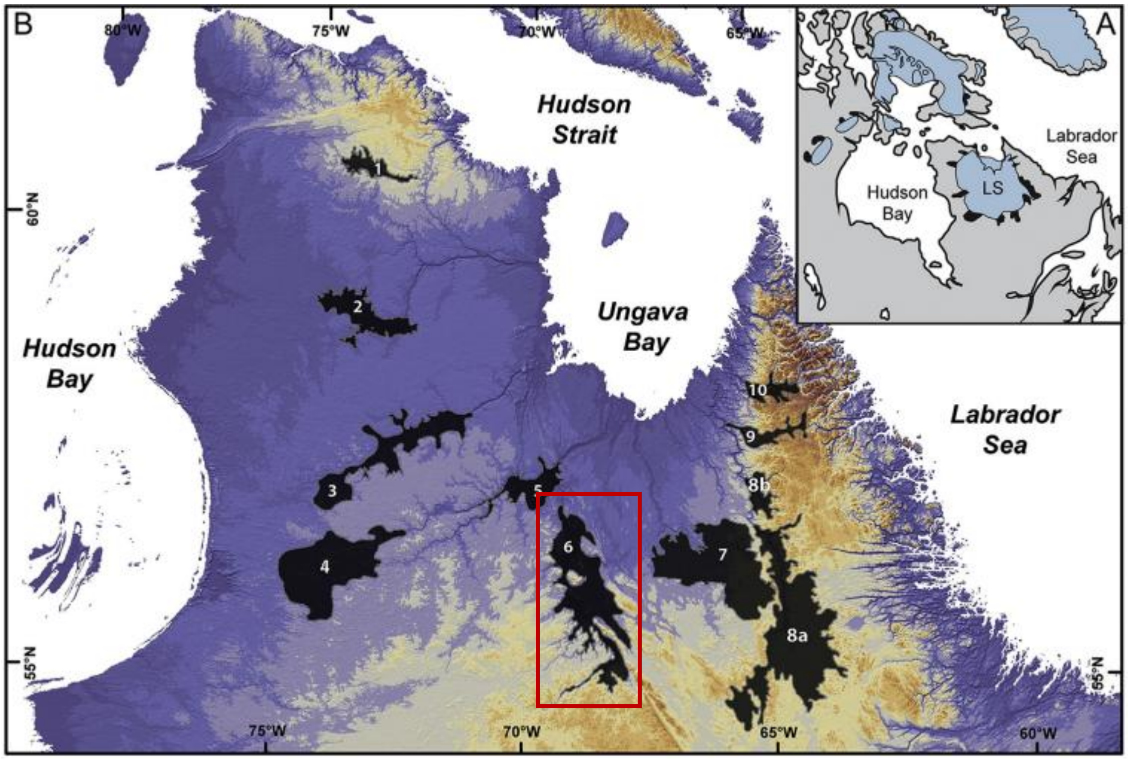

Figure 0.1 (A) Carte schématique de l'inlandsis Laurentidien à la fin de la déglaciation (~10 cal a BP; modifié de Dyke, 2004) et des lacs glaciaires (noirs) du secteur du Québec-Labrador (LS). (B) Localisation des lacs glaciaires du Nord du Québec pendant la dernière déglaciation : 1) Lac Nantais, 2) Lac Payne, 3) Lac Minto, 4) Lac à l'Eau-Claire, 5) Lac Mélèzes, 6) Lac Cambrien, 7) Lac McLean, 8) Lac Naskaupi, 9) Lac Ford et 10) Lac Koroc (Dubé-Loubert et al., 2018).

L'étude de ces lacs revêt d'une importance particulière en raison de la proximité de ceux-ci avec la mer du Labrador qui forme un secteur clé dans le fonctionnement de la circulation océanique méridionale de l'Atlantique (*Atlantic Meridional Overturning Circulation* : *AMOC*) (Clark et al., 2001; Barber et al., 1999; Teller et al., 2002; Carlson et Clark, 2012). En effet, de nombreuses études associent les variations climatiques de la dernière déglaciation à des injections massives d'eau de fonte en provenance du drainage de grands lacs glaciaires (Broecker et al., 1989, 1992; Alley et al., 1997; Barber et al., 1999; Carlson et Clark, 2012). Ces injections massives et répétées d'eau de fonte auraient affecté les sites de formation de masses d'eau profonde de l'Atlantique Nord (*North Atlantic Deep Water* : *NADW*) et provoqué un ralentissement significatif de la circulation thermohaline globale qui régule en partie le climat planétaire (Manabe et Stouffer, 1995; Barber et al., 1999; Alley et al., 2001).

Ces oscillations climatiques sont enregistrées dans de nombreuses archives paléoclimatiques comme celles basées sur les carottes de glace polaire et les sédiments marins (Heinrich, 1988; Dansgaard et al., 1993; Bond et Lotti, 1995; Bond et al., 1997; Klitgaard-Kristensen et al., 1998; Rasmussen et al., 2014). L'anomalie climatique la plus marquée de l'Holocène correspond au refroidissement de 8 200 ans B.P, alors que les températures ont chuté de 4 à 8°C au centre du Groenland et de 1,5 à 3°C autour de l'Atlantique Nord (von Grafenstein et al., 1998; Thomas et al., 2007). Ce refroidissement d'environ 160 ans aurait été initié par la vidange du grand Lac glaciaire Agassiz-Ojibway (Alley et al., 1997; Barber et al., 1999; Kleiven et al., 2008; Roy et al., 2011; Brouard et al., 2021). Les travaux de modélisation indiquent cependant que les volumes d'eau de fonte proposés pour le drainage du Lac Agassiz-Ojibway ne peuvent expliquer l'amplitude et la durée du refroidissement de 8,2 ka (LeGrande and Schmidt, 2008; Clarke et al., 2009), ce qui souligne la complexité de ce forçage en eau douce. De récents travaux indiquent que d'autres lacs glaciaires auraient pu se drainer pendant cet intervalle temporel critique de la dernière déglaciation, notamment ceux en provenance du centre de l'Ungava (Dubé-Loubert et al., 2018; Lefebvre-Fortier et al., 2024). Ainsi, bien que les seuils de sensibilité du système océanique à ces injections d'eau douce soient encore incertains, certaines études suggèrent un lien de causalité entre les décharges répétées d'eau de fonte dans la mer du Labrador (Jennings et al., 2015) et des perturbations climatiques ayant menées à des réavancées de glaciers sur l'Île de Baffin et au Groenland (Young et al., 2020).

Cependant, l'impact du drainage de ces lacs glaciaires sur le système océanique et climatique en général, ainsi que leur contribution respective, est difficile à évaluer du fait que la plupart d'entre eux sont encore peu documentés quant à leur configuration (étendue, volume), évolution et chronologie (Dalton et al., 2020). En effet, le développement de ces lacs glaciaires est intrinsèquement lié à la position et la configuration de la marge glaciaire – deux paramètres qui comportent beaucoup d'incertitudes dans les reconstructions paléogéographiques (Lauriol et Gray 1987; Teller, 1995). Ces incertitudes découlent notamment du peu de contrôle géomorphologique sur le retrait glaciaire, en plus du manque de données géochronologiques à l'intérieur des terres, majoritairement associées à l'absence de matériel organique nécessaire à la datation au radiocarbone (Dyke, 2004; Ullman, 2016; Godbout et al., 2020).

À cet égard, les lacs glaciaires de l'Ungava demeurent encore peu étudiés, à l'exception du Lac Naskaupi situé au pieds des montagnes Torngat dans l'est (Dubé-Loubert et Roy, 2017; Dubé-Loubert et al., 2018). Ceci découle en grande partie des patrons complexes de la déglaciation de ce secteur de l'inlandsis Laurentidien (cf. Clark et al., 2000; Dubé-Loubert et al., 2021). Cette situation s'applique particulièrement à la région au sud de la baie d'Ungava où les travaux antérieurs suggèrent un historique de déglaciation relativement complexe (Dyke et Prest, 1987; Veillette et al., 1999; Clark et al., 2000). Les schémas de retrait actuels indiquent que la glace du Secteur du Québec-Labrador en décrépitude se soit scindée en plusieurs masses de glace secondaires à un stade tardif de la déglaciation (Gray et al., 1993; Dalton et al., 2020). Toutefois, la chronologie de cette fragmentation, de même que l'emplacement exact de ces culots de glace qui auraient pu obstruer les vallées de certaines rivières s'écoulant vers la baie d'Ungava sont encore à ce jour relativement méconnus (Clark et al., 2000). De plus, les évidences de terrain suggèrent que la grande vallée qui englobe les rivières Caniapiscau et Koksoak, et qui renferme le Lac Cambrien, aurait pu accueillir un bassin glaciolacustre. Cependant, bien que la présence de rivages soulevés très profondément à l'intérieur des terres au sud tend à soutenir cette hypothèse (Gray et al., 1993), certaines études attribuent plutôt une origine glaciomarine à ces formes de terrain (Low, 1896; Drummond, 1965), soulignant une fois de plus le manque de données.

Les travaux de recherche de ce mémoire de maîtrise visent à documenter les enregistrements géomorphologiques du Lac Cambrien et des secteurs adjacents de la vallée de la rivière Caniapiscau dans le nord du Québec où l'on retrouve de nombreux rivages et deltas perchés. Comme le développement de lac glaciaire dans cette région est intimement lié à la position de la marge glaciaire en retrait dans le sud de la baie d'Ungava, un objectif attenant des travaux porte sur la reconstruction du patron de déglaciation régional. Ainsi, la cartographie détaillée des formes de terrain comme les eskers et moraines devrait renseigner sur le schéma de retrait glaciaire et sur l'historique du front glaciaire au cours de la déglaciation. De plus, l'étude détaillée de la répartition de ces séquences de rivages et leur datation devraient permettre de distinguer les formes de terrain associées à un possible lac glaciaire de celles reliées à la Mer d'Iberville. Globalement, ces travaux devraient permettre de renforcer le contexte paléogéographique et un cadre chronologique cohérents pour le secteur au sud de la baie d'Ungava. Ces travaux permettront également d'accroître les efforts déployés dans l'apport de nouvelles contraintes chronologiques au pourtour de la baie d'Ungava.

Les principaux objectifs de ce projet de maîtrise se divisent ainsi :

1. Documenter l'évolution spatio-temporelle de la marge glaciaire et son influence sur le développement du Lac glaciaire Cambrien ;
2. Distinguer les enregistrements géomorphologiques associés à l'incursion des eaux marines de ceux reliés à l'épisode glaciolacustre ;
3. Reconstruire l'étendue (configuration) et les volumes associés au Lac glaciaire Cambrien ;
4. Contraindre la chronologie du développement du lac ainsi que de l'incursion marine subséquente via l'application de la méthode de datation par isotopes cosmogéniques (^{10}Be) sur des formes littorales et deltaïques.

Pour répondre à ces objectifs, une carte géomorphologique recensant les eskers, moraines et chenaux d'eau de fonte a été produite à partir de l'étude d'images satellitaires et d'un logiciel de système d'information géographique (SIG). Les paléo-rivages glaciolacustres et glaciomarins, de même que les autres formes de terrain associées à leur existence (deltas, terrasses, chenaux, etc) ont également été cartographiés afin de brosser un portrait de la configuration respective de chacune de ces étendues d'eau. Ces données et observations ont été validés par des travaux de terrain qui ont permis et mesurer l'élévation de ces formes de terrain à l'aide d'un GPS différentiel à haute précision.

Des échantillons de blocs présents à la surface de ces anciens rivages ont été collectés afin d'être dater par isotopes cosmogéniques (^{10}Be). Le traitement des échantillons a été effectué par l'entremise d'un stage de formation au centre de recherche *Lamont-Doherty Earth Observatory* (LDEO) de *Columbia University* (New-York, États-Unis). À partir des données collectées et des approches géomatiques, une modélisation des volumes d'eau de fonte contenu dans le Lac glaciaire Cambrien a pu être réalisée.

Ce projet de maîtrise s'inscrit dans un projet de plus grande envergure qui vise à faire de la région des lacs Cambrien (*Mistisiipuw*) et Nachicapau (*Nachacapau*) une aire protégée. Ce projet a été initiée par la Nation Naskapie de Kawawachikamach, en partenariat avec le gouvernement régional de Kativik, la Société Makivik, le gouvernement du Québec ainsi qu'Hydro-Québec via une entente approuvée par décret gouvernemental et signée par les partis en 2018 (Denton et McCaffrey, 2021). La région à l'étude est profondément liée à l'histoire des Naskapis qui occupent ce territoire depuis des millénaires et qui sont spirituellement attachés à la terre et aux ressources qu'elle leur fournit. Nos travaux se joignent à ceux d'archéologues, de biologistes et de botanistes afin de décrire le caractère exceptionnel de cette région quant à sa richesse biologique, géologique et historique, en fournissant un cadre chrono-physiographique qui devrait contribuer aux recherches archéologiques sur l'occupation humaine menées dans la région.

Ce mémoire est composé de deux chapitres. Le premier synthétise les principaux éléments physiographiques et géologiques de la région à l'étude. L'état des connaissances quant à la déglaciation du sud de la baie d'Ungava est également sommairement présenté afin de contextualiser les travaux dans lesquels s'insèrent ce projet de recherche. Le second chapitre aborde la dualité entre le développement du Lac glaciaire Cambrien et l'incursion par la Mer d'Iberville en se basant sur l'ensemble des résultats obtenus par le biais des travaux de cartographie et des datations par isotopes cosmogéniques. Ces résultats sont présentés sous forme d'article scientifique intitulé : *Differentiating the Glacial Lake Extent from Glaciomarine Incursion in the Geomorphological Record of South-Central Ungava-Labrador (Canada)* et qui devrait être soumis à la revue *Journal of Quaternary Science*. Finalement, la conclusion résume l'ensemble des travaux réalisés dans le cadre de ce projet, les principaux résultats qui en découlent ainsi que leurs apports aux connaissances scientifiques dans le domaine de la géologie du Quaternaire.

CHAPITRE 1

CADRES PHYISOGRAPHIQUE ET GÉOLOGIQUE

1.1 Localisation et hydrographie

La région du lac Cambrien se trouve au sud de la baie d’Ungava, à environ 330 kilomètres au sud-ouest de Kuujjuaq (Nunavik). Le réseau hydrographique est principalement articulé autour de la rivière Caniapiscau et de ses principaux tributaires qui incluent du sud au nord, les rivières de la Mort, Chateauguay et Swampy Bay. La rivière Caniapiscau et la rivière aux Mélèzes sont les deux affluents de la rivière Koksoak qui s’écoule vers le nord pour se déverser dans la baie d’Ungava avec un débit moyen de 1336 m^3/s (MELCCFP, 2023a). Outre le lac Cambrien, qui forme un renflement dans la rivière Caniapiscau, de nombreux plans d’eau d’importance recouvrent le territoire, tels que le lac Lemoyne, le lac Nachicapau et le lac Otelnuk. Le territoire couvert par ce présent mémoire correspond à quatre feuillets SNRC à l’échelle 1 : 250 000, soit les feuillets 024C, 024D, 024E et 024F. La vallée du lac Cambrien est en entièreté contenue dans le feuillet 024C.

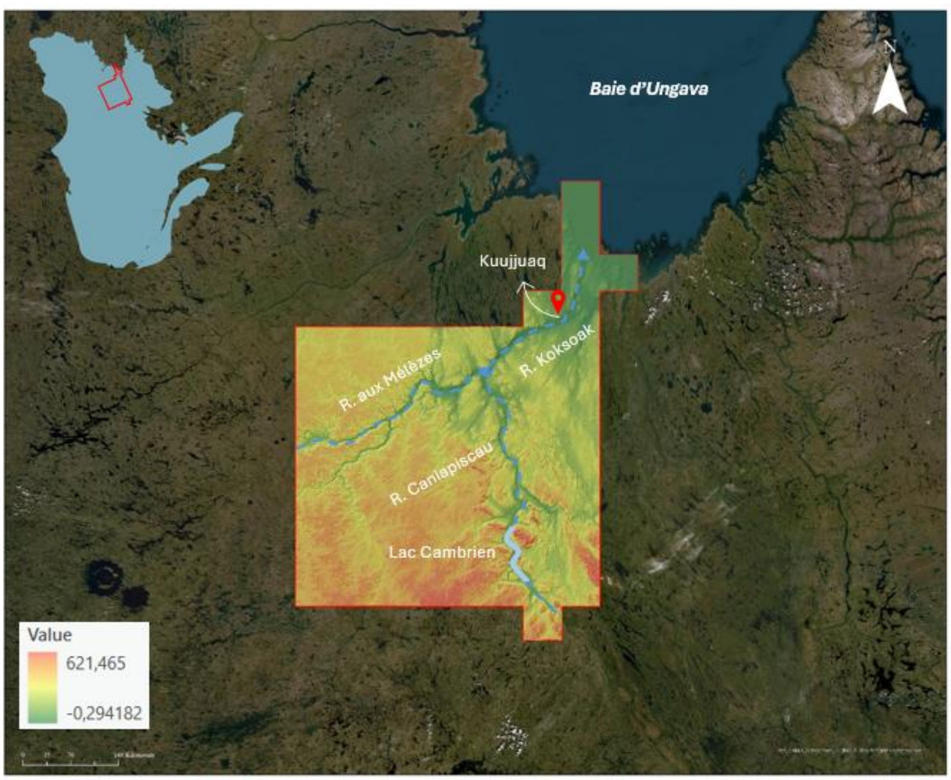

Figure 1.1 Physiographie et hydrographie de la zone d’étude.

1.2 Physiographie

L’ouest du lac Cambrien est bordé par les hauts plateaux de la province naturelle du plateau central du Nord-du-Québec, particulièrement au sud où les points culminants peuvent atteindre 700 mètres (Li et al., 2019). Le plateau vallonné qui occupe le sud-ouest de la région cède place au nord à un vaste champ de drumlins orientés NNE-SSO avec des élévations comprises entre 300 et 400 mètres et qui s’étend jusqu’à la confluence des rivières Caniapiscau et aux Mélèzes (Drummond, 1965). L’est du lac Cambrien est caractérisé par une grande dépression associée à la province naturelle du bassin de la baie d’Ungava. Cette dernière s’incline progressivement du sud où l’élévation avoisine les 500 mètres, jusqu’à atteindre le niveau de la mer au nord (Li et al., 2019). Le terrain est relativement accidenté alors que se succèdent plusieurs crêtes étroites et vallées profondes, topographie propre à la Fosse du Labrador (Low, 1896 ; Li et al., 2019). Des dépôts morainiques sont également retrouvés de ce côté du lac. Le territoire est occupé du sud au nord par des moraines côtelées, des moraines de décrépitude et des drumlins orientés N-S. L’élévation moyenne des plateaux immédiats à la vallée du lac Cambrien avoisine les 400 mètres alors que le niveau actuel de celui-ci est de 75 mètres (Drummond, 1965 ; Clark, 1984). De grandes terrasses fluvioglaciaires de 100 mètres d’épaisseur longent le lac et recouvrent le roc (Clark, 1984).

1.3 Climat et végétation

La région à l’étude est caractérisée par un climat subpolaire froid avec des températures moyennes sous le point de congélation de novembre à avril (Li et al., 2019 ; MELCCFP, 2023b). La saison estivale est relativement courte et fraîche avec une température moyenne de 13°C (Moore, 1974). Le climat est humide en raison des précipitations modérées qui atteignent environ 750 millimètres par an, majoritairement sous forme de pluie (MELCCFP, 2023b). Les hivers rigoureux, couplés aux variations saisonnières et quotidiennes d’ensoleillement, se traduisent par une période de croissance de la végétation limitée (Moore, 1974 ; Li et al., 2019).

La région du lac Cambrien est située dans le domaine bioclimatique de la toundra forestière qui marque la transition entre la zone boréale à laquelle elle appartient et la zone arctique (Saucier et al., 2003). Ce domaine bioclimatique est fortement dominé par l’épinette noire, mais comprend également d’autres conifères adaptés au froid, tels que le mélèze laricin, l’épinette blanche, le sapin baumier ainsi que de rarissimes bosquets de feuillus (Payette, 1976 ; MFFP, 2022). La strate végétale basse est quant à elle dominée par des lichens et des arbustes rabougris (Payette, 1976 ; MFFP, 2022). Celle-ci occupe initialement les zones les plus exposées au sud, tels que les sommets des collines, puis gagne progressivement du terrain jusqu'à prédominer au nord (Dressler, 1979 ; Saucier et al., 2003).

1.4 Géologie du substratum rocheux

La région à l'étude est située à cheval entres les provinces géologiques du Supérieur et du Churchill (Fahrig, 1957). La province du Supérieur constitue le cœur du Bouclier canadien et ses deux sous-provinces les plus septentrionales, Minto et Ashuanipi, occupent l'ouest du lac Cambrien. La sous-province de Minto est majoritairement composée de roches plutoniques felsiques d'âge archéen, telles que des tonalites, des granites, des granodiorites et des charnockites, orientées grossièrement NNO-SSE (Madore et al., 1999 ; Simard et al., 2008). La sous-province d'Ashuanipi couvre une faible superficie au sud-ouest de la zone à l'étude et est quant à elle formée d'un ensemble de roches métasédimentaires et d'intrusions tonalitiques hautement métamorphisées et déformées, (Clark, 1984 ; Percival et al., 1992). L'est du lac Cambrien se situe dans la portion sud-est de la province géologique du Churchill, majoritairement dans la Fosse du Labrador, une ceinture volcano-sédimentaire d'âge protérozoïque (Hodgson, 1990; Hoffman 1990; Clark 1994; Clark et Wares, 2004). Vers l'extrémité est de la zone à l'étude s'étend une plaine faiblement accidentée qui correspond à la Zone Noyau. Cette dernière est composée de gneiss archéens et de granites protérozoïques variablement déformées et métamorphisées jusqu'au faciès des amphibolites et des granulites (Wardle et al. 1990; James et al., 1996).

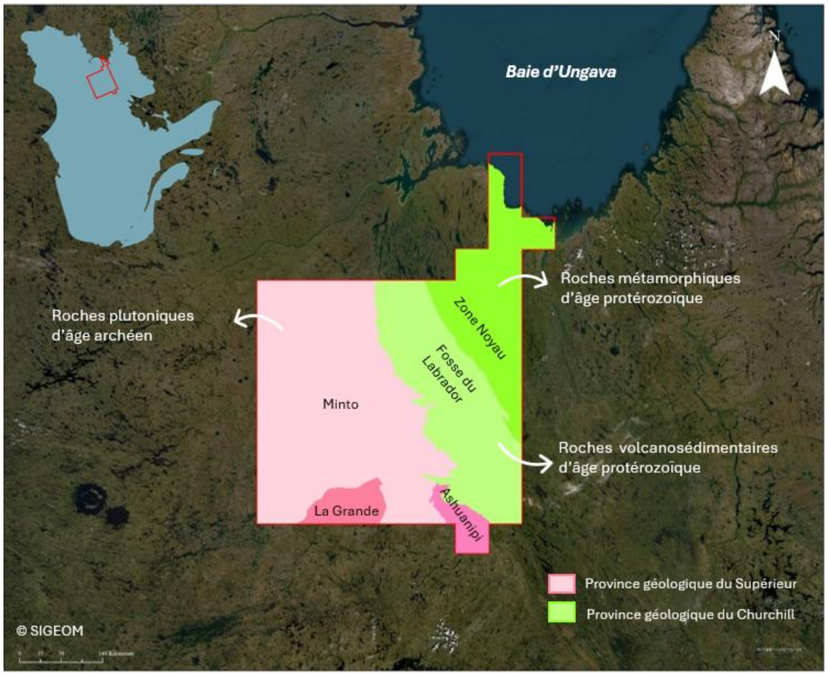

Figure 1.2 Provinces géologiques de la zone d'étude.

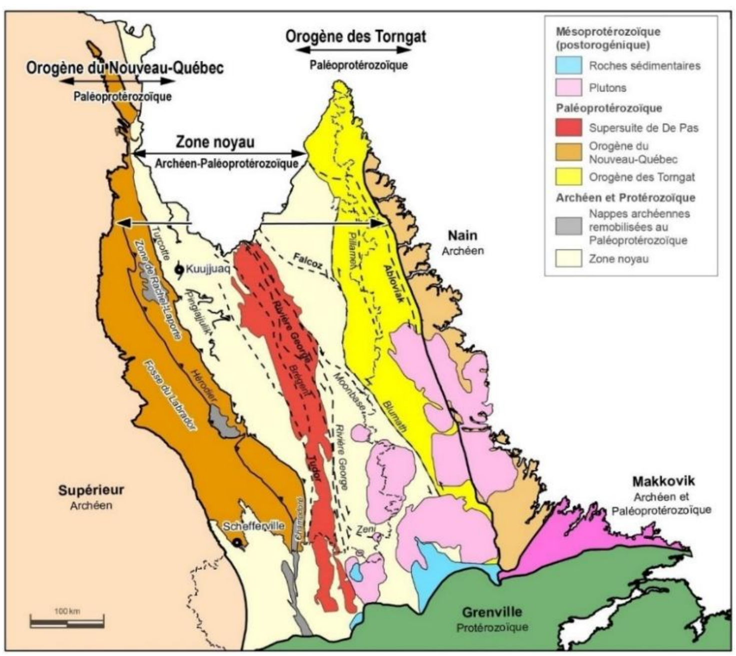

Figure 1.3 Les entités géologiques qui composent le sud-est de la province géologique du Churchill (D'Amours et Simard, 2012)

1.5 Géologie du Quaternaire et travaux antérieurs

1.5.1 Contexte général de la dernière glaciation

Le complexe glaciaire qui a recouvert la partie septentrionale de l'Amérique du Nord au Wisconsinien était composée de trois inlandsis, soit l'Inlandsis Innuitien, l'Inlandsis de la Cordillière et l'Inlandsis Laurentidien (Dyke et Prest 1987). Ce dernier s'étendait sur l'ensemble du Bouclier canadien ainsi qu'une partie des Prairies canadiennes et a atteint son extension maximale dans le nord des États-Unis il y a environ 22 000 ans (Clark et al., 2009 ; Dalton et al., 2020). L'Inlandsis Laurentidien était organisé autour de trois grands centres de dispersion, soit les secteurs de Fox-Baffin, du Keewatin et du Québec-Labrador qui recouvrait le territoire à l'étude (Dyke et Prest, 1987 ; Fulton et Prest, 1987 ; Dyke et al., 2002). Le secteur du Québec-Labrador fut l'un des dômes les plus dynamiques de la dernière glaciation, marqué par d'importants changements dans sa configuration associés à la migration de son centre de dispersion (Dyke et al., 1982 ; Dyke et Prest, 1987 ; Boulton et Clark, 1990 ; Teller, 1995). La région d'étude se situe au cœur de ce secteur.

Figure 1.4 Les trois principaux dômes de l'Inlandsis Laurentidien : Québec-Labrador (Q-L), Keewatin (K) et Foxe-Baffin (F) (Stokes, 2017).

1.5.2 Ensembles géomorphologiques au sud de la baie d'Ungava

La dynamique glaciaire polyphasée associée au secteur du Québec-Labrador se reflète notamment par la complexité des enregistrements géomorphologiques et sédimentaires (Prest, 1968 ; Dubé-Loubert, 2019). En effet, ce secteur présente deux grands ensembles de formes glaciaires et fluvioglaciaires qui témoignent de systèmes d'écoulement glaciaire distincts aux directions opposées. Ces deux ensembles géomorphologiques sont départagés par une ligne courbée qui circonscrit les basses-terres de la baie d'Ungava et qui est communément appelée le *Horseshoe Unconformity* (Dyke et Prest, 1987 ; Clark et al., 2000) ou le *Horseshoe Intersection Zone* (Veillette et al., 1999; Dubé-Loubert et al., 2021).

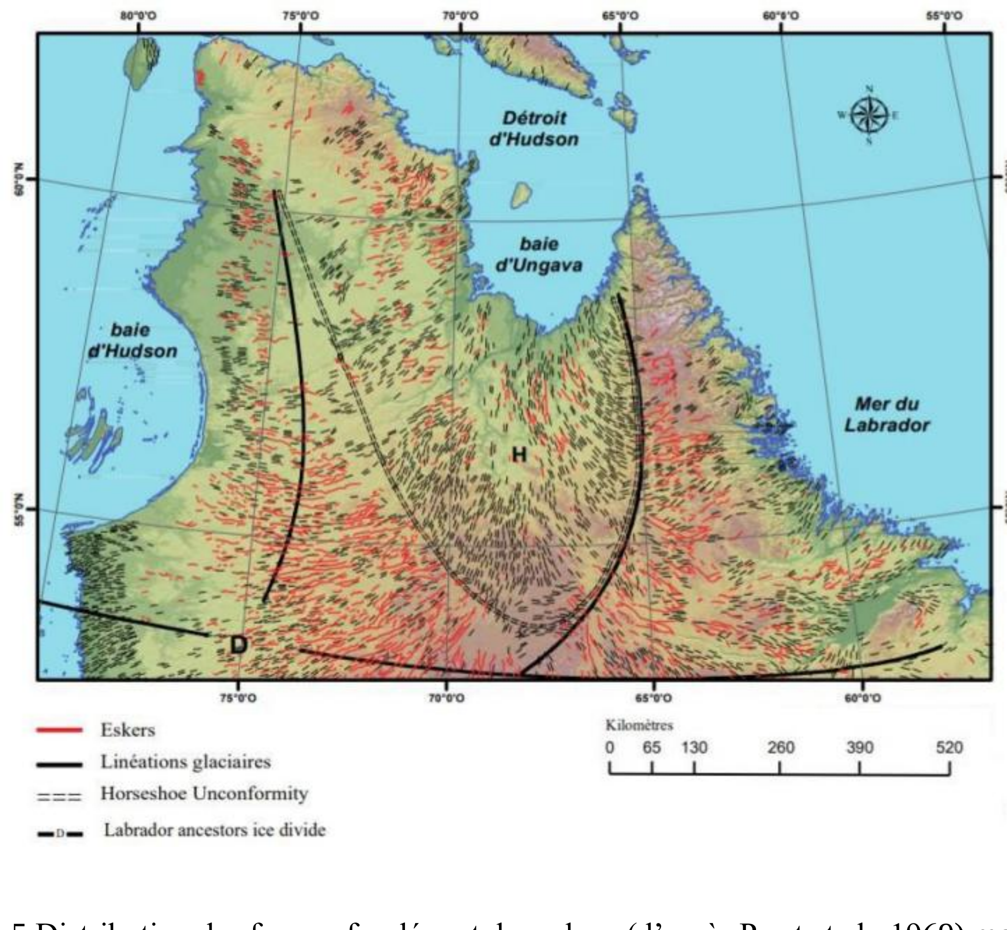

Figure 1.5 Distribution des formes fuselées et des eskers (d'après Prest et al., 1969) montrant les deux grands systèmes d'écoulement glaciaire. La limite entre ces deux systèmes correspond au *Horseshoe Unconformity* (Dubé-Loubert et Roy, 2017).

La zone au sud de cette discontinuité regroupe des formes fuselées (drumlins, flûtes, crag-and-tail) orientées vers l'ouest, le sud et l'est et qui témoignent d'un écoulement glaciaire radial divergent. L'orientation des eskers suggère une déglaciation qui s'est globalement effectuée du sud vers le nord (Veillette et al., 1999 ; Clark et al., 2000). La zone au nord du *Horseshoe Unconformity* est caractérisée par divers groupements de formes fuselées (*flow-sets*) convergeant vers la baie d'Ungava, c'est-à-dire que ces formes ont été mises en place par un écoulement glaciaire globalement orienté vers le nord tandis que les eskers indiquent un retrait subséquent de la marge glaciaire vers le sud (Jansson et al., 2003).

Deux principales hypothèses ont été soulevées afin d'expliquer le contraste entre ces systèmes d'écoulement. La première propose que la limite du *Horseshoe* sépare des terrains d'âges différents. En effet, Kleman et al. (1994) et Jansson et Kleman (1999) suggèrent que les formes fuselées retrouvées au nord de la limite seraient des formes palimpsestes associées à une glaciation antérieure (Illinoienne, *Marine Isotopic Stage* 6). Ces formes anciennes auraient été préservées par un dôme de glace centré sur la baie d'Ungava avec des conditions de glace à base froide (Clark et al., 2000 ; Jansson et al., 2002). La seconde hypothèse associe cette dichotomie morphologique au développement d'une ligne de partage glaciaire au sud de la baie d'Ungava résultant de l'appel de glace provoqué par l'affaissement de la section nord du dôme du Québec-Labrador lors du tardiglaciaire (Hughes, 1964; Klassen et Thompson 1993; Veillette et al., 1999; Dubé-Loubert et al., 2021). Cette réorganisation du dôme et l'activité subséquente des courants de glace convergeant vers le nord auraient tronqué le mouvement radial dirigé vers le sud (Clark et al., 2000 ; Dubé-Loubert et al., 2021).

Cette deuxième interprétation est celle qui fait présentement consensus auprès de la communauté scientifique. Les travaux de Veillette et al. (1999) ont démontré que les formes fuselées retrouvées au nord du *Horseshoe Unconformity* recoupaient celles situées au sud de la limite, infirmant ainsi l'hypothèse que le système retrouvé au nord soit le plus ancien. Les récents travaux de Dubé-Loubert et al. (2021) et Dubé-Loubert et Roy (2017) appuient également cette dernière interprétation. En effet, les datations cosmogéniques (^{10}Be) réalisées sur des deltas glaciomarins indiquent que l'ensemble morphologique au nord de la limite est d'âge tardi-wisconsinienne (8 400 ans ± 300 ans), révoquant ainsi leur origine pré-Wisconsinienne telle que proposée par la première hypothèse (Dubé-Loubert et al., 2021). La configuration de cette zone d'intersection entre les deux principaux systèmes d'écoulements glaciaires reflète un contrôle topographique. En effet, la forme en U qui sépare le système divergent au sud du système convergeant au nord correspond en grande partie à la ligne des bassins versant se jetant dans la baie d'Ungava, démontrant ainsi l'influence de la topographie sur le système d'écoulement glaciaire au tardiglaciaire et à la déglaciation (Dubé-Loubert et al., 2021).

1.5.3 Formation de grands lacs glaciaires et incursion marine post-glaciaire

La déglaciation du sud de la baie d'Ungava a permis le développement de grands bassins glaciolacustres dans les vallées des principales rivières s'écoulant vers la baie d'Ungava (Ives 1960 ; Barnett 1963 ; Gray et al 1993 ; Drummond 1965). La formation et la durée de vie de ces lacs glaciaires a été étroitement influencée par la persistance et l'intégrité du barrage de glace qui retenait ces eaux dulcicoles (Gray et Lauriol, 1985 ; Clague et Evans, 2000). Le retrait progressif de la marge glaciaire a mené à la dislocation du barrage, provocant leur drainage abrupte vers la baie d'Ungava. Le réajustement glacio-isostatique n'ayant pas été complété, le retrait des glaces est également accompagné par l'invasion concomitante du continent déprimé par la Mer d'Iberville. Cette déglaciation complexe souligne l'importance d'établir des contraintes chronologiques au développement et à l'évolution de ces lacs glaciaires afin de mieux les intégrer aux reconstructions paléogéographiques.

1.5.4 Chronologie et patron de la déglaciation du sud de la baie d'Ungava

Les premières ébauches d'un patron de retrait pour l'Amérique du Nord ont été proposées par Bryson et al. (1969) et Prest et al. (1969) à partir d'âges radiocarbones obtenus via des coquilles de mollusques marins. Elles ont ensuite été retravaillées par Dyke (2004) suite à l'accroissement du nombre de nouvelles dates ^{14}C acquises dans les régions côtières du pourtour de la péninsule d'Ungava. Les cartes paléogéographiques de la déglaciation de l'Inlandsis Laurentidien ont récemment été à nouveau actualisées par Dalton et al. (2020; 2023) afin d'intégrer de plus récents travaux cartographiques (e.g. Daigneault, 2008 ; Dubé-Loubert et al., 2018) ainsi que de nouvelles datations (e.g. Lajeunesse et Saint-Onge, 2008, Dubé-Loubert et al., 2017, 2018) produites depuis la publication des travaux de Dyke (2004).

La déglaciation du secteur du Québec-Labrador est caractérisée par un retrait asymétrique des marges glaciaires, avec un taux rapide au sud et plus lent au nord (Clark et al., 2000 ; Dyke, 2004 ; Ullman et al., 2016). Les ajustements suggérées par Dalton et al. (2020) comprennent notamment un retrait plus rapide et prononcé que ce que proposait Dyke (2004), ce qui a mené à une reposition de plusieurs marges plus profondément à l'intérieur des terres. Au sud de la baie d'Ungava, le dôme du Québec-Labrador s'est grossièrement retiré de l'est vers l'ouest (Dyke et Prest, 1987 ; Dalton et al., 2020), ce qui fait du sud-est de la baie d'Ungava l'un des premiers secteurs libérés de glace entre 7,9 et 7,3 ka cal BP (Dalton et al., 2020). Les isochrones de déglaciation suggèrent un retrait glaciaire dans la région d'étude peu après 6,8 ka cal BP. La péninsule d'Ungava a quant à elle accueilli les derniers stades de désintégration de ce dôme (Ives, 1960) alors qu'elle s'est divisée en plusieurs masses secondaires (Gray et Lauriol, 1985 ; Taylor 1982). Ce schéma est concordant avec le modèle de retrait (scénario C) présenté par Clark et al. (2000) qui suggère que les culots de glace formés par la fragmentation de la calotte glaciaire ont pu obstrué les vallées des principales rivières s'écoulant vers la baie d'Ungava, permettant ainsi la développement de lacs glaciaires.

Ce patron de retrait est également appuyé par plusieurs contraintes chronologiques qui positionnent la marge glaciaire dans les environs de Nain, sur la côte de la mer du Labrador, vers 9140 ± 250 ans cal. BP (Short 1981 ; Clark et Fitzhugh, 1992). La calotte en retrait à ensuite traverser les monts Torngat avant de s'installer dans les basses terres de la baie d'Ungava (Teller, 1995). L'application de la datation par isotopes cosmogéniques à des rivages du Lac glaciaire Naskaupi dans le bassin de la rivière George implique la présence d'une marge glaciaire à l'ouest de cette rivière vers 8300 ± 300 ans (Dubé-Loubert et Roy, 2017 ; Dubé-Loubert et al., 2018), ce qui est cohérent avec les données radiocarbones de Allard et al. (1989) qui situent l'invasion marine de ce secteur à 7700 ± 120 ans cal BP. Sur la côte est de la péninsule d'Ungava, les données géochronologiques de Lefebvre-Fortier et al. (2024) indiquent une déglaciation rapide et positionnent l'incursion du territoire par la mer d'Iberville entre 8900 ± 200 ans au nord (Quaqtaq) et 7900 ± 200 ans au sud (Rivière-aux-Feuilles). Ces dates sont plus vieilles que les âges radiocarbones proposés par des travaux antérieurs qui suggèrent que la déglaciation de la côte orientale de la péninsule d'Ungava se soit effectuée entre 7220 ± 115 ans BP et 6300 ± 75 ans BP (Gangloff et al., 1976 ; Gray et al 1980 ; Lauriol et Gray, 1987).

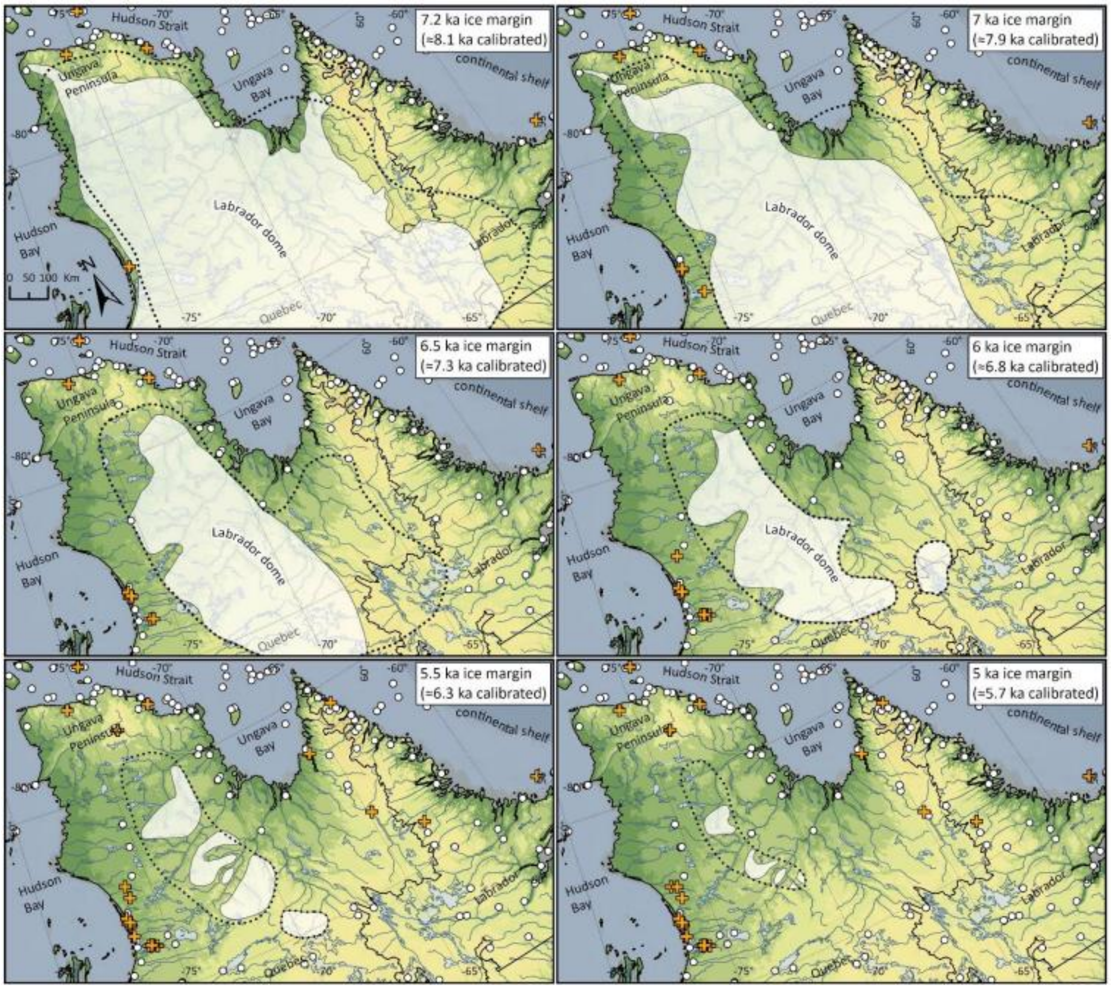

Figure 1.6 Marges glaciaires actualisées de Dyke (2004) montrant la déglaciation du dôme du Québec-Labrador à des intervalles sélectionnés (Dalton et al., 2020)

Nonobstant le rôle fondamental qu'a joué le radiocarbone dans l'établissement des premières contraintes spatio-temporelles de la déglaciation de l'Amérique du Nord, les reconstructions paléogéographiques uniquement basées sur cette méthode présentent certaines limitations chronologiques. En effet, l'utilisation de cette méthode est majoritairement limitée aux secteurs qui ont été submergés par les mers post-glaciaires et dont les dépôts qu'elles ont laissé sur le territoire regorgent de matériel organique. L'avènement et l'intégration de la datation par isotopes cosmogéniques aux autres données géochronologiques ont permis de fournir des contraintes chronologiques robustes et ainsi raffiner les isochrones de déglaciation de l'Inlandsis Laurentidien (Carlson et al., 2007 ; Dalton et al., 2023; Dubé-Loubert et al., 2018).

1.5.5 Dynamique glaciaire et déglaciation du secteur du Lac Cambrien

Dans la région d'étude, l'orientation et la distribution des formes fuselées indiquent un écoulement glaciaire convergeant vers la baie d'Ungava (Douglas et Drummond, 1953 ; Henderson, 1959 ; Prest, 1969 ; Gangloff et al.,1976). La géomorphologie de surface est caractérisée par de grandes plaines de till mince et zones de roc affleurant (Hughes, 1964 ; Kirkland, 1950). La déglaciation progressive de ce secteur a permis de mettre à jour une myriade d'eskers qui témoigne d'un retrait des glaces vers le sud-sud-ouest (Drummond 1965). Des traces d'anciennes lignes de rivages perchées encore visibles à ce jour dans la vallée de la rivière Caniapiscau et du bassin du lac Cambrien ont d'abord été observées par Low (1896). Les pourtours de la baie d'Ungava au nord sont recouverts de sédiments marins et de formes littorales associées à l'incursion de la Mer d'Iberville qui s'est effectuée peu après 6,8 ans cal BP (Dalton et al., 2020). L'occurrence d'argiles rythmées rapportée par Low (1896) près de la gorge du Manitou, à quelques kilomètres en amont de l'embouchure de la rivière aux Mélèzes, implique que l'incursion marine se soit minimalement étendue jusqu'à ce point et possiblement au-delà. Bergeron (1965) signale la présence d'argiles varvées dans ce même secteur, qu'il associe à l'existence d'un grand lac glaciaire. Ces observations remettent en question l'origine des rivages retrouvés dans la vallée de la rivière Caniapiscau. En effet, l'origine de ces formes, à savoir si elles sont associées à des épisodes glaciolacustres ou glaciomarins, fait l'objet de débats depuis les premières études qui ont été entreprises dans ce secteur, notamment du fait que la dualité de ces deux épisodes majeurs, de même que leur étendue et durée respectives sont encore peu documentées dans la littérature.

Outre les travaux de Drummond (1965) qui sont les plus significatifs, les rapports sur la géologie glaciaire dans le secteur du lac Cambrien et ses alentours sont peu exhaustifs et sont généralement limités à l'observation de formes de terrain et marques d'érosion indicatrices de la direction de l'écoulement glaciaire (Owens, 1955 ; Bergeron, 1954, 1979; Henderson, 1959 ; Hughes, 1964). Drummond (1965) suggère que les paléo-rivages retrouvés dans la vallée de la rivière Caniapiscau témoignent d'un épisode marin puisqu'il n'arrive pas à expliquer le barrage de ce secteur, contrairement aux régions adjacentes à l'est pour lesquelles les travaux antérieurs montraient des évidences pour les lacs glaciaires McLean et Naskaupi dans les vallées des rivières à la Baleine et George, respectivement (Ives, 1960). Tanner (1944) suggère que la masse de glace qui entravait le drainage des rivières à la Baleine et George vers la baie d'Ungava s'étendait probablement également au-dessus de la région du lac Cambrien ou du moins couvrait les tronçons inférieurs de la rivière Koksoak. Toutefois, l'emplacement exact du barrage de glace dans la rivière Koksoak-Caniapiscau de même que les étapes de son retrait final sont encore méconnus.

Dans une reconstruction régionale de la déglaciation du secteur nord du Dôme du Labrador, Jansson (2003) rapporte la présence d'une succession de plans d'eau glaciolacustres qui ont occupé le bassin de la rivière Caniapiscau et ses environs. Jansson et Kleman (2004) propose que le Lac glaciaire Cambrien se soit drainé en deux à-coups, suivant la dislocation du barrage de glace qui a entrainé l'ouverture de nouveaux exutoires. Le premier drainage se serait déroulé après 6,5 ka et le second vers 6,0 ka, avec des volumes respectifs de 274 km^3 et 200 km^3. Ces reconstructions sont toutefois basées sur de la modélisation et de la cartographie à distance (*remote mapping*), sans contrôle de terrain ou datations concrètes, en plus d'être articulées autour d'un schéma de déglaciation basé sur le retrait d'un dôme de glace à base froide pour lequel aucune donnée géologique ne soutient (Jansson, 2002, 2003 ; Kleman et al., 1994). Conséquemment, ces travaux revêtent peu d'intérêt aujourd'hui.

Ces divergences dans l'interprétation de la géomorphologie glaciaire et de l'histoire quaternaire du secteur du lac Cambrien découlent principalement de données de terrain fragmentaires et d'un manque d'études détaillées sur ses enregistrements géomorphologiques et sédimentaires, en plus de refléter le caractère historique lié aux outils d'étude accessibles lors des différentes périodes de travaux. En effet, les nouvelles technologies permettent désormais la production de modèles d'élévation numérique détaillés, d'images satellites de haute résolution et de méthodes de datation robustes qui permettent aujourd'hui d'apporter un nouvel éclairage sur ce secteur.

CHAPITRE 2

DIFFERENTIATING THE GLACIAL LAKE EXTENT FROM GLACIOMARINE INCURSION IN THE GEOMORPHOLOGICAL RECORD OF SOUTH-CENTRAL UNGAVA-LABRADOR (CANADA)

Ce chapitre prend la forme d'un article scientifique qui documente la dualité entre le développement du Lac glaciaire Cambrien et l'incursion des eaux postglaciaires de la Mer d'Iberville à la suite du retrait de l'Inlandsis Laurentidien dans une région au sud de la baie d'Ungava. L'article présente une brève revue des travaux antérieurs et le contexte physiographique de ce secteur. Les méthodes utilisées pour la cartographie et la datation des rivages glaciolacustres et glaciomarins sont ensuite décrites. Les résultats de la cartographie et les nouveaux âges ^{10}Be obtenus sur ces formes littorales sont présentés et discutés. L'ensemble des données est ensuite utilisé pour modéliser l'étendue et les volumes des différents plans d'eau, ainsi que pour produire une reconstruction paléogéographique qui décrit les principales étapes de la déglaciation.

Cet article résulte de la collaboration étroite de plusieurs chercheurs. Arianne Vallée a réalisé les travaux de terrain, la cartographie, les analyses en laboratoire ainsi que la rédaction de l'article. Martin Roy et Hugo Dubé-Loubert (HDL) ont contribué à l'élaboration du projet et supervisé l'ensemble des travaux. HDL a aussi participé aux travaux de terrain. Joerg M. Schaefer a pour sa part supervisé les travaux de datation au laboratoire de nucléides cosmogéniques du Lamont-Doherty Earth Observatory à New York (États-Unis). Tous les auteurs ont participé à l'interprétation des données et ont collaboré aux révisions qui ont mené à la version finale de l'article.

Differentiating the glacial lake extent from glaciomarine incursion in the geomorphological record of south-central Ungava-Labrador – implications for ice-margin configuration

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Mots-clés : déglaciation, lacs glaciaires, cartographie quaternaire, datation par nucléides cosmogéniques
Keywords : deglaciation, glacial lake, quaternary mapping, cosmogenic dating

Résumé

Le retrait de l'Inlandsis Laurentidien dans le nord du Québec et du Labrador (Canada) a mené à la formation de plusieurs grands lacs de barrage glaciaire. Le drainage de ces lacs glaciaires pourrait potentiellement avoir affecté la circulation océanique de l'Atlantique Nord et le climat au cours de la déglaciation. L'évaluation de l'impact de ces décharges répétées d'eau de fonte sur le système océan-climat est cependant limitée par le manque de données sur la configuration (étendue et volume) et la chronologie de ces lacs glaciaires, de même que sur la position de la marge glaciaire qui a contrôlé leur évolution. De plus, l'incursion des eaux marines postglaciaires sur le territoire complexifie l'interprétation de certaines séquences de rivages qui enregistrent ces événements, notamment dans la région centre-sud de l'Ungava. La compréhension des processus géomorphologiques qui ont façonné le territoire est également d'intérêt pour les recherches archéologiques qui ont révélé la présence de plusieurs sites pré-contact témoignant de l'occupation du territoire (campements, routes migratoires, etc.) par des groupes autochtones.

Ce projet de maîtrise se penche sur les enregistrements géomorphologiques et sédimentaires de la région englobant les vallées des rivières Caniapiscau et Koksoak, au sud de Kuujjuaq (Nunavik). La cartographie des eskers, moraines et chenaux d'eau de fonte, effectuée à partir d'images satellitaires et de modèles d'élévation numérique, a permis de reconstruire le patron de déglaciation régional. L'étude des paléo-rivages glaciolacustres et glaciomarins, deltas et terrasses a quant à elle permis d'établir la configuration respective de ces deux étendues d'eau. Les observations cartographiques ont été validées par des travaux de terrain qui ont également permis la prise de mesures d'élévation au GPS différentiel de haute précision (± 1 m) des formes clés le long d'un transect nord-sud de 190 km. La reconstruction des plans d'eau est basée sur un système d'information géographique (SIG) qui inclus l'utilisation de paléosurfaces illustrant la physiographie régionale approximative au moment de leur existence (~7 ka BP).

Les résultats indiquent que les rivages présents dans les vallées des rivières Caniapiscau et Koksoak et dans le bassin du lac Cambrien sont majoritairement d'origine glaciomarine. La combinaison du patron du retrait glaciaire déterminé à partir des données cartographiques et des modélisations indique qu'un lac glaciaire s'est développé dans le sud du lac Cambrien et dans les bassins adjacents à l'est, avec une étendue d'environ 2500 km^2 et un volume de 105 km^3. De plus, l'application de la datation par isotopes cosmogéniques à des blocs présents sur des rivages de différentes élévations a donnée 14 âges ^{10}Be qui indiquent que le drainage du Lac glaciaire Cambrien et l'incursion marine concomitante se sont produits aux alentours de 7200 ans ± 200 ans BP. L'exondation progressive du territoire causée par le rebond post-glaciaire a culminé avec le retrait des eaux marines de la zone d'étude vers 4400 ans ± 200 ans BP.

Globalement, ces résultats renforcent le schéma et la chronologie du retrait glaciaire dans la région et fournit un cadre cohérent pour le développement d'un lac glaciaire lors de la dernière déglaciation. Les nouveaux âges ^{10}Be permettent de mieux contraindre le moment de l'incursion marine dans la région, qui coïncide avec l'effondrement de la masse de glace retenant le lac. Ensemble, ces résultats améliorent les reconstructions paléogéographiques et affinent le bilan des décharges d'eau de fonte provenant de l'Ungava, fournissant des données essentielles pour les modèles paléoclimatiques visant à mieux comprendre le rôle des apports d'eau douce dans les variations climatiques du début de l'Holocène.

Abstract

The retreat of the Laurentide Ice Sheet in northern Quebec and Labrador (Canada) led to the formation of several large ice-dammed lakes that drained into the Labrador Sea, a critical component of the Atlantic Meridional Ocean Circulation. Assessing the potential impact of these freshwater inputs on ocean circulation and climate is, however, limited by the lack of constraints on the configuration (extent and volume) and chronology of these glacial lakes, which reflect uncertainties on the ice retreat pattern and the position of the ice margin that dammed these lakes and controlled their evolution. Additionally, interpretation of the extensive record of raised shoreline sequences is complicated by the incursion of postglacial marine water deep into the continent's interior, notably south of Ungava Bay where distinguishing glacial lake strandlines from marine sequences is difficult.

Here we studied the geomorphological and sedimentary records of the region encompassing the valleys of the Caniapiscau and Koksoak rivers, south of Kuujjuaq (Nunavik). Mapping provided an inventory of eskers, moraines, and meltwater channels mapped on high-resolution satellite images, in addition to raised shorelines, terraces, and deltas that were formed in either glaciolacustrine or glaciomarine water bodies. Remote observations were validated by fieldwork, which also allowed precise measurements of the elevation of key landforms along a 190 km north-south transect using a high-precision differential GPS (± 1 m). Results were first used to reconstruct the regional pattern of ice-retreat, which shows a scission of the ice front that allows the damming of a glacial lake. Shoreline-elevation data derived from field-based measurements and the Canadian Digital Elevation Model (CDEM) were projected onto a paleo-surface from the time of deglaciation (~7 ka BP) to obtain the original (horizontal) attitude of the former glaciolacustrine and marine water planes. Results indicate that the shorelines present in the valleys of the Caniapiscau and Koksoak rivers and the Lake Cambrien basin are predominantly glaciomarine in origin. Yet, high-elevation strandlines in the basin of present-day Cambrian Lake in the southern part of the study area clearly belong to a glacial lake. Results on the ice retreat pattern were combined with strandline records to reconstruct glacial Lake Cambrian, which covered an area of 2462 km² for a volume of 105 km³. A total of 14 ^{10}Be ages were obtained from the application of surface exposure dating to boulders lying on well-defined shorelines at four sites spanning three different elevations. Results indicate that the drainage of Glacial Lake Cambrien and the concomitant marine incursion occurred around 7200 ± 200 years BP. Post-glacial rebound subsequently caused the progressive withdrawal of marine waters, with complete land emergence at around 4400 ± 200 years BP.

Overall, this study reinforces the pattern of ice margin retreat in the region and provides a coherent framework for the development of a glacial lake during the last deglaciation. The new ^{10}Be ages constrain the timing of the marine incursion in the region, which is concomitant with the collapse of the ice mass that dammed the lake. Together, these results improve paleogeographic reconstructions and refine the budget of meltwater discharges coming from Ungava, which forms key data for paleoclimate model trying to better assess the role of freshwater forcing in early Holocene climatic variations.

2.1 Introduction

The Québec-Labrador Ice Dome was one of the largest components of the Laurentide Ice Sheet (LIS), covering most of eastern and northeastern Canada during the last glaciation (Dyke et al., 1982; Dyke et Prest, 1987). In northern Quebec and Labrador, the broad array of sedimentary and geomorphological records indicates that ice withdrawal across this region was accompanied by the formation of several ice-dammed lakes around Ungava Bay (Ives, 1959 and 1960; Prest, 1969; Lauriol, 1982; Dyke, 2004; Dubé-Loubert and Roy, 2017). These lakes developed as the retreating ice margin occupied the lower reach of the major rivers flowing into Ungava Bay, thereby impeding their natural flow and allowing significant accumulations of meltwater in river valleys and associated watersheds (Ives, 1960; Gray et al., 1993; Teller, 1995) (cf. Figure 2.1). Apart from Lake Naskaupi, located at the foot of the Torngat Mountains in the east (Ives, 1960; Dubé-Loubert and Roy, 2017; Dubé-Loubert et al., 2018), most of the Ungava glacial lakes remain poorly documented in terms of configuration, evolution, and chronology, complicating their integration into paleogeographic reconstructions (Dyke, 2004; Dalton et al., 2020, 2023). Additionally, the identification of glacial lakes can also be challenging in some areas such as south-central and western Ungava where postglacial marine waters have penetrated deep into river valleys, making the interpretation of shoreline sequences and associated geomorphological evidence complex.

Part of the uncertainties surrounding the configuration of the Ungava glacial lakes stems from the sparse regional mapping surveys, which have yielded broad deglaciation schemes with largely schematic ice-margin outlines. Current withdrawal patterns indicate that the late stages of the deglaciation in Québec-Labrador were accompanied by the segmentation and isolation of several secondary ice masses on the Ungava Peninsula and south of Ungava Bay (Dalton et al., 2020, 2023). However, the timeline of this fragmentation, as well as the precise location and configuration of these ice masses that could have obstructed certain river valleys remain relatively unknown (Lauriol, 1982; Clark et al., 2000; Dubé-Loubert et al., 2018). The region south of Ungava Bay presents challenges due to the overall convergence of ice retreat patterns – east-to-west retreat in the eastern sector and north-to-south in the western sector, which complicates the mechanisms necessary for the development of ice-dammed lakes (Dyke et Prest, 1987; Veillette et al., 1999; Clark et al., 2000).

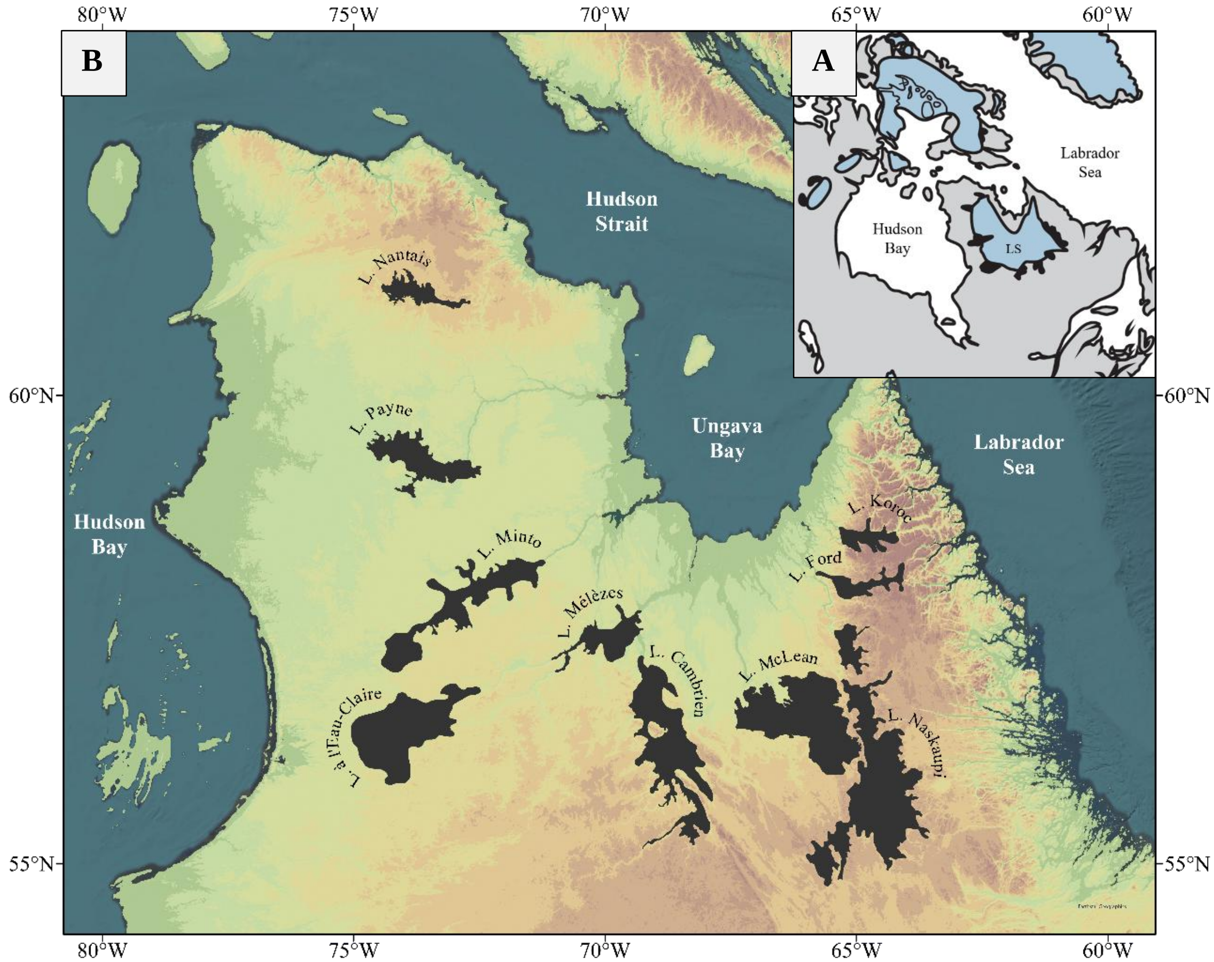

Figure 2.1 (A) Schematic map of the Laurentide Ice Sheet late in the deglaciation (B) Glacial lakes associated with the deglaciation of the Québec-Labrador Sector of the Laurentide Ice Sheet (modified from Dubé-Loubert and Roy, 2017).

During the late deglaciation stages of northern Quebec and Labrador, the bulk of the meltwater produced by the decay of Labrador Ice Dome and the attendant drainage of ice-dammed lakes was routed towards Ungava Bay, which is located near the Labrador Sea – an area of deepwater convection and important component of Atlantic Meridional Overturning Circulation (AMOC). Massive and repeated injections of meltwater in this region are believed to have significantly slowed down the AMOC, a critical regulator of Earth's climate (Manabe and Stouffer, 1995; Barber et al., 1999; Alley et al., 2001). Recent studies (Dubé-Loubert et al., 2018; Lefebvre-Fortier et al.,

2024) suggest that the drainage of glacial lakes from the Ungava region may have contributed to the freshwater forcing responsible for the largest climatic excursion of the Holocene – the 8.2 ka cooling event, which is commonly attributed to the drainage of Lake Agassiz-Ojibway, a large glacial lake that formed at the south-central LIS margin (Alley et al., 1997; Barber et al., 1999; Teller et al., 2002; Kleiven et al., 2008; Roy et al., 2011; Brouard et al., 2021). Despite being smaller than Lake Agassiz-Ojibway, the Ungava glacial lakes still hold substantial potential for significant disruption by meltwater injections, particularly given their number and geographical position close to the Labrador Sea. Yet, the potential for freshwater forcing events from Ungava lakes is still debated, as the source, timing, and magnitude of these meltwater fluxes remain poorly documented. Similarly, assessing the role of the meltwater discharges from Ungava region in the 160-year-long cooling event is complicated, as the opening of drainage pathways is intricately linked to the position and configuration of the ice margin. These two parameters are, however, poorly constrained due to the overall lack of chronological data on the continental mainland, which translates into large uncertainties on the spatiotemporal evolution of the ice sheet retreat (Dalton et al., 2020; Lauriol and Gray, 1987; Teller, 1995).

Here, we report a sequence of raised shorelines from the Koksoak and Caniapiscau River valleys, south of Ungava Bay, and reconstruct the evolution and extent of glacial Lake Cambrien and the post-glacial d'Iberville Sea. Our work is based on a combination of field observations, remote mapping data, and GIS modeling incorporating the paleotopography for the late deglaciation interval. We document the pattern of ice withdrawal through the mapping of key deglacial landforms of a large area encompassing these river valleys. Additionally, we apply surface exposure dating (SED) to boulders of raised shorelines and deltas and use the resulting ^{10}Be ages to constrain the evolution of these water bodies. Together, these results contribute to refining the ice-margin retreat in paleogeographic reconstructions in the southern Ungava Bay region, while placing a timing on the glacial lake discharges and marine incursion into the global deglaciation framework of the area.

2.2 Physiography and deglaciation setting

The physiography of the study area comprises two main geological domains. The eastern part of the study area is mainly underlain by Proterozoic volcano-sedimentary rocks of the Labrador

Trough of the Churchill geological province (Hodgson, 1990; Hoffman 1990; Clark 1994; Clark et Wares, 2004). The topography of this region is typically rugged, with rocky peaks alternating with elongated depressions. This terrain gradually transitions westward into an undulating plateaus characteristic of the underlying Archean crystalline rocks of the Superior Province (Madore et al., 1999; Simard, 2008). The hydrographic network is organized around the Caniapiscau River, which joins the Koksoak River the north to form a long northward flowing system that reaches Ungava Bay (Figure 2.2). In its lower course, the Caniapiscau River widens to form Lake Cambrien, located approximately 270 km downstream from its confluence with the Mélèzes River.

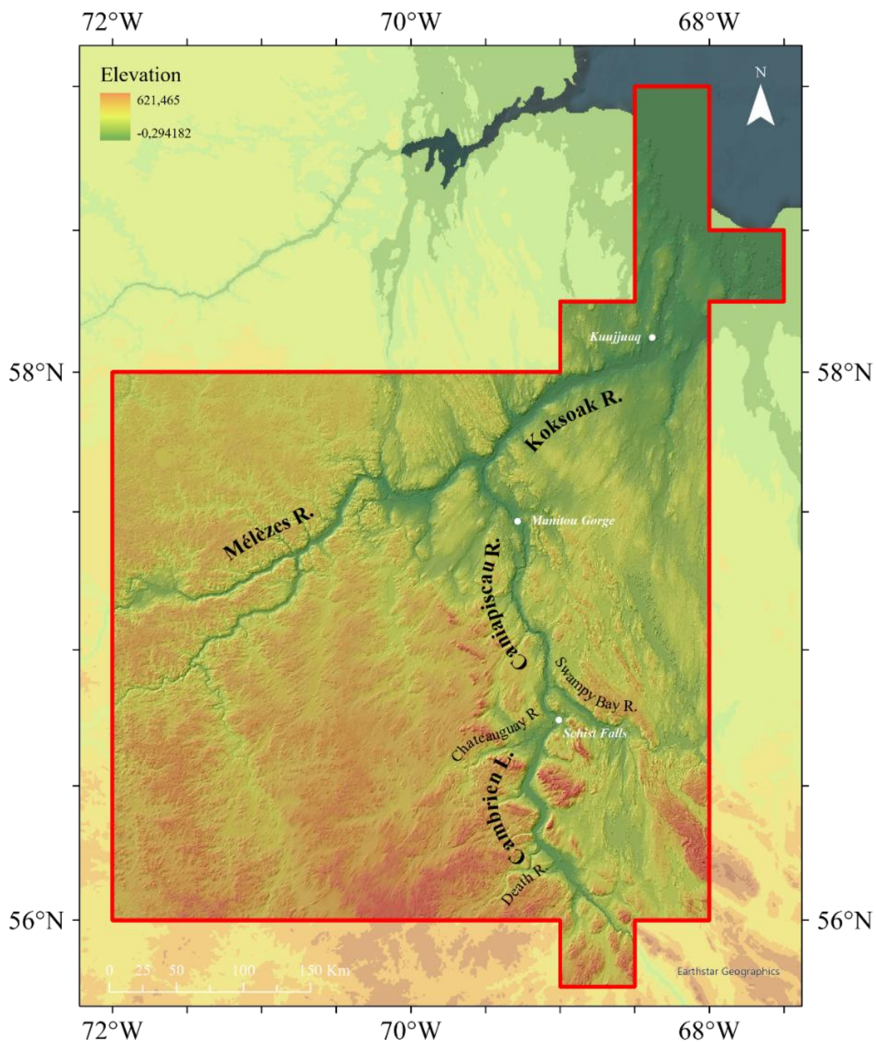

Figure 2.2 Physiography of the study area showing the main rivers and associated tributaries and location of the present-day Cambrien Lake basin.

The late-glacial interval in north-central Quebec and Labrador was marked by the development of a series of ice streams, as indicated by swarms of streamlined landforms converging towards Ungava Bay (Winsborrow et al., 2004; Margold et al., 2018). This system of massive ice flows has been associated with a thinning of the ice mass and a concomitant drawdown of the northern flank of the Labrador Sector (Hughes, 1964; Veillette et al., 1999; Dubé-Loubert et al., 2021), which was likely linked to the opening (disappearance of ice) of the Hudson Strait (Dyke, 2004). The subsequent deglaciation of the Labrador Sector core region was complex, with the distribution of elongated landforms and eskers suggesting two opposing directions of ice withdrawal: the eastern ice margin retreated westward from the Torngat Mountains, while the northern ice front retreated from Ungava Bay towards the continental interior, with an overall southward direction (Dyke, 2004; Dalton et al., 2020, 2023). These two systems of landforms and associated ice withdrawal patterns are separated by a line, which forms a branch of the so-called Horseshoe Unconformity (Clark et al., 2000) or Horseshoe Intersection Zone (Dubé-Loubert et al., 2021) – a U-shaped line that follows the contour of Ungava Bay and separates two major opposing ice-flow systems of the Labrador Ice Dome during the deglaciation (Figure 2.3).

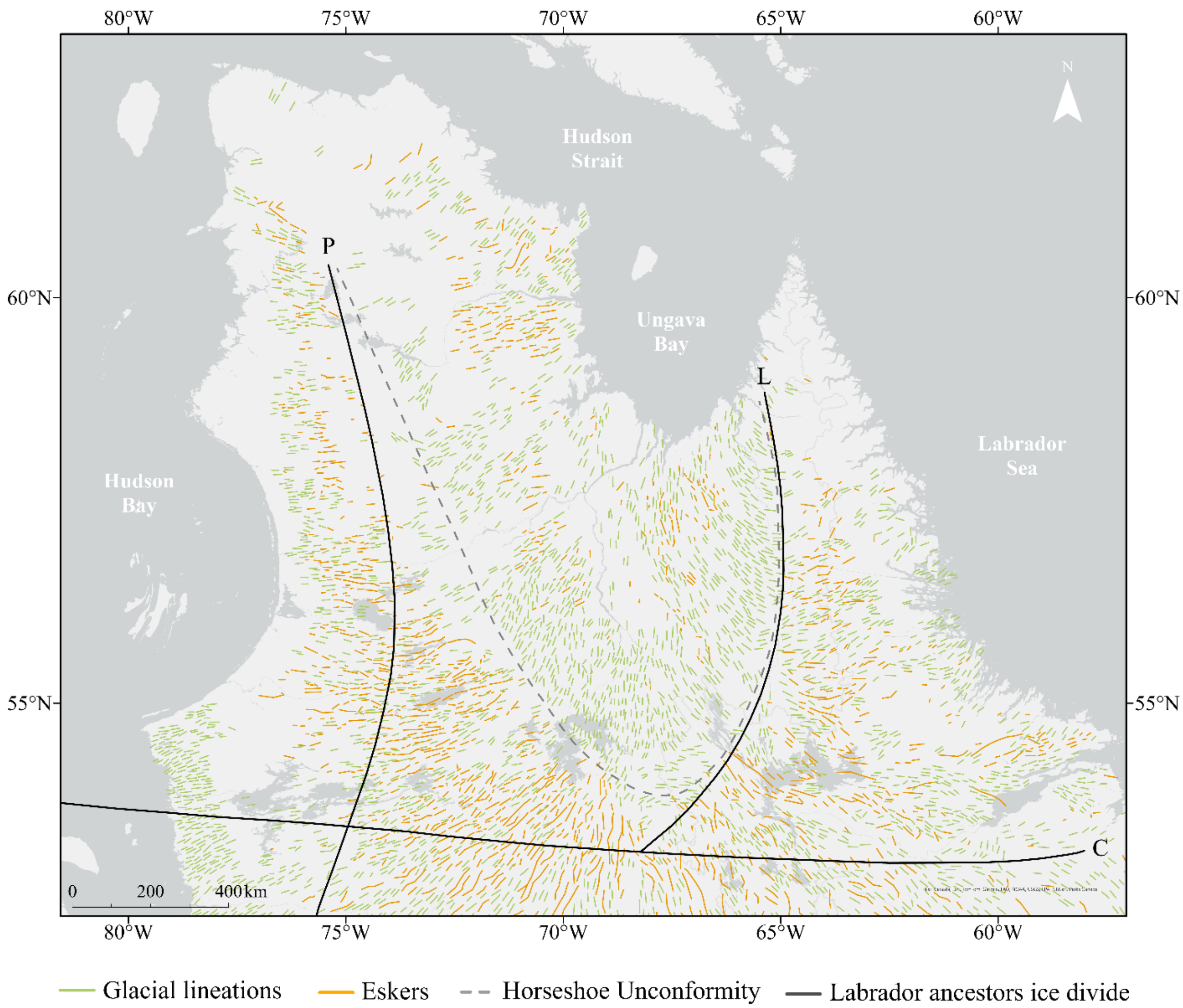

Figure 2.3 Distribution of streamlined forms and eskers (based on Prest et al., 1968) showing the two major ice-flow systems : a divergent flow towards the south and a convergent flow towards Ungava Bay in the north. The boundary between these two systems is separated by the Horseshoe Intersection Zone (or unconformity; dotted line). The black lines correspond to former ice divides (P: Payne; L: Labrador; C: Caniapiscau ice divides).

In general, the ice retreat pattern for the mainland of Ungava and Labrador (outside coastal areas) is poorly dated due to the scarcity of organic material. However, recent studies report ^{10}Be ages positioning the ice front near the George River to the east at ~ 8000 ± 300 years (Dubé-Loubert et al., 2018), consistent with the few available ^{14}C ages (Short 1981; Clark et Fitzhugh, 1992). At that time, the northern ice margin was in the vicinity of the southern coast of Ungava Bay (Dubé-Loubert et al., 2021). The 7900-8000 years interval also comprises the onset of the postglacial marine incursion to the west and southwest of Ungava Bay, where the d'Iberville Sea submerged the isostatically depressed coastal areas and river valleys (Lefebvre-Fortier et al., 2024). Beyond these points, little is known about the exact timing and onward pattern of ice withdrawal in south-central Ungava. Nonetheless, paleogeographic reconstructions indicate that the final stages of the deglaciation were characterized by an ice retreat from the Ungava lowlands towards the south, in the highlands of Quebec, with residual ice masses resting near Schefferville and to the southwest of Ungava Bay (Drummond, 1965; Dyke, 2004; Dalton et al., 2020, 2023).

The deglacial geomorphology of the region is characterized by sequences of stepped shorelines, terraces, deltas, and meltwater channels extending from the coast of Ungava Bay to the south of Lake Cambrien (Ives, 1960; Drummond, 1965). The occurrence of clayey rhythmites near Manitou Gorge was initially interpreted as recording the minimal extent of marine water in the Caniapiscau River valley (Low, 1896), but they were later associated with the existence of a glacial lake (Bergeron, 1979), consistent with scattered occurrences of raised shorelines interpreted as evidence for a glacial lake (Bergeron, 1965). These contrasting interpretations raise questions about the origin of the shorelines in the Caniapiscau River valley and the Lake Cambrien basin. This ambiguity reflects the limited number of studies in this area, combined with the lack of detailed information on the withdrawal pattern, which prevents a firm assessment of the mechanisms required to dam a glacial lake in the area. Nonetheless, their occurrences deep inland to the south tend to support the hypothesis of the existence of a glacial lake (Bergeron, 1965; Gray et al., 1993).

The overall lack of detailed information on the glacial and deglacial geomorphology in the Cambrien Lake region and surrounding areas currently limits the interpretation of these shoreline sequences, which could either be related to a glacial lake or the d'Iberville Sea. Accordingly, our study aims to document and characterize the geomorphological record of the Koksoak-Caniapiscau Rivers valley and provide new geochronological data that will refine the timing of the main events of the deglaciation.

2.3 Methods

2.3.1 Mapping of landforms

The regional pattern of ice retreat was characterized by systematic mapping of eskers and ice-marginal features such as meltwater channels and minor moraines in a large area encompassing the river valley and covering four SNRC map sheets at the 1:250 000 scale (24C, 24D, 24E, and 24F) in addition to 7 NTS map sheets at the 1:50,000 scale (24K01, 02, 08, 09, 16, 24J05, and 23N15). The extent and evolution of former glaciomarine and glaciolacustrine bodies in the study area were documented through mapping of raised shorelines, terraces, deltas, and associated landforms in the Koksoak-Caniapiscau River valley and the Cambrien Lake basin using satellite imagery (*Maxar;* 5-m resolution). Mapping was carried out with GIS software (*ArcPro 3.2.1*) and the different features were plotted using the Canadian Digital Elevation Model (CDEM; 12-m resolution). The elevations of remotely mapped landforms were obtained from the CDEM.

Remote observations were validated during fieldwork, which allowed elevation measurements of the most representative and well-developed strandline sequences and deltas using a high-precision differential GPS (DGPS model *SX BLUE*; 0,5-m resolution). At some sites, a succession of several strandlines could be measured. Specifically, elevation measurements were taken at the top of deltas or the foot of the shoreline slope break, i.e. the inflection point where the flat terrain at the base of the strandline meets the onset of the slope.

2.3.2 Reconstruction of strandline sequences and paleogeographic modeling

We plotted the different strandlines in a north-to-south elevation–distance diagram to assess the evolution of the water bodies in the basin. The elevation of the different landforms found in the study area has been significantly affected by postglacial rebound since their formation, complicating the correlation of strandlines sequences and the interpretation of their origin (glacial lake vs postglacial sea). To adequately reconstruct the extent (configuration) and history of these water bodies, the mapped strandlines and associated landforms were projected onto a digital elevation model (DEM) that integrates paleotopography at the time of the deglaciation. For this purpose, we use readily available rebound (isobases) surfaces (Godbout et al., 2023), which were produced from postglacial crustal deformation data derived from the ICE-6G model (7-m resolution), a robust glacio-isostatic adjustment model (Peltier et al., 2015).

We chose the 7 ka paleosurface, as this interval comprises the stages of deglaciation of interest in the ICE-6G model, in addition to being consistent with paleogeographic reconstructions (Dalton et al., 2020, 2023). This surface also represents a good temporal compromise knowing that this study seeks to reconstruct the water planes linked to two events of potentially slightly different ages. The crustal deformation data were then interpolated at a 20-meter resolution and subtracted from present-day elevations obtained from the CDEM to derive a paleosurface. The GIA-corrected elevations of mapped and field-measured landforms were subsequently extracted from this paleosurface and plotted in another north-to-south elevation–distance diagram. This approach provides a first-order overview of the spatial organization of landforms at the time of their formation, which removes warping (deformation) of the sequence and helps delineate the realistic extent of former water planes. Furthermore, this approach can help distinguish glaciolacustrine landforms from those linked to the glaciomarine episode. Using this paleosurface and an outline of the ice dam based on field constraints and ice-margin positions (Dalton et al., 2023), we reconstruct the extent of the glaciolacustrine and glaciomarine episodes and calculate the corresponding meltwater volume using GIS techniques.

2.3.3 Stratigraphic investigations

Field investigations revealed sedimentary sequences exposed along riverbank sections, consistent with earlier observations in the Lake Cambrien and Caniapiscau River valley regions (Drummond, 1965). Three stratigraphic sections were documented to gain insights into former depositional environments. The first 30-40 cm of the sediment exposures were removed over a width of about one meter to expose fresh (unweathered) and undisturbed material. The different units were described (composition, texture, and structure), measured, and photographed. Samples of fine-grained rhythmites were collected from one of these stratigraphic sections (CAMB8) to analyze the micropaleontological content (foraminifera and dinoflagellate cysts), which were conducted at the GEOTOP Micropaleontology Laboratory (UQAM), following standard protocols (de Vernal et al., 2010).

2.3.4 Surface Exposure Dating

Deglacial environments of former ice sheet interiors are largely devoid of organic material, preventing the use of radiocarbon dating. Constraints on the timing of the deglaciation in the study area were obtained from SED of glaciolacustrine and glaciomarine landforms, a method that has been applied successfully for Ungava region (Dubé-Loubert et al., 2018, 2021; Lefebvre-Fortier et al., 2024). This approach relies on the accumulation of cosmogenic isotopes, such as ^{10}Be, produced by cosmic ray interactions with exposed rock surfaces, such as boulders found on the surface of shorelines, terraces, and deltas. The quantity of these nuclides in a given surface is proportional to its exposure duration. Given the known production and decay rates of these nuclides, an age estimate can be calculated. Thus, the ages obtained should reflect the time of formation of the landforms sampled because the depositional settings of these boulders were likely characterized by shallow water conditions that would only slightly attenuate the production of cosmic rays.

Four sites were selected based on the quality of the landforms and the presence of large (meter-size) granitic boulders showing flat surfaces. These boulders were securely embedded in the sediment, ensuring that they remained stable since their original deposition. Preference was given to boulders with faceted surfaces and sub-rounded edges, indicating significant erosion during glacial transport, in the hope of diminishing potential inheritance issues. The outer two centimeters of boulder surfaces were sampled using a battery-powered rock saw and a chisel. A total of 20 boulders were sampled (5 per site), each weighing approximately 1,5 kg. Four boulders per site for CAMB14 and CAMB40, and three per site for CAMB25 and CAMB32, for a total of 14 samples that were sent for dating.

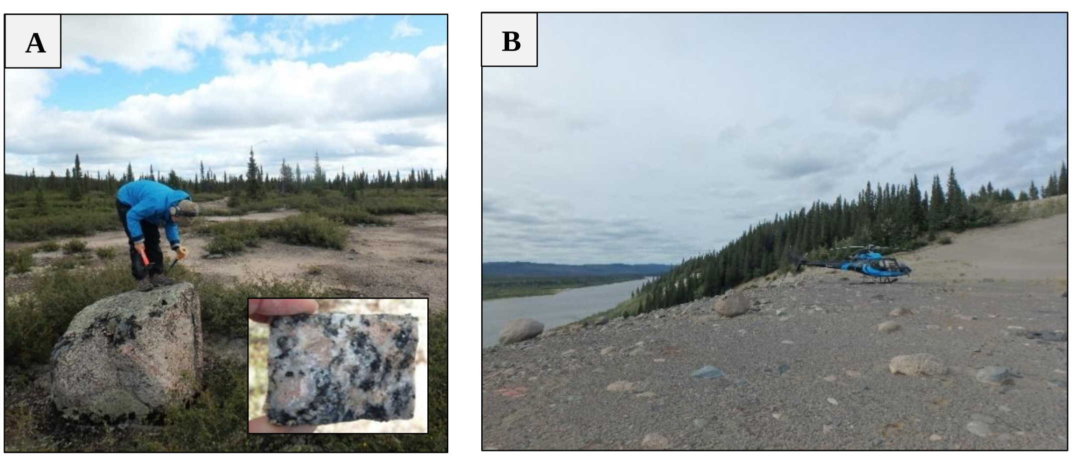

Figure 2.4 Examples of some sampled sites for SED. (A) Ground view showing a granitic boulder (CAMB32) and (B) overall view of a well-developed glaciomarine delta (CAMB14).

Sample preparation was conducted at the cosmogenic dating laboratory of Lamont-Doherty Earth Observatory (Columbia University, New York), following the internal laboratory protocol (Schaefer and al., 2009). After cleaning, approximately 350 g of each sample was crushed to obtain a grain size fraction ranging between 125 to 500 µm, depending on the quartz content available. The quartz fraction was subsequently separated from other minerals using foaming solutions, hydrofluoric acid (HF) leaching, heavy liquid, and ultrasonic bath techniques. Then, 25 g of clean quartz was collected from each sample, to which a carrier (^{9}Be) was added for subsequent corrections associated with potential contamination during sample preparation. Two blanks containing this carrier were also included in the sample set. The samples then underwent various acid attacks ($HClO_4$ and HCl) and anion-cation exchange columns to isolate trace elements (Fe, Ti, Al) and extract the ^{10}Be from the quartz. The final step involved the precipitation and combustion of beryllium, with the resulting beryllium oxide inserted into a niobium-containing cathode. These cathodes were then sent to the Lawrence Livermore National Laboratory (University of California, California) for measurements of $^{10}Be/^{9}Be$ ratios using mass spectrometry.

Ages were computed using the CRONUS-Earth online calculator (version 3; https://hess.ess.washington.edu/) using the Baffin Bay ^{10}Be production rate of 3,96 ± 0,15 (Young et al., 2013). This production rate is derived from three calibration sites based on glacial deposits in western Greenland and Baffin Island. Given the geographical proximity of our study area to these sites and considering the broadly similar glacio-isostatic rebound history experienced in both regions, this calibration site provides an adequate production rate estimate for our study. Lm scaling scheme was used in the calculations (Lal, 1991; Stone, 2000; Nishiizumi et al., 1989).

Exposure ages of the raised shorelines were calculated using the arithmetic mean of the individual samples from this landform. The arithmetic mean, rather than the error-weighted mean, is typically preferred when the geological uncertainty outweighs analytical uncertainty (e.g., Cuzzone et al., 2016). Geological uncertainty refers to the standard deviation of ages at a given site, while the analytical uncertainty represents the mean uncertainty of mass spectrometer measurements for samples from the same site. Internal uncertainties account for measurement uncertainties on the nuclide concentration only, whereas external uncertainties encompass both measurement and production rate uncertainties (Balco, 2008).

Formerly glaciated regions continue to experience post-glacial readjustment, which translates into an uplift of land masses (Gray et al., 1980, 1993). Since the production rate of cosmogenic isotopes is altitude-dependent, this rebound could potentially have had a time-varying effect on increasing the ^{10}Be production rate during the deglaciation period (Cuzzone et al., 2016). Although corrections can be applied to account for the effect of that glacio-isostatic readjustment (Rinterknecht et al., 2006; Cuzzone et al., 2016), some studies suggest that the uplift correction could be offset by changes in air pressure associated with retreating ice sheets (Stone, 2000; Staiger et al., 2007; Young et al., 2013) and eustatic sea-level changes (Bard et al., 1996). Furthermore, coupled atmospheric-ocean general circulation models indicate that changes in atmospheric thickness have negligible effects on production rates in geological settings similar to our study area (Staiger et al., 2007; Cuzzone et al., 2016; Ullman et al., 2016). Therefore, we opted not to include this correction in our exposure age calculations, as its inclusion would introduce as many uncertainties as it resolves.

2.4 Results

Systematic mapping in the Koksoak-Caniapiscau Rivers valley and surrounding areas revealed a wide range of glacial and deglacial landforms that we use to document the regional pattern of ice retreat and reconstruct the glaciolacustrine and glaciomarine history (Figure 2.5).

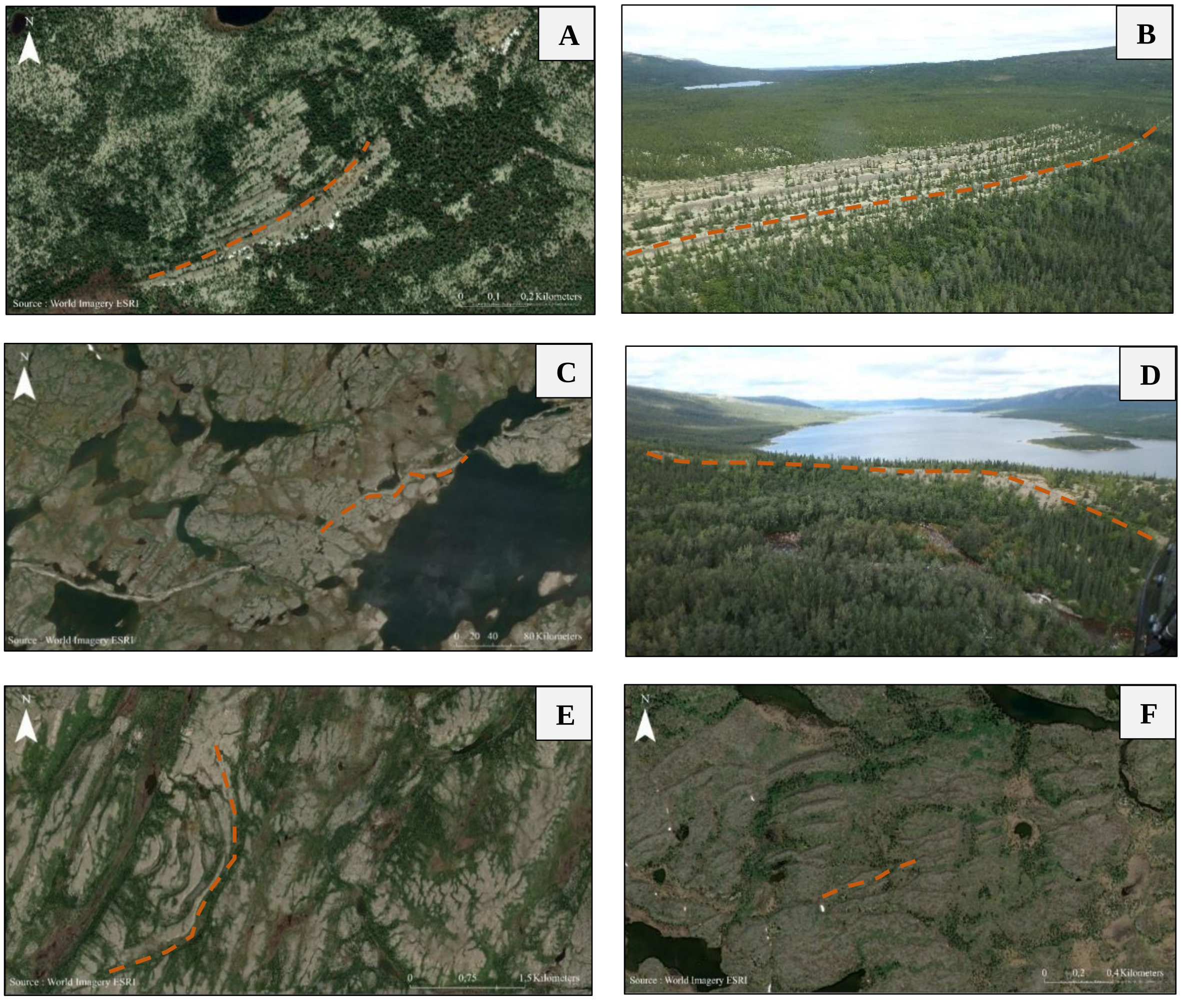

Figure 2.5 Satellite images (A, C, E, F; World Imagery ESRI) and oblique areal views (B, D) of mapped landforms. (A, B) Strandline sequences, (C, D) ESE-WNW oriented esker, (E) Ice-marginal channels north-west of Lake Cambrien, (F) NW-SE oriented minor moraines.

2.4.1 Eskers

Detailed mapping yielded an inventory of 1047 esker segments. In the study area, these glaciofluvial landforms are often discontinuous, and form elongated and slightly sinuous ridges; the alignment of isolated segments suggests that they once belonged to the same original subglacial conduit. They consist of rounded decametric blocks supported in a sand and gravel matrix. These eskers are modest in size, with an average length of 718 meters and heights typically under 5 meters. In certain areas, these ridges may be quite narrow, spanning only a few tens of meters wide, while in others, they show a broader shape or even a more complex braided pattern, extending several hundred meters in width.

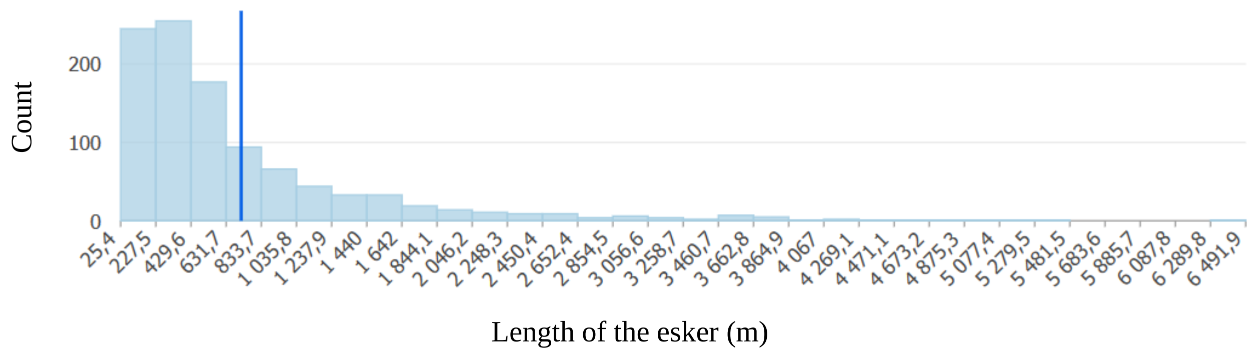

Figure 2.6 Histogram showing the length of esker segments mapped, which have an average length of 718 m (thin blue line).

The orientation and spatial distribution of esker segments reveal two distinct esker systems. One is located to the east of Lake Cambrien and regroups eskers oriented in an NNW-SSE axis, while the other one is located to the west of the river, showing eskers oriented in an ENE-WSW axis (Figure 2.7). The later set of eskers is consistent with those mapped in this area (Dubé-Loubert et al., 2021). Considering that eskers were formed perpendicularly to the ice margin of warm-based ice sheets during ice retreat (Clark et al., 2000) their orientation provides information on the orientation of ice withdrawal (Stokes et al., 2009; Margold, 2012; Margold et al., 2013; Storrar, 2014). These two esker sets thus indicate that the ice margin likely split during deglaciation, with one sector of the ice front retreating towards the south-southwest and the other retreating towards the south.

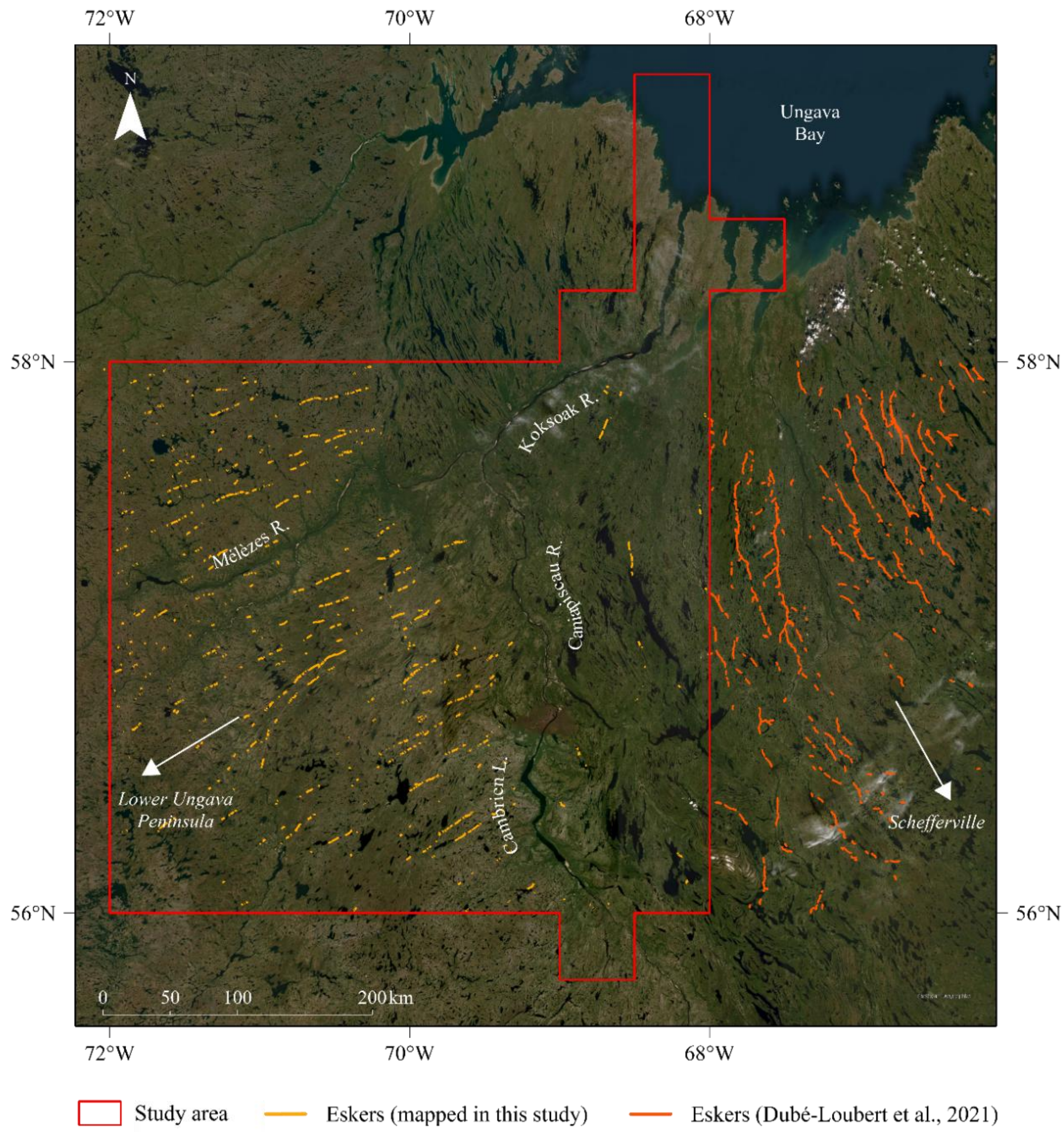

Figure 2.7 Distribution of the two esker systems separated by the Labrador Trough. In orange are eskers mapped in this study and in red are those from Dubé-Loubert et al. (2021). The arrows represent the respective directions of ice retreat for each sector.

2.4.2 Meltwater channels

Numerous types of meltwater channels (subglacial, proglacial, marginal) are present in the study area. Meltwater channels are erosional features carved into rock and sediments by flowing water beneath or near ice-sheet margins (Atkins, 2011). Therefore, their distribution and orientation can be used to reconstruct the retreat pattern of the glacier front (Kleman, 1992). Although these channels present some variability in terms of morphology, they generally occur as single or ramified (braided) slightly winding, and elongated depressions (Atkins, 2011; Greenwood et al., 2007).

Here, only ice-marginal meltwater channels were systematically mapped to document the withdrawal of the ice front. These channels formed during the retreat of an active (warm-based ice) or partially stagnant (polythermal ice mass). Under these conditions, meltwater produced at or near the ice front may flow at the surface or percolate under the ice and it is forced to flow laterally along the ice margin. The flow of water between the substrate and the glacier margin erodes the adjacent material, resulting in the formation of nested sequences of parallel channels perpendicular to the direction of ice retreat (Greenwood et al., 2007). Their orientation is roughly perpendicular to eskers, suggesting that their formation is contemporaneous with the establishment of these fluvioglacial landforms, thus associated with the retreat of the glacier margin (Storrar, 2014).

In the study area, twelve networks of ice-marginal meltwater channels were mapped, recording a succession of ice-margin positions. They are located between the Mélèzes River to the north and the Caniapiscau River to the east and indicate the retreat of the ice front into the interior of the Ungava Peninsula, thus consistent with the orientation of the esker system in this region. Their size ranges from 50 to 100 m in width and from 0,5 to 1,5 km in length. We report their occurrences in groupings that generally comprise between 3 and 7 channels, covering areas between 300 and 2000 m^2. They are mostly located in the uplands and can terminate abruptly or in downslope chutes (Atkins, 2011).

2.4.3 Minor moraines

Minor moraines were identified in six sectors: three in the north along the coastal areas fringing Ungava Bay, and three in the south, on the east side of the Koksoak-Caniapiscau Rivers. These landforms are composed of till and occur in groups of parallel and evenly spaced straight ridges. These sectors cover areas ranging from 35 km^2 and 18,000 km^2. Their formation is associated with the down-wasting of moderately active or partially stagnant ice. The alignment of the long axis of minor moraines is oriented transverse to the direction of ice movement (Boulton et al., 2001). Therefore, their NW-SE orientation indicates the direction of retreat of the ice front, consistent with the spatial distribution of the system of eskers to the east.

2.4.4 Strandlines

Mapping yielded an inventory of 1034 of raised beaches, terraces, and deltas. The strandlines typically form stacks of well-defined terraces composed of well-sorted sand and gravel, which generally result from the reworking of the underlying glacial deposits by the former water planes that occupied the river valleys. The surface of some of these strandlines has a layer of cobbles brought by floating ice and washed by the action of waves and wind. These strandlines generally span tens of meters to kilometers in length, with widths ranging from 10 to 200 meters. However, higher elevation strandlines tend to be less extensive and occur over a shorter elevation spread, while lower elevation ones are better developed, extensive, and spread over a broader elevation range. Deltas also consist of sand and gravel accumulations, and extend across extensive areas, commonly reaching widths up to 3 kilometers. Deltas are mostly found at the mouth of rivers or long topographic depressions that likely formed tributaries flowing into the main river valley.

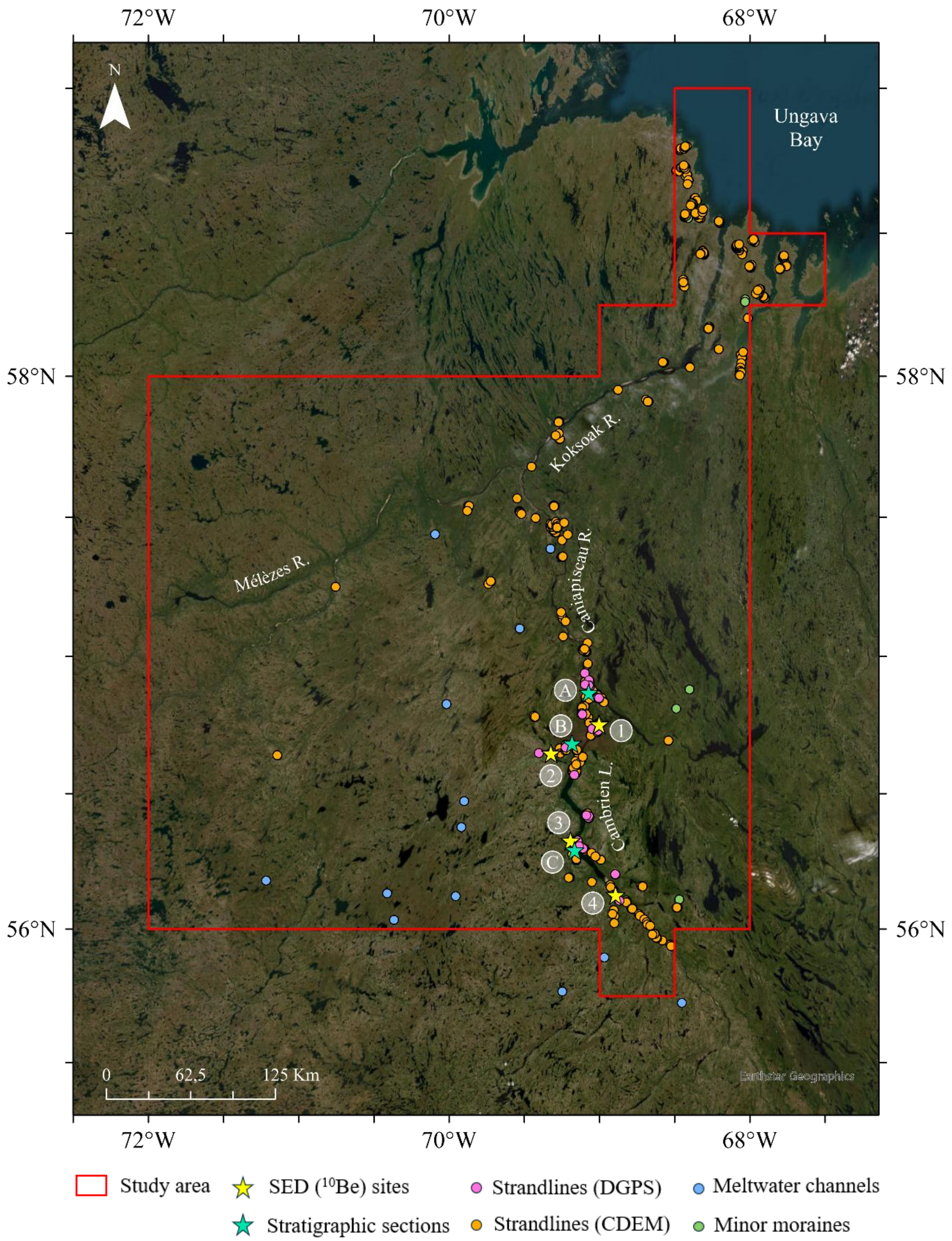

Figure 2.8 Distribution of strandlines with elevation measured with a DGPS (pink) or taken from the CDEM (orange), ice-marginal meltwater channels (blue) and minor moraines (green). SED sites (yellow star) : (1) CAMB14, (2) CAMB32, (3) CAMB25, and (4) CAMB40, and stratigraphic sections (turquoise star) : (A) CAMB8 (B) CAMB33 (C) CAMB19

A total of 44 elevation points were obtained from strandlines and deltas measured with a high-precision DGPS in the field, mostly in the basin of Lake Cambrien where previous work reported several occurrences. Additionally, we used the elevation of 1034 remotely mapped shorelines and associated landforms, which were taken from the CDEM (Figure 2.8).

Projection of these shorelines in an elevation-distance diagram covering a 190-km north-south transect shows that the distribution of shorelines is characterized by a progressive decrease in shoreline elevations towards the north (Figure 2.9). The present-day elevations of these raised shorelines range from 307 m in the south to 10 m near Ungava Bay. The uppermost shorelines along the transect define an apparent northward-dipping tilt. This overall lowering of the shoreline elevations reflects the withdrawal of the margin towards the south, where a greater amount of ice was present (thus higher postglacial rebound in the south vs north), along with the influence of the regional topographic gradient (the topography decreases in elevation towards the bay). Despite fieldwork evidence for three apparent levels at 190, 130, and 110 m in the basin of Lake Cambrien, where DGPS measurements were concentrated, the overall distribution of shoreline elevation-points reported here shows a near continuous vertical spread suggesting a gradual lowering of the water level below 200 m. This apparent vertical continuity may also be due to the CDEM data since they show a larger uncertainty, which introduces a reduction in the resolution of the data set (discussed below).

Plotting of the strandlines and deltas with elevations taken from paleo-topography reconstructed from a rebound surface dating to 7 ka BP (Godbout et al., 2023) removes the south-to-north tilt, as expected. This elevation-distance diagram yields a strandline distribution where the bulk of the well-developed and vertically extensive shoreline sequences occur at or below the 0 m elevation, which corresponds to the sea level at this time (as defined in the GIA outputs of the ICE-6G model outputs Peltier et al., 2015) (Figure 2.10). This diagram with the paleo-surface also outlines the presence of scattered high-elevation strandlines in the southern region, which clearly stand out from the rest of the dataset in terms of extent and vertical spread.

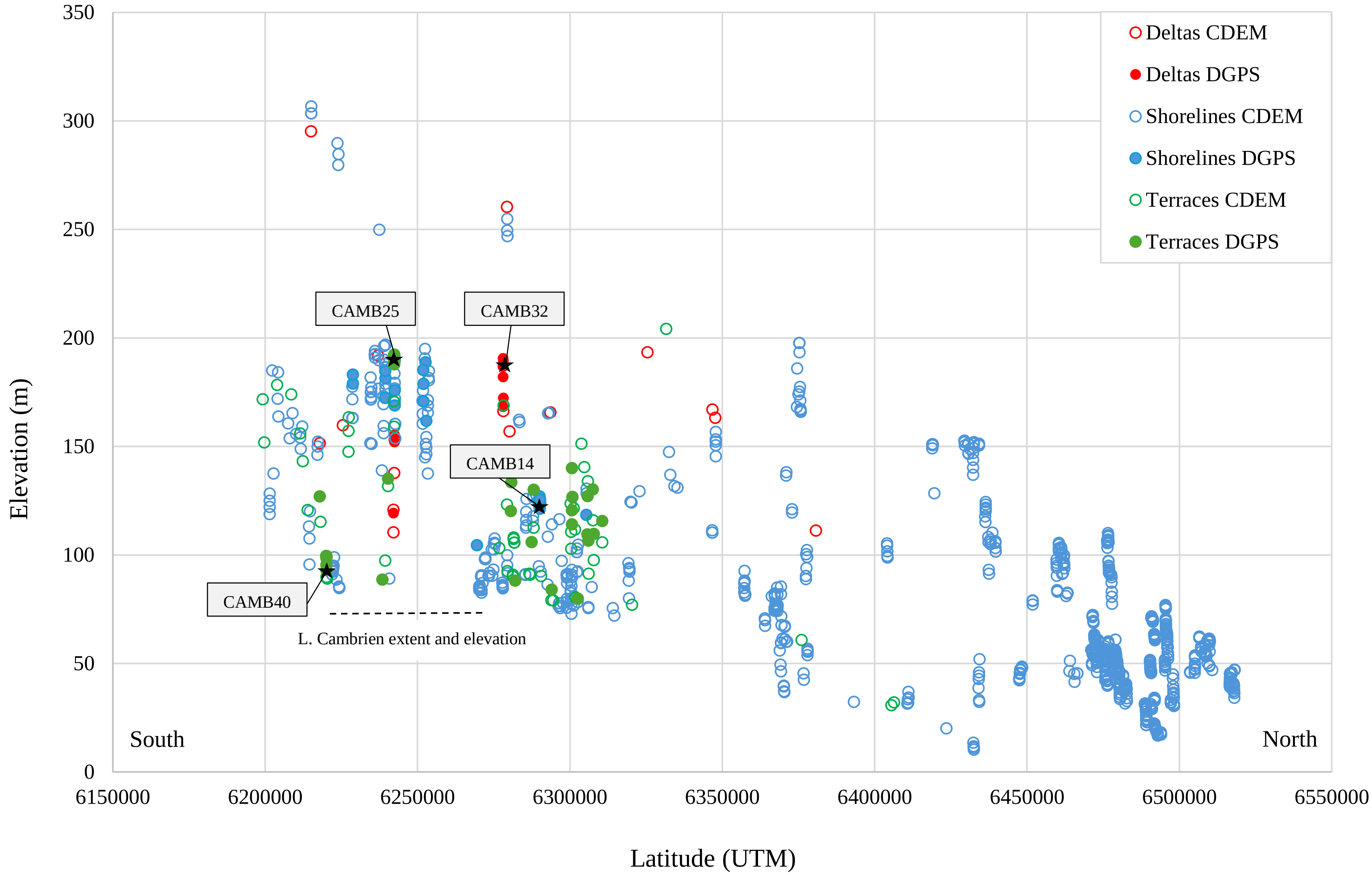

Figure 2.9 Elevation-distance diagram showing the latitudinal (south-to-north) distribution of remotely mapped (open circles) and field-measured (solid circles) shorelines (blue), deltas (red) and terraces (green) with elevations taken from the present-day surface-topography.

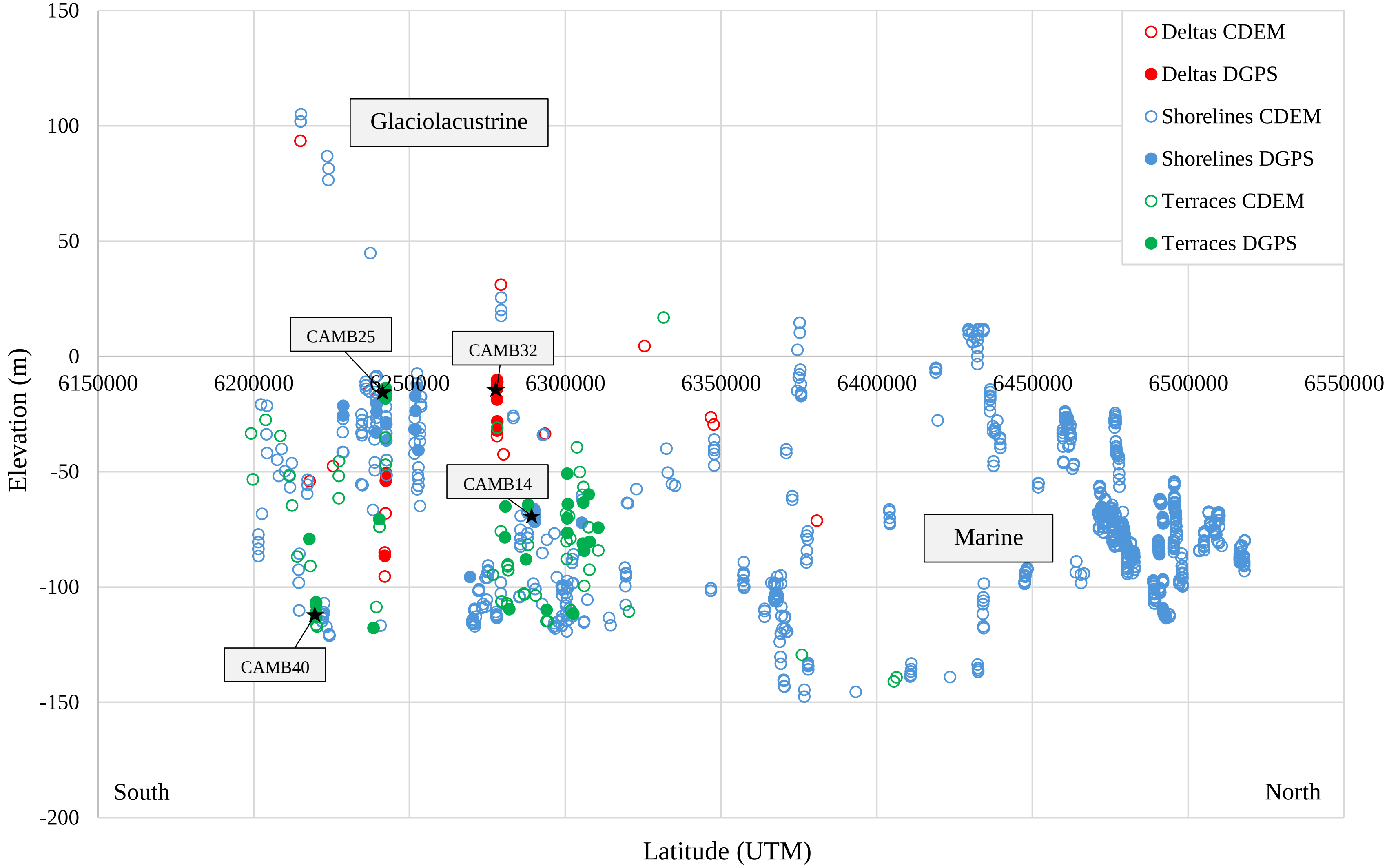

Figure 2.10 Elevation-distance diagram showing the latitudinal distribution of mapped (open circles) and field-measured (solid circles) shorelines (blue), deltas (red) and terraces (green) with elevations derived from a 7 ka B.P paleosurface.

2.4.5 Geochronology

Results from ^{10}Be surface exposure dating of 14 boulders sampled from strandlines at four sites are presented in Table 2.1. Overall, except for one sample, the ^{10}Be ages obtained form a coherent dataset whereby ages show a younging trend with decreasing elevations, with no occurrences of age overlap. Specifically, exposure ages are internally consistent within each sampling site, and the thirteen samples range between 4400 ± 100 and 7500 ± 200 years BP, with analytical uncertainties between 1,4% and 4,3%. Sample CAMB40-002 may be considered an outlier, as it exhibits an age of 15 600 ± 300 years BP, which falls outside of the two-standard deviation (2σ) statistical discrimination method. This age is also inconsistent with paleogeographic reconstructions in the region, which position the ice margin near the Labrador coast at that time (Dyke, 2004; Dalton et al., 2020, 2023). This older age likely reflects the presence of inherited cosmogenic nuclides from a previous period of exposure due to insufficient glacial erosion of the boulder sampled.

Tableau 2.1 Sample information, exposures ages and associated uncertainties

Sample no.	Latitude (DD)	Longitude (DD)	Elevation (m)	Thickness (cm)	[10Be] ± 1σ (10^4 atoms/g)	Lm ± 1σ (a)	1σ (%)
CAMB25-005	56,325	-69,193	192	2,83	3,98 ± 0,089	7600 ± 200	2,6
CAMB25-003	56,326	-69,192	190	3,14	3,91 ± 0,084	7500 ± 200	2,7
CAMB25-002	56,325	-69,190	188	2,88	3,91 ± 0,133	7500 ± 300	4,0
				Mean ^{10}Be age for CAMB25 site		**7500 ± 200**	
CAMB32-003	56,646	-69,321	188	2,57	3,57 ± 0,069	6900 ± 100	1,4
CAMB32-001	56,646	-69,322	188	2,37	3,58 ± 0,078	6900 ± 200	2,9
CAMB32-002	56,647	-69,322	187	1,91	4,02 ± 0,096	7700 ± 200	2,6
				Mean ^{10}Be age for CAMB32 site		**7200 ± 200**	
CAMB14-003	56,754	-69,004	127	2,80	3,55 ± 0,071	7300 ± 200	2,7
CAMB14-005	56,754	-69,004	127	2,79	2,60 ± 0,071	5300 ± 200	3,8
CAMB14-002	56,754	-69,004	122	2,80	2,93 ± 0,072	6000 ± 200	3,3
CAMB14-001	56,755	-69,004	121	2,43	2,86 ± 0,072	5900 ± 200	3,4
				Mean ^{10}Be age for CAMB14 site		**6100 ± 200**	
CAMB40-005	56,125	-68,893	100	1,98	2,06 ± 0,067	4300 ± 100	2,3
CAMB40-004	56,125	-68,893	99	4,45	1,97 ± 0,063	4200 ± 100	2,4
CAMB40-002	56,125	-68,895	95	3,44	7,27 ± 0,136	15600 ± 300	1,9
CAMB40-001	56,125	-68,895	93	3,03	2,20 ± 0,084	4700 ± 200	4,3
				Mean ^{10}Be age for CAMB40 site		**4400 ± 100**	

All samples come from granitic boulders found at the surface of strandlines. Rock density is the same for all samples: 2,65 g/cm^3. Shielding correction was negligible and has been fixed at 1,00. AMS standard used is the 07KNSTD.

2.4.6 Stratigraphic investigations

Three stratigraphic sections exposed along riverbanks were documented. These sedimentary sequences exhibit diverse sediment facies that provide insights into the spatial-temporal evolution of the retreating ice margin and former depositional environments.

The Swampy Bay River stratigraphic profile (CAMB8; Figure 2.11A) (N495623; E6302563) is a 45-meter-high section located at the confluence of the Swampy Bay River and the Caniapiscau River. The first 10 meters at the base of this section comprises clay rhythmites, with summer layers showing a transition in thickness towards the summit, going from thin (~1 mm) to thicker (~5 mm) layers, where they become as thick as the winter layers (~5 mm) (Window A, Figure 2.12A, B, C). The overlying unit consists of a coarse sand bed about 8 cm thick which indicates a significant influx of material. This bed is overlain by stratified clays that suggest a lull in the input of coarse sediments, which is in turn followed by another coarse sand unit with ripples indicating reverse drainage towards the east (105°; i.e. against the present-day river gradient) (Window B, Figure 2.12D). The next unit is characterized by a gradual loss of sedimentary structures and the reappearance of varves at the top. The reddish color of the winter layers indicates a change in provenance (Window C, Figure 2.12E). The remaining of the section shows alternating cross-bedded and/or frontal sand layers and massive sand beds (Windows D to H, Figure 2.12F, H, I). Clastic lenses of massive clay about 10-15 cm thick were also observed (Window E, Figure 2.12E). Micropaleontological analyses were carried out on clay samples CAMB-001, -002 and -003 collected at the base of the section. Results revealed very few fossils, with the notable absence of foraminifera, which are typically found in marine environments (Gupta, 1999; Pawlowski et al., 2003).

The Châteauguay stratigraphic section (CAMB33, Figure 2.11C) (N488833; E6282023) is located upstream of the Caniapiscau River, approximately 20 km before it widens to form Lake Cambrien. This 10-meter-high section shows dark-gray clay beds (~5 cm thick) displaying some rhythmicity with thinly laminated horizontally sand beds (~4 cm) (Window A, Figure 2.13A). The thickness of the sandy beds increases towards the upper part of the section.

The Death River stratigraphic section (CAMB19, Figure 2.11B) (N48974; E6238441) is located around 550 meters upstream from the confluence with Lake Cambrien. The base of the section is covered by 2-3 meters of slump deposits, beneath which appear numerous sub-angular blocks suggesting the presence of till or possibly alluvial deposits. The overlying unit spans approximately 10 meters and consists of rhythmites showing fine sand summer layers that alternate with predominantly silty winter layers with a small proportion of fine sand (Window B, Figure 2.14A). At the base, the summer layers are ~0,5 cm thick and the winter layers ~1 cm thick. This rhythmicity decreases towards the top where summer beds are ~0,5 mm thick and winter beds ~2 mm. The overlying two meters contain poorly defined rhythmites, suggesting deposition proximal to the ice margin or in a poorly developed basin (Window C, Figure 2.14B, C). Ripple marks are present in some summer layers, with the thickness of these sandy summer layers increasing towards the top, forming a broad band of fine sand. The next unit is two meters thick and is composed of regularly bedded rhythmites capped by a layer of fine sand and silt trapped between two layers of massive clays at the top (Window D, Figure 2.14D). The remaining four meters of this section show a transition from well-defined rhythmicity to thick layers of fine sand and massive clays, in which the sand layers exhibit current ripples towards the north of the valley (5°) (Window E, Figure 2.14E, F).

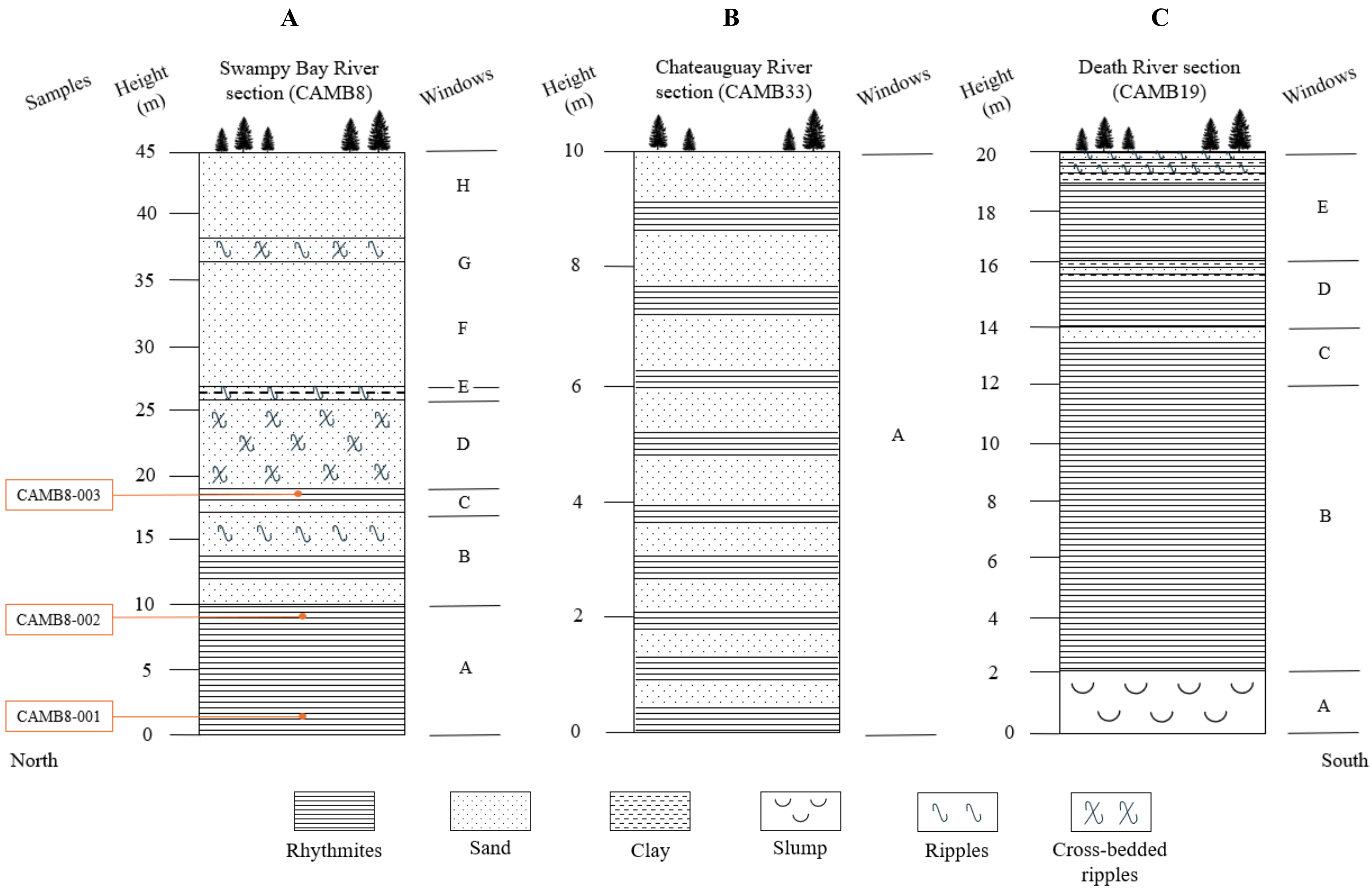

Figure 2.11 Studied stratigraphic sections in the Lake Cambrien basin. (A) Swampy Bay River section (CAMB8), (B) Chateauguay River section (CAMB33), and (C) Death River section (CAMB19).

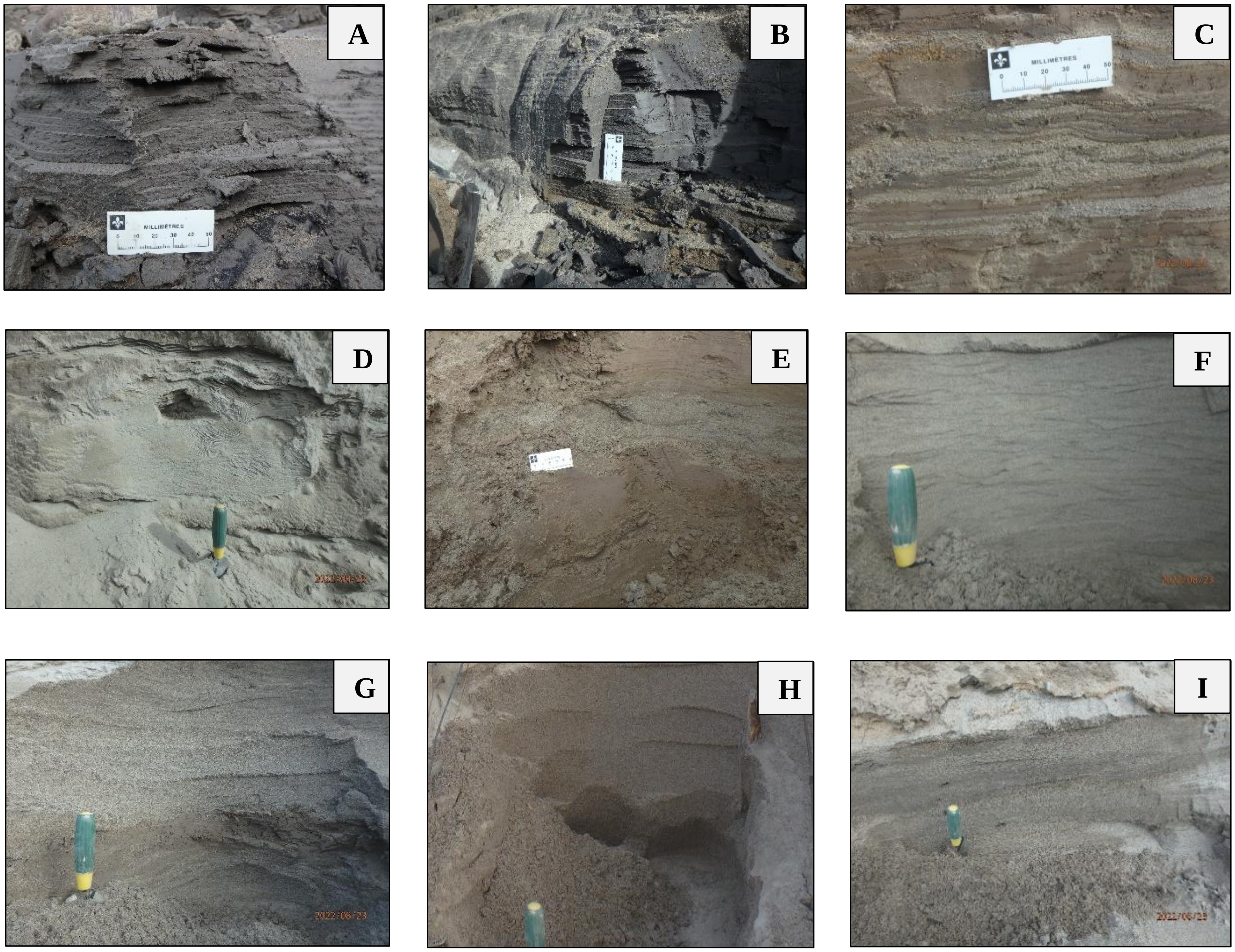

Figure 2.12 Close-up images of the Swampy Bay River section (CAMB8). (A, B, C) Increase in summer layer thickness from the base (A) to the top (C) of window A, (D) Coarse sand bed in window B, (E) Reddish rhythmites in window C, (F) Cross-bedded ripples in the sand bed, (G) Clastic lenses of massive clay in window E, (H) Massive sand bed in window F, (I) Frontal ripples in the sand bed of window H.

Figure 2.13 Close-up images of the Chateauguay River section (CAMB33). (A, B) Plastic clay beds in window A, (C) Rhythmites showing fine sand summer layers in window A.

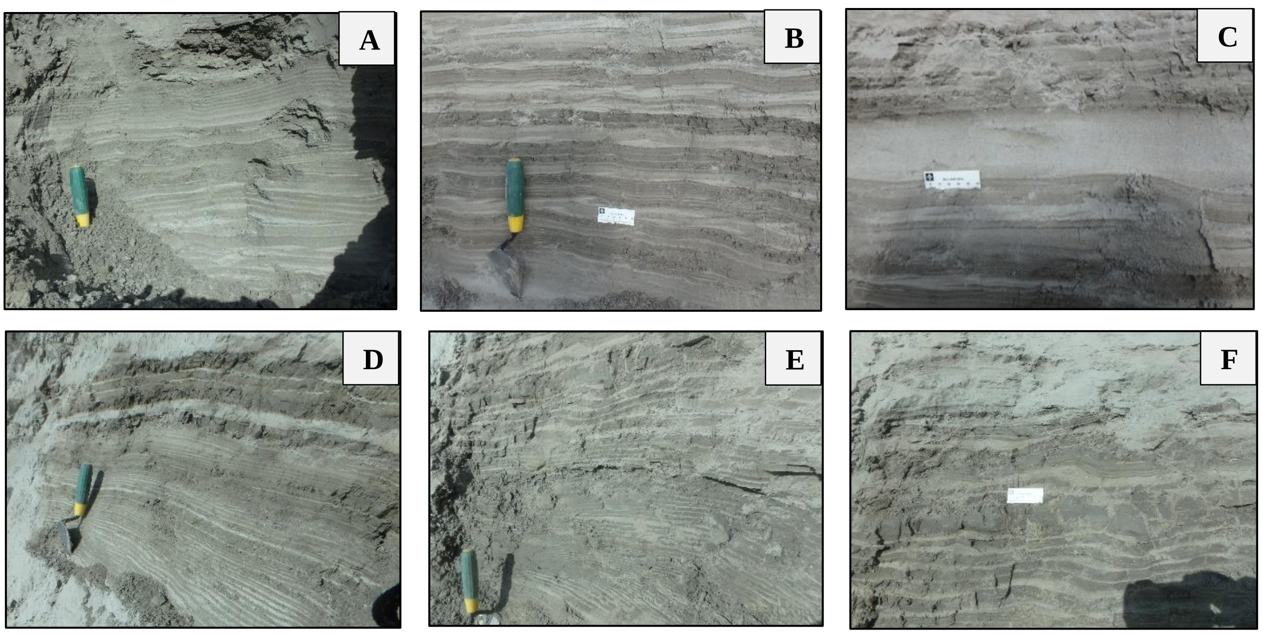

Figure 2.14 Close-up images of the Death River section (CAMB19). (A) Well-defined rhythmites in window B (B, C) Decrease in rhythmicity from the base (B) to the top (C) of window C, (D) Regularly bedded rhythmites in window D, (E, F) Increase in winter layers thickness from the base (E) to the top (F) of window E.

2.5 Discussion

2.5.1 Regional deglaciation

The recognition of significant glacial lakes in south-central Ungava (south and southwest of Ungava Bay) has always been hampered in part by large uncertainties in the regional pattern of ice retreat, which do not provide sufficient details on the position and configuration of the ice margin and thus on the location of the ice dam(s) that could have led to the development of glacial lakes (e.g., Clark et al., 2000). Indeed, most paleogeographic reconstructions available show a broad retreat of the ice margins, going westward from the Torngat mountains and southward from Ungava Bay, but with little details on the evolution of the ice front that eventually led to the residual ice masses of the Québec-Labrador Sector (Clark et al, 2000; Dyke, 2004; Dalton et al., 2023).

The two sets of eskers reported here provide the first insights into where the ice front likely separated during the deglaciation and allowed drainage obstruction and the subsequent accumulation of meltwater in the river valley. The results indicate that one part of the ice margin retreated southwestward towards the lower Ungava Peninsula, while the other segment of the ice front retreated southward towards Schefferville, in the highlands of north-central Quebec. This is also supported by the spatial distribution and orientation of ice-marginal meltwater channels mapped on the western side of Lake Cambrien, which indicates a retreat towards the lower Ungava Peninsula. This deglaciation pattern is consistent with the earlier work of Douglas and Drummond (1955), which was also based on the orientation of glaciofluvial landforms.

The separation of the ice front indicated by these two esker systems could be linked to the thinning of the ice mass and the concomitant increasing influence of the underlying topography, as the separation occurs near the hilly and high-relief terrains of the Labrador Through. The development of the different ice stream systems in the Ungava Bay lowlands in late-glacial time (Winsborrow et al., 2004; Stokes et al., 2009; Margold et al., 2018) may have contributed to the thinning of the ice mass and allowed the exhumation of these high reliefs. This scenario is also supported by the highly fragmented and low-profile esker segments of the two systems mapped, which suggest formation under a thin ice mass (Dubé-Loubert et al., 2021). Changes in the density of esker distribution, particularly between these two systems further support this interpretation. The individualization of ice mass remnants that characterize the late deglaciation southwest and west of the study area also requires the occurrence of ice fronts that retreat independently from each other – a separation process that may have been dictated by the topographical characteristics of the study area.

Considering the north-south orientation of the Caniapiscau River valley, as well as the two patterns of ice withdrawal documented here, the development of a lake is only possible by invoking an earlier withdrawal of the eastern portion of the ice front and the preservation of the western ice front, or part of it, north of the river in order to dam the meltwater, as the natural drainage pathways flow north. In this context, meltwater was naturally channeled in the topographical/structural depression of Lake Cambrien and confined by the topographical barrier of the Labrador Trough to the east and by the retreating margin to the north and west. The absence of eskers in the immediate valleys of the Koksoak-Caniapiscau Rivers suggests that these valleys served as the main channels for carrying large volumes of meltwater to the basin. In short, the ice margin segment retreating southwestward impeded meltwater flow in the Caniapiscau valley and allowed the development of a glacial lake in the southern part of Cambrien Lake and the nearby river catchments.

2.5.2 Origin of shoreline sequences

Although most strandlines of the study area show a similar composition, remote mapping and field investigations revealed that these strandline sequences can be divided into two groups based on their geomorphological characteristics, spatial extent, and elevation. We associate the low-elevation (< 200 m) well-defined and laterally extensive strandline sequences that show a near-continuous vertical spread over several tens of meters to the postglacial incursion of the d'Iberville Sea. These characteristics are consistent with a major reworking of the glacial sediment cover by littoral/wave erosion and coastal processes associated with a long-lasting water plane in the area, which was influenced by postglacial isostatic recovery over some time, as reflected by the significant vertical spread of the strandlines (Bednarski, 1988). This is typical of a glaciomarine environment and similar raised shoreline sequences associated with the d'Iberville Sea have been reported from the coastal areas all around Ungava Bay (Wilson et al., 1958; Matthews, 1968; Lauriol, 1982; Gray et al, 1993; Dubé-Loubert et al., 2021; Lefebvre-Fortier et al., 2024). The second group of strandlines, which consists of high-elevation shorelines that are spatially restricted and scattered vertically, is associated with the presence of a glacial lake in the study area. These characteristics reflect formation by water planes with a short life span typical of a glaciolacustrine environment. Unlike post-glacial seas, glacial lakes are transient features on the landscape, as they result from the temporary damming by an actively retreating ice margin, which causes the liberation (freeing from ice) of outlets and the concomitant opening of new territories resulting in abrupt and rapid changes in lake levels. This type of raised shorelines and development setting has been reported in many places elsewhere in Ungava-Labrador (Ives, 1960, Matthews, 1968; Andrews and Barnett, 1972; Lauriol et al, 1993; Dubé-Loubert and Roy, 2017).

Correlation of the uppermost strandlines of the glaciomarine sequences shows a tilted water plane (37 cm/km) in the elevation-distance diagram with the present-day topography, which is caused by greater post-glacial uplift to the south and reflects a thicker ice mass in this region, thus coherent with paleogeographic reconstructions. Although glacial lake sequences are expected to show greater deformation (warping) due to their earlier development during deglaciation (Andrews and Barnett, 1972), the correlation of scattered shorelines separated over long distances is difficult and remains highly speculative, making the determination of tilt values very subjective.

The results thus argue for the occurrence of a glacial lake in the Caniapiscau River valley, unlike earlier interpretations of these sequences in the field (Drummond, 1965). Remote mapping in earlier studies did show a complex succession of extensive glacial lake stages in the region (Jansson, 2003; Jansson and Kleman, 2004), but these theoretical reconstructions are based on an obsolete (unrealistic) ice retreat model (Kleman et al., 2010). Differentiating the lowermost glacial lake shorelines from the uppermost marine sequences is difficult when considering the effect of GIA on these sequences. In the valley of the Koksoak-Caniapiscau Rivers, our data indicate that the elevation of the maximum marine limit is around 200 m. To the east, this maximum limit of marine submergence is 175 m in the Aux-Feuilles River valley and 125 m in the Arnaud River valley (Lefebvre-Fortier et al., 2024), while it reached 160 m in the Whale River valley and 100 m in the George River valley south-east of Ungava Bay (Dubé-Loubert et al., 2021). These variations in elevations across the Ungava Bay coastline and nearby river valleys reflect an asynchronous marine incursion, influenced by varying ice thicknesses and different ice retreat rates, which affected the magnitude and timing of glacio-isostatic rebound (Lauriol, 1982; Lauriol et al, 1993; Dubé-Loubert et al, 2021; Lefebvre-Fortier et al., 2024).

To distinguish landforms associated with a former glacial Lake Cambrien from those related to the d'Iberville Sea, we use shoreline-elevation points extracted from a paleosurface representing this interval of the deglaciation (i.e., 7 ka in the GIA model; Peltier et al., 2015). Plotting of the shorelines in an elevation-distance diagram using GIA-corrected elevations has the main advantage of bringing the shorelines back to their near-original surface of formation (i.e., horizontal), thus circumventing the effects of post-glacial (uplift) deformation. In Figure X, the 0 m elevation corresponds to the mean sea level at 7 ka BP, which is the time slice for the marine incursion in the reconstruction used to derive this paleosurface (Godbout et al., 2023). Accordingly, the fact that the bulk of the extensive shoreline sequences we report occur at or below 0 m suggests that most of these shorelines are marine in origin, consistent with our earlier interpretation based on the geomorphic characteristics of these strandlines.

Consequently, the high-elevation strandlines in the southern part of the study area that plot above this 0 m elevation line likely belong to former levels reached by a glacial lake. In the same way, their disappearance in the north segment of the valley (~628 000 UTM) places a minimum limit on the lake extent, which is around Châteauguay River, 15 km north of Lake Cambrien. However, given the uncertainties of the GIA model and those linked to in-situ (field) and remote elevation measurements, this 0 m elevation limit cannot be taken as a firm constraint on the interpretation of the origin of shorelines, as marine and glacial lake strandlines may occur above or below this arbitrary threshold (± 12 m). For this reason, we believe that the degree of development of these shorelines remains an important criterion to distinguish the marine shoreline from the glacial lake shorelines. We also acknowledge that glacial Lake Cambrien may have extended north of the limit identified here, as the evolution of this basin, and thus its spatial extent, was rapid and controlled by a rapidly retreating ice margin. Additionally, low-elevation (under 0 m) shorelines formed by glacial Lake Cambrien may also have been reworked or even entirely remobilized by the subsequent incursion of marine water.

Key to the understanding of the extent of the glacial lake is the interpretation of the sediment sections exposing thinly bedded varves or rhythmites. Based on the presence of stratified clay deposits in the Koksoak and lower Caniapiscau Rivers that were assigned to marine origin (Low, 1896), the Glacial Map of Canada (Wilson et al., 1958) shows a marine submergence along the Ungava Bay coast that extends in the Koksoak River valley up to around 65 km south of the

Mélèzes-Caniapiscau Rivers junction. However, the stratified clays found at this location were subject to conflicting interpretations, as to whether they were marine (Low, 1896; Drummond, 1965) or glaciolacustrine in origin (Bergeron, 1979). Drummond associated these bedded sediments with the marine incursion and explained the stratification of the clays by the fact that the estuarine water of the proto-Koksoak River was fresher due to the large volumes of glacial meltwater. Flocculation of clay minerals occurs predominantly where fluvial waters mix with the marine waters, such as in estuaries (salinity near 10 psu; Sutherland et al., 2015; Ó Cofaigh and Dowdeswell, 2001). No varved clays have been reported in the literature between the Manitou Gorge and the Shale Falls. South of this location, no consensus on the origin of stratified sediments has been established, likely due to the complexity introduced by the marine incursion and the concomitant drainage of the glacial lake, whereby marine water likely reworked preexisting glaciolacustrine sediments before the deposition of glaciomarine sediments.

The laminated sediment found in the sections studied here reveals significant sedimentological changes reflecting fluctuations in the magnitude of the incoming water fluxes and depositional conditions in the basin of Cambrien Lake. These variations likely reflect a set of variables, such as changes in the distance from the ice margin, the amount and rate of ice wastage on the surrounding plateaus, and subsequently, the opening of drainage pathways (e.g., Drummond, 1965).

The varved clays of the Death River section (CAMB19) appear typical of glaciolacustrine environments, as they show clearly defined couplets consisting of fine-grained winter layer (silt/clay) and coarse-grained summer layer (sand/silt) that can be interpreted as sedimentation controlled by seasonal variations in sediment input (Ashley, 1975; Sturm, 1979; Smith and Ashley, 1985). Generally, the occurrence of such well-defined layered sediments requires a water column of at least 30 meters deep (Veillette, 1994). Variations in the thickness of the summer and winter layers can be attributed to the proximity of the ice margin. In proximal conditions, the summer layer is thicker than the winter layer, while in more distal conditions, the winter layer may be thicker (Ó Cofaigh et Dowdeswell, 2001). The medium-to-dark-gray, massive clays of the Châteauguay River (CAMB33) section show faint laminations and some internal rhythmicity that are typical of glaciomarine environments. Such clays are commonly deposited by suspension settling during the marine flooding phase, where constant depositional conditions occur over a long period, allowing the formation of well-defined layers (Mackiewicz et al., 1984; Cowan et al., 1999).

The medium-gray silty rhythmites and overlying reddish-brown clays interbedded with fine sand at the base of the Swampy Bay section (CAMB8) could be interpreted as glaciolacustrine rhythmites based on the micropaleontological analysis of clay facies, which did not reveal the presence of foraminifera. However, the absence of these marine microfossils does not necessarily imply that these sedimentary facies are not of marine origin. The deep inland location of the Swampy Bay River section may have formed an estuarian environment where the large volumes of meltwater runoff at that time may have significantly diminished the salinity conditions. Decreases in salinity and pH affect foraminiferal calcification and limit their presence in these habitats (Iglikowska et Pawlowska, 2015; Holzmann et al., 2021). Furthermore, the absence of microfossils may also be explained by the high sedimentation rates of ice-proximal environments (proximity to the ice margin), leading to unfavorable conditions for faunal colonization, whether in freshwater or saltwater environments (Syviktski et al., 1989; Ó Cofaigh et Dowdeswell, 2001). Given that micropaleontological analysis was not fully conclusive, and that we cannot prove the annual pattern of rhythmicity, the origin of these thinly bedded sediments cannot be confirmed. Nonetheless, if these rhythmites were correlated with those observed in the Death River section, this would imply an ice dam further north, a position not supported by strandline elevation measurements. We therefore associate these rhythmites with the glaciomarine incursion.

Sedimentological and stratigraphic evidence presented above strongly supports the existence of a glacial lake that occupied at least the southern part of the current Lake Cambrien basin. Rather than invoking an ice dam in the Caniapiscau River valley or over the lower Koksoak River, Drummond (1965) suggested that the glacial lake was held up by a higher drift or rock dam at Schist Falls. However, geomorphological data – including eskers and meltwaters channels – along with distance-elevation measurements indicate that the development of Glacial Lake Cambrien was rather linked to the presence of ice cover over the Châteauguay River (~ 628 000 UTM), which dammed the Caniapiscau River and Lake Cambrien valleys. North of this area, high-elevation shorelines are absent. This location regarding the ice dam is consistent with the studied stratigraphic section which shows that the rhythmites in the Châteauguay River—and likely those in the Swampy Bay River—are of marine origin. In contrast, the varved clays found in the Death River were deposited in a glacial lake.

Additionally, a significant swarm of meltwater channels between the mouth of the Châteauguay River and the Schist Falls, located 20 km to the north, may reflect the gradual breaching of this dam and the subsequent drainage of the glaciolacustrine water. Schist Falls, which marks the geological contact between the rocks of the Labrador Trough and the Superior Province, creates a depression that could have further channeled and maintained the ice front in the region. Notably, downstream of the waterfall, the river's course undergoes a marked deflection to the west, making the Caniapiscau River depression nearly perpendicular to the mapped esker trains, which may have supported the maintenance of the dam.

2.5.3 Modeling of glacial Lake Cambrien and post-glacial d'Iberville Sea

Given the uncertainties in the location of the ice dam, we used available ice margin position provided by paleogeographic reconstructions (Dalton et al., 2020; 2023) to reconstruct the extent of glacial Lake Cambrien (Figures 2.15 and 2.16). The combination of this damming scenario with a paleo-surface topography at 7 ka shows that the water of glacial Lake Cambrien submerged the southern part of the present-day basin and extended eastward into the present-day Castignon, Chakonipau, Nachicapau, and Le Moyne Lake sectors, covering an area of 2462 km^2, for a volume of 105 km^3. We used this reconstruction of the lake extent to look for geomorphologic evidence supporting the presence of the lake outside of our study area. Scattered strandlines and wave-washed trimlines were found, although in very few numbers. This is consistent with our observations in the core basin of Lake Cambrien that suggest a short-lived lake. This reconstruction indicates that glacial Lake Cambrien was not as large as presented in some previous reconstructions (Gray et al., 1993; Jansson et Kleman, 2004). These differences likely reflect the lack of field-based constraints and/or the use of an inadequate ice retreat pattern. This volume appears realistic with respect to other Ungava glacial lakes, as a recent reconstruction of glacial Lake Naskaupi to the east yielded a total volume of meltwater of 575 km^3 (Dubé-Loubert et al., 2018).

We used the same approach to reconstruct the extent of marine incursion in the study area (Figures 2.17 and 2.18). Considering the presence of the ice dam to the south and the different geomorphologic evidence, modeling using the paleosurface (7 ka) indicates that marine waters penetrated deep into the Koksoak-Caniapiscau Rivers. Glaciomarine deltas and other ice-contact landforms indicate that the retreating ice front was in contact with the d'Iberville Sea, at least for the early stages, likely reaching the ice dam to the south. At this point, the postglacial sea to the north and the glacial lake to the south likely coexisted, being separated by an ice segment a little more than a hundred kilometers wide. The retreat of the damming ice front eventually allowed the meltwater to drain into Ungava Bay, with a concomitant incursion of the postglacial d'Iberville Sea into the Lake Cambrien basin. Subsequently, the marine waters progressively receded due to glacio-isostatic adjustment, as indicated by the well-defined sequences of marine strandlines that show a gradual lowering in the Koksoak and upper Caniapiscau Rivers. Modeling the marine extent using a younger paleosurface (at 4 ka) reproduces the end of the marine incursion in the study area, as the water corresponds to the proto-Caniapiscau River. The modeling of the marine water for that time period and cosmogenic data (CAMB40) are well aligned (see below).

Although paleogeographic reconstructions position the southern limit of the glacial lake ice dam in the middle part of present-day Cambrien basin (~625 730 UTM) at 7 ka BP (Dalton et al., 2020, 2023), our geomorphological and stratigraphic data suggest that it should be placed 54 km further north, in the vicinity of the Châteauguay River. Placing the ice dam further north would result in a larger extent and volume for this glacial lake.

These results highlight the complexity of that kind of paleogeographical reconstructions and the lack of field-based and temporal constraints. These elements form key inputs in the modeling of ice-dammed lakes and marine incursions. Therefore, refinement work must be carried out on the pattern of ice retreat to precisely determine the exact boundary between marine and glaciolacustrine waters.

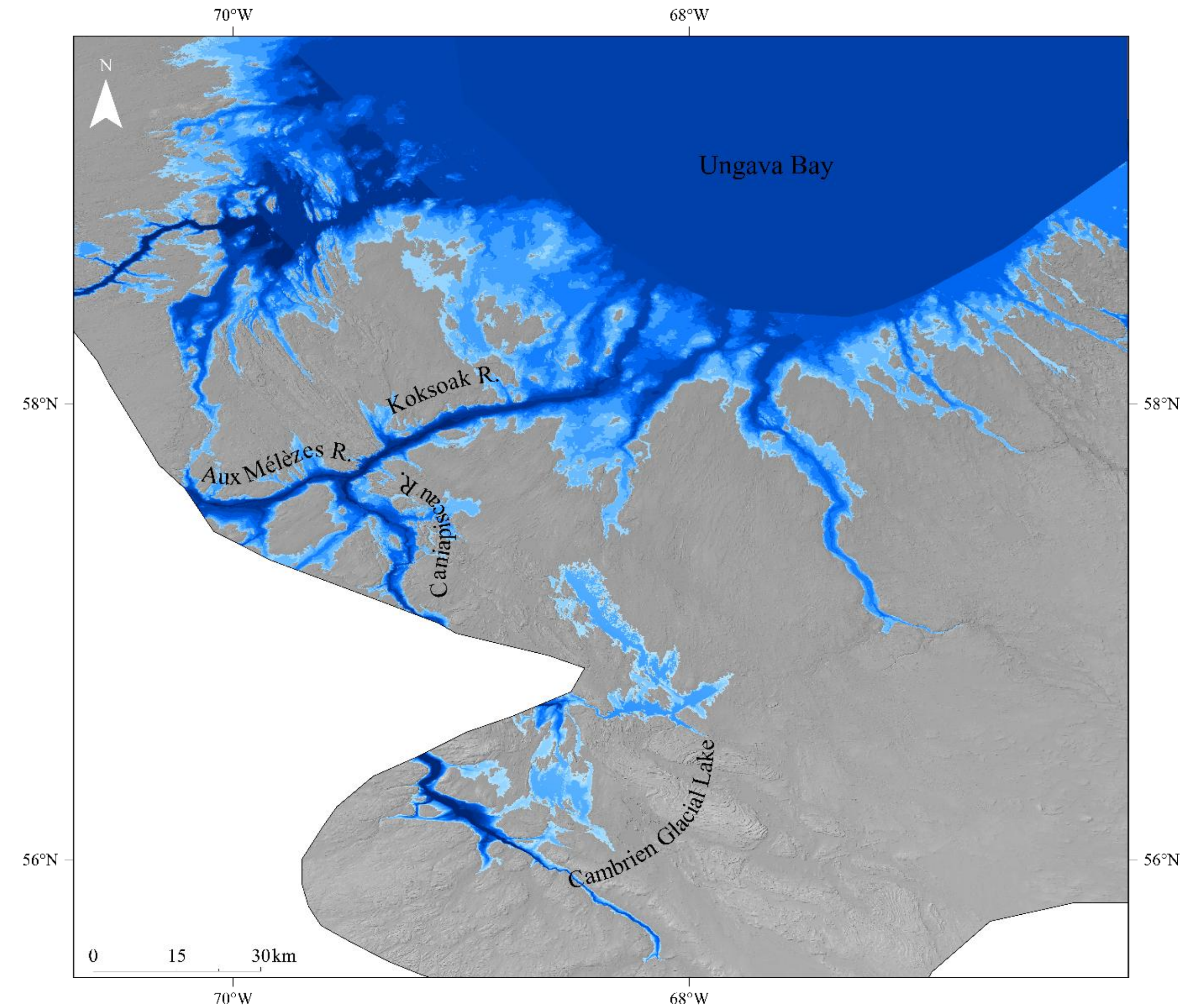

Figure 2.15 Reconstruction of the extent of glacial Lake Cambrien and of the d'Iberville Sea at 7 ka. Coexistence of the two water planes separated by an ice mass (white) (ice margin from Dalton et al., 2020, 2023), with the d'Iberville Sea to the north and glacial Lake Cambrien to the south

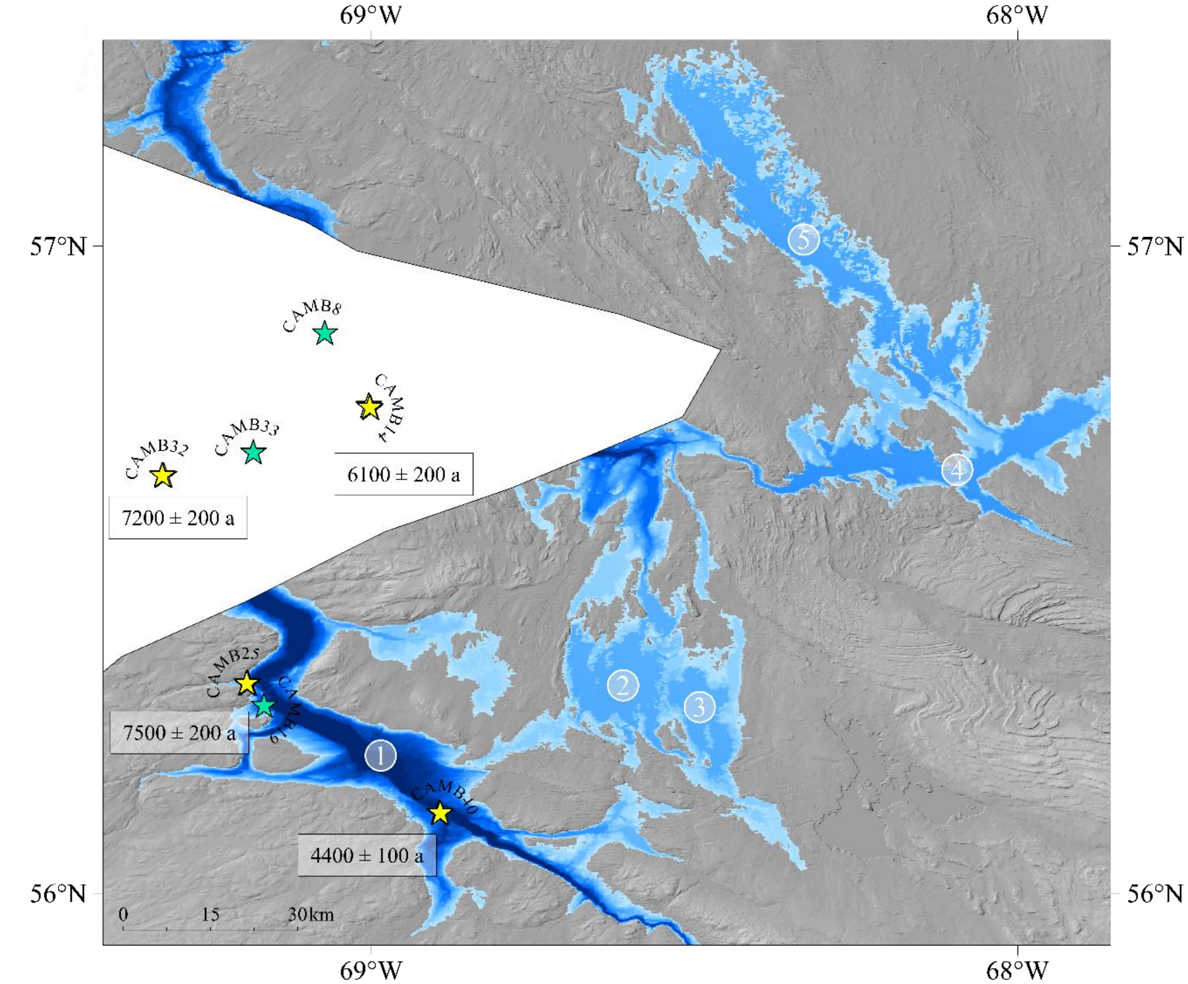

Figure 2.16 Close-up of the Lake Cambrien basin (ice margin from Dalton et al., 2020, 2023). Yellow stars correspond to the location of SED sites and turquoise stars correspond to the location of studied stratigraphic sections. Glacial Lake Cambrien extended in the basin of the present-day (1) Cambrien Lake, (2) Castignon Lake, (3) Chakonipau Lake, (4) Nachicapau Lake and (5) Le Moyne Lake.

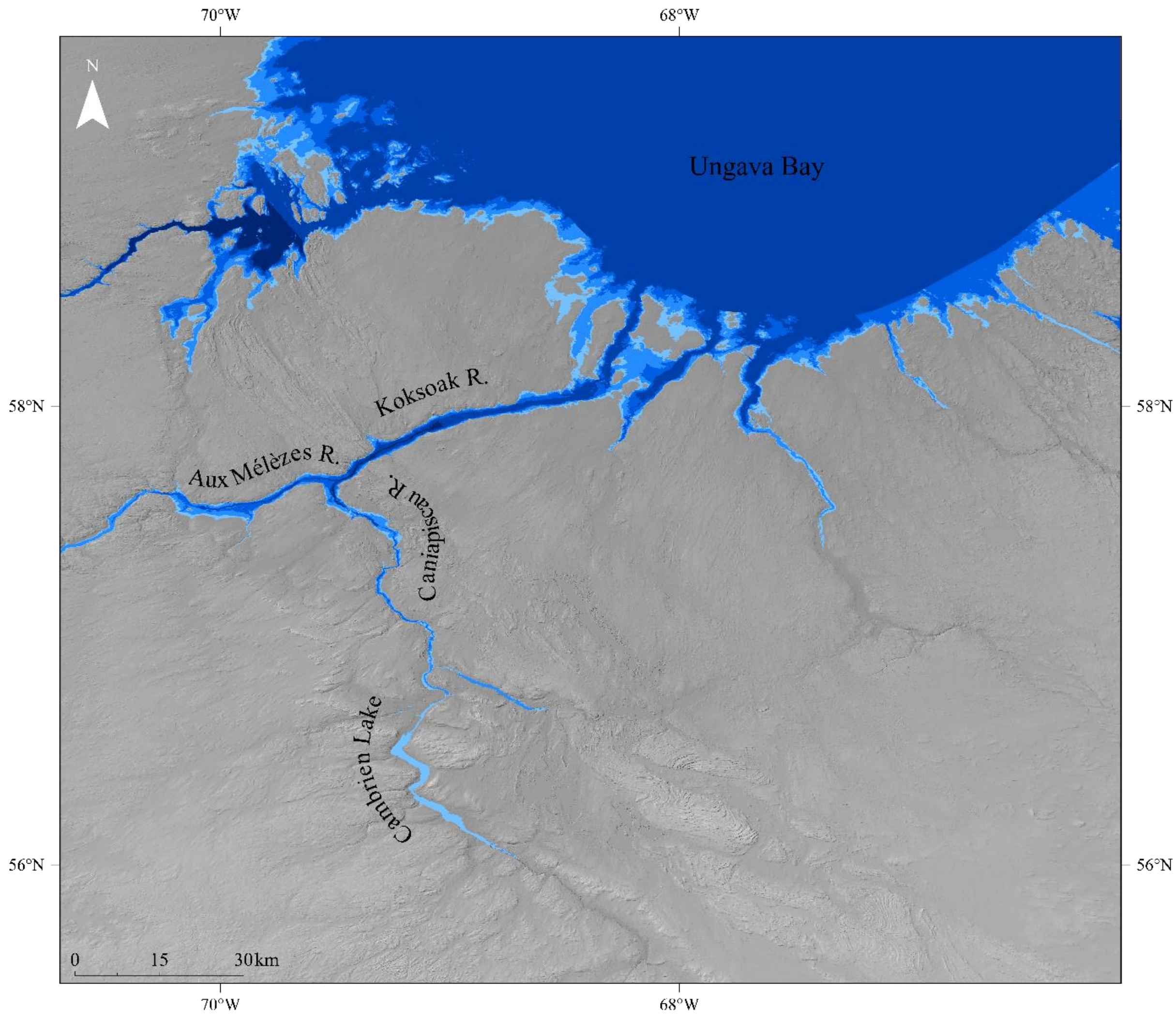

Figure 2.17 Reconstruction of the extent of the d'Iberville Sea at 4 ka.

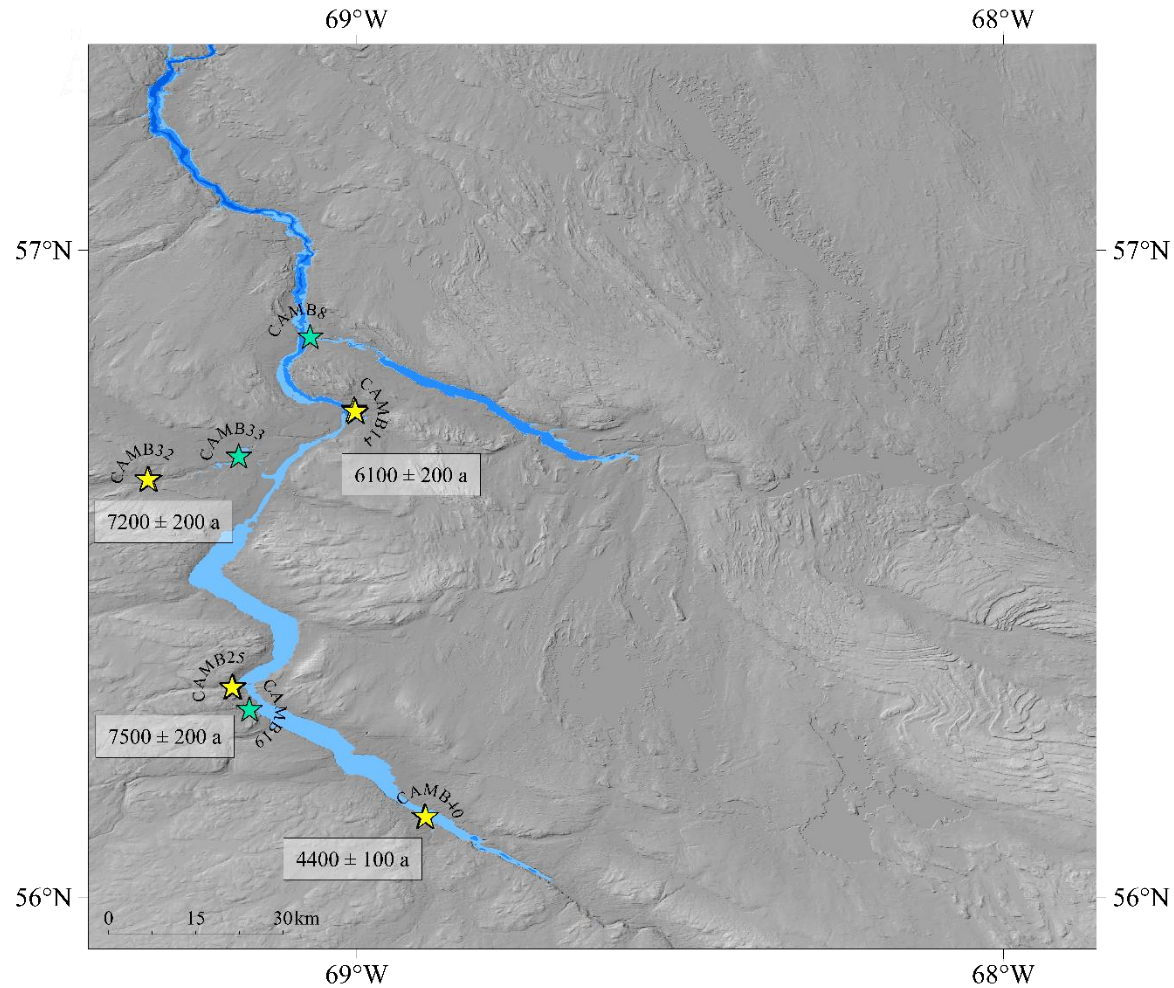

Figure 2.18 Close-up of the marine submergence in the basin of Cambrien Lake, along with 10Be ages. Yellow stars correspond to the location of SED sites and turquoise stars correspond to the location of studied stratigraphic sections.

2.5.4 Geochronology

The application of surface exposure dating to a set of three raised shorelines of different elevations at four sites yielded a coherent and younging trend of ^{10}Be ages. According to our reconstruction, the two lower terraces clearly belong to the marine incursion. However, the two upper terraces plot close to the upper marine limit and can thus be associated with either the glaciolacustrine or the glaciomarine environments. In particular, the elevation of the southernmost site CAM25 is close (~10 m) to the maximal marine elevation and the associated uncertainties of the ICE-6G model and the resolution of the CDEM further compilates interpretation. We therefore use additional criteria to interpret the origin of this terrace at site CAM25, as well as site CAMB32 which is at the same elevation.

From a geomorphological perspective, site CAMB25 consists of high-elevation stepped deltas with a relatively limited extent. Furthermore, the configuration of the site indicates that these deltas were fed by waters with an east-west component, suggesting a glaciofluvial origin (meltwater from the ice margin). Its deep inland location makes it difficult to argue for a marine origin as it would require an incursion occurring very far to the south and yet still being in contact with the ice margin at that time.

In contrast, site CAMB32, located to the north along the Châteauguay River, is a widespread delta displaying several scars from retrogressive landslides, indicating the presence of marine clay beneath, which is coherent considering its proximity with CAMB33 section where marine clays are present. Similarly, the presence of varved clays close to site CAMB25 reinforces our glaciolacustrine interpretation. Finally, while the origin of each site can not be exclusively assessed based on these criteria, it is noteworthy that site CAMB32 is slightly younger and further depressed on the paleo-DEM compared to site CAMB25, despite both being at the same elevation.

Our results thus indicate that Glacial Lake Cambrien developed south of the Chateauguay River around 7500 ± 200 years BP (highest glaciolacustrine strandline; ~190 m), while to the north, the incursion of the d'Iberville Sea was progressing. The marine incursion in this area began around 7200 ± 200 years BP (highest glaciomarine strandline; ~188 m). Given that the incursion of the post-glacial d'Iberville Sea into the study area implies the withdrawal (disappearance) of the ice mass that dammed the axis formed by the Caniapiscau River-Cambrien Lake, the ^{10}Be ages obtained for the onset of the marine incursion also provide a minimum age constraint for the drainage of Glacial Lake Cambrien. This chronological framework for the development of Glacial Lake Cambrien is also coherent with the regional deglaciation. Cosmogenic dating of Glacial Lake Naskaupi shorelines to the east positioned the ice front on the lower reach of the George River, to the west of the Torngat Mountains, at 8300 ± 300 years BP (Dubé-Loubert et al., 2018). Together, these results indicate that the ice retreated from the Torngat Mountain foothills to the Caniapiscau River valley area in about 800 to 900 years.

The gradual emergence of the landscape caused by postglacial uplift culminated with a withdrawal of marine water from the study area at around 4400 ± 200 years BP (lowest marine strandlines; ~95 m). To our knowledge and considering the ^{10}Be age of 6100 ± 200 years BP obtained for an intermediate elevation strandline (~125 m), this is the first time that such a sequence is successfully dated (with no occurrence of age overlap), thereby providing firm constraints on the isostatic response to ice retreat, which indicate a rapid uplift of approximately 30 cm per year.

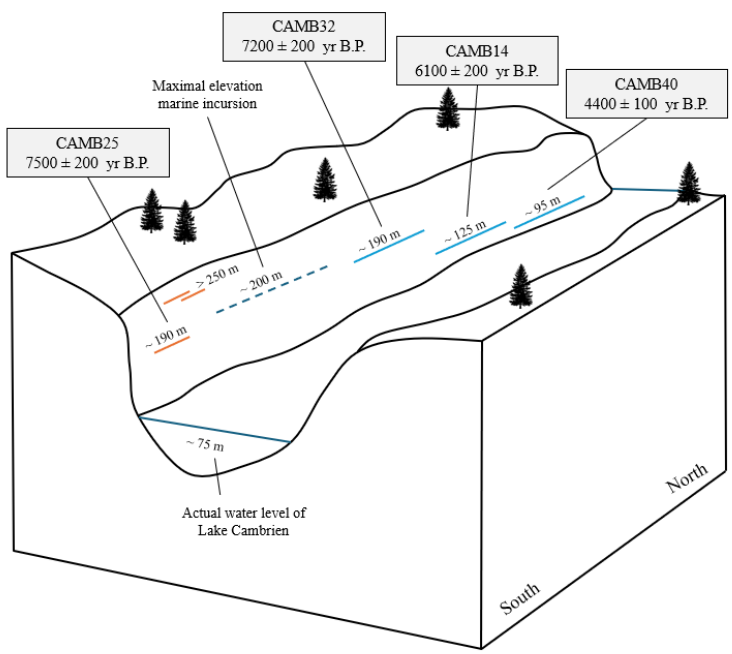

Figure 2.19 Schematic representations of the shorelines dated along with the mean ^{10}Be age for each site. Blue indicates glaciomarine origin and orange indicates glaciolacustrine origin.

Cosmogenic dating of raised marine shorelines in Ungava indicates that the d'Iberville Sea submerged the glacio-isostatically depressed coastal areas and large river estuaries of southern Ungava Bay at around 7900 ± 200 years to the west of the study area (Lefebvre-Fortier et al., 2024) and 8000 ± 400 years to the east (Dubé-Loubert et al., 2021). Our age of 7200 ± 200 years (production rate uncertainties now included) for the onset of the marine incursion in the study area is consistent with these results, although it may be considered slightly young at face value. This may be explained by the physiographic setting of the study area, which is located further inland (south), as well as the context of the regional deglaciation. Indeed, because of its southern geographic location, the ice front likely persisted later than in the other regions mentioned above. Accordingly, the early stages of the d'Iberville Sea were likely in contact with the ice margin, preventing glaciomarine invasion in the Lake Cambrien basin.

The new ^{10}Be ages thus provide key constraints on the development and drainage of glacial Lake Cambrien, making it possible to assess its potential contribution to meltwater discharges of the last deglaciation. Recent studies have shown that glacial Lake Naskaupi and other glacial lakes of the Ungava Peninsula (west of Ungava Bay) drained over the time interval encompassing the 8.2 ka cold event (Dubé-Loubert et al., 2018; Lefebvre-Fortier et al., 2024), suggesting that these meltwater discharges may have contributed to the main freshwater forcing originating from the drainage of the large glacial Lake Agassiz-Ojibway (Alley et al., 1997; Barber et al., 1999; Kleiven et al., 2008; Roy et al., 2011; Brouard et al., 2021). Given that climate models have shown that the proposed meltwater volumes for this drainage alone are insufficient to account for the magnitude and/or duration of this 160-year cooling event (LeGrande and Schmidt, 2008; Clarke et al., 2004; Morrill et al., 2014), this situation underlines the important role that the Ungava glacial lakes may have played, notably given their proximity to the site of deepwater convection in the Labrador Sea.

Although glacial Lake Cambrien was comparable with other Ungava glacial lakes, with an areal extent of 2462 km^2 and a volume of 105 km^3, its drainage at 7200 ± 200 years occurred too late to be involved in the freshwater forcing linked to the 8.2 ka climate perturbation. The available data indicate that Lake Cambrien was among the last major glacial lakes to form and drain from the Québec-Labrador Sector. Yet, relative sea-level records reveal a sharp rise of approximately 4,5 m around 7600 ± 400 cal yr BP (Yu et al., 2007), likely reflecting significant ice mass loss from continental ice sheets during the mid-Holocene thermal maximum. Notably, the final stages of the deglaciation of the Québec-Labrador Ice Dome of the Laurentide Ice Sheet occurred around the same period. This is further supported by a sudden depletion of surface-water $\delta^{18}O$ isotopes in the Labrador Sea (Hillaire-Marcel et al., 2001) and by ^{10}Be dates that revealed an abrupt retreat of ~600 km of the Québec-Labrador Sector between 7400- and 6800-years BP (Carlson et al., 2007). In this context, the geochronological data and meltwater volume estimate presented here argue for a contribution of the south-central Ungava lakes to this relative sea level rise.

2.6 Conclusion

Systematic mapping of deglaciation landforms (eskers, meltwater channels, minor moraines) in a large region south of Ungava Bay has yielded critical details on the regional pattern of ice retreat, thereby providing the parameters required to understand the development of an ice-dammed lake in the Koksoak-Caniapiscau River valleys. Reconstructions of the extent of glaciolacustrine and glaciomarine water bodies using an extensive record of raised shorelines indicates that the postglacial d'Iberville Sea and Glacial Lake Cambrien coexisted in these river valleys and associated watersheds for an interval of the last deglaciation. Reconstruction of the lake and marine water planes using the paleo-elevations of shorelines derived from a rebound surface of the late deglaciation (~7 ka BP) show that the marine limit was around 200 meters, thereby indicating that most shorelines in these valleys are of glaciomarine origin, consistent with their widespread occurrences and near-continuous vertical spread throughout the study area. In contrast, glaciolacustrine shorelines are limited in extent, in addition to showing geomorphological features suggesting a short lifespan for the glaciolacustrine episode. The presence (and extent) of a glacial lake in the Cambrian Lake basin is also supported by the occurrence of varved clays in the vicinity of the Chateauguay River located north of Cambrian Lake. GIS modeling considering the different datasets indicates that Glacial Lake Cambrian covered an area of 2462 km^2, for a total volume of 105 km^3.

The application of ^{10}Be SED to raised shorelines indicates that Glacial Lake Cambrien existed until about 7500 ± 200 years BP. Considering that the onset of the marine incursion in the region occurred at 7200 ± 200 years BP and that the penetration of the d'Iberville Sea in the study area requires the collapse of the ice mass that was damming the lake, this age may be used to estimate the drainage of the lake. Together with the remaining ^{10}Be ages from the lower shorelines of the sequence, the results document a younging trend with decreasing elevation, which also indicates a complete emergence of the land by 4400 ± 200 years BP. Considering that the early stages of that marine transgression occurred in contact with the ice front, the combined geochronological and mapping data constrain the timing and pattern of the landward retreat of the ice margin that allowed the development of Glacial Lake Cambrien and the subsequent delayed marine incursion.

Furthermore, the new data also challenges previous paleogeographic reconstructions depicting ice margin positions, indicating that the ice front was approximately 50 km farther north than previously suggested. Additionally, an ice margin position at 7000 years BP is inconsistent with the ^{10}Be SED ages presented that indicate that the valley was ice-free by at least 7200 years BP, thereby highlighting some inconsistencies in current models. New ice margin positions should thus be redrawn to refine deglaciation models for this part of the central Ungava-Labrador region.

Overall, our data indicate that Glacial Lake Cambrien was probably one of the latest significant glacial lakes to have formed and drained from the Québec-Labrador Sector of the LIS during the last deglaciation. These results suggest that while the drainage of Glacial Lake Cambrien did not contribute to the 8.2-ka cooling event, meltwater discharges from Ungava's glacial lakes likely influenced early Holocene climate variations. This study refines the paleogeographic deglaciation models for the southern Ungava Bay area, providing a clearer understanding of the timing, magnitude, and impacts of meltwater discharges during the last deglaciation and into the early Holocene.

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CONCLUSION

Les derniers stades de la déglaciation du nord du Québec ont été marqués par le développement et le drainage de plusieurs lacs d'obturation glaciaire et par l'invasion subséquente de la Mer d'Iberville sur le pourtour de la baie d'Ungava. Cette succession de plans d'eau a laissé en héritage des formes littorales perchées dans les vallées des principales rivières s'écoulant vers la baie d'Ungava. Dans la vallée de la rivière Caniapiscau, l'existence d'un lac glaciaire a longtemps été remise en question en raison de la complexité du patron de retrait glaciaire requis pour expliquer son développement. De ce fait, les rivages parsemant la vallée ont longtemps été attribués à l'incursion des eaux marines.

La formation des lacs glaciaires étant étroitement liée à la dynamique du retrait glaciaire, les nombreuses incertitudes entourant la position et la configuration de la marge glaciaire constituent un obstacle majeur à la reconstruction précise de ces bassins glaciolacustres (étendue, volume). Ces incertitudes découlent principalement du manque de données géomorphologiques de détails sur le retrait glaciaire, ainsi que l'absence généralisée de contraintes géochronologiques sur le retrait glaciaire – une situation qui s'applique particulièrement bien au cœur de l'Ungava.

Ce mémoire de maîtrise visait donc à évaluer les cadres paléogéographique et géochronologique existants de ce secteur pouvant permettre le développement d'un lac glaciaire et le cas échéant, sa relation avec l'incursion des eaux marines postglaciaires. La cartographie des eskers, moraines et chenaux à partir d'analyse d'images satellitaires haute résolution et d'observations de terrain a permis, dans un premier temps, de documenter le retrait de la marge glaciaire. Les résultats indiquent que le retrait glaciaire régional a été marqué par une scission de la marge glaciaire en deux entités distinctes qui auraient évolué de façon indépendante : l'une se retirant vers le sud en direction de Schefferville et l'autre vers le sud-ouest en direction de la basse péninsule d'Ungava. Le retrait plus tardif de l'entité ouest de la marge glaciaire aurait permis d'endiguer la rivière Caniapiscau et ainsi permettre l'accumulation des eaux de fonte.

Les mesures d'élévation des rivages recueillies *in-situ* (DGPS) et *ex-situ* (CDEM) témoignent d'un abaissement progressif des plans d'eau. L'utilisation des élévations des rivages tirées d'une paléo surface contemporaine à la déglaciation tardive (7 ka BP) a permis d'établir la limite marine maximale de la zone d'étude à environ 200 m et de distinguer l'origine des rivages. Ainsi, la majorité des rivages bien développés dans la vallée des rivières Koksoak et Caniapiscau se trouvent aux environs ou en-dessous de cette limite de 200 m, leur attribuant ainsi une origine glacio-marine. La présence de rivages élevés situés franchement au-dessus de la limite marine maximale, bien qu'ils soient peu nombreux, soutient l'existence d'un lac glaciaire dans la région. La découverte de varves à la base de la rivière de la Mort, un tributaire du Lac Cambrien, corrobore la présence de ce lac dans cette région. Ensemble, ces résultats confirment l'existence d'un lac glaciaire dans le bassin du Lac Cambrien – un élargissement de la rivière Caniapiscau à 180 km au sud de Kuujjuaq. Ce plan d'eau aurait coexisté pour un bref moment avec la Mer d'Iberville; les deux plans d'eau ayant été séparés un barrage de glace.

Une modélisation des volumes d'eau de fonte contenus dans le Lac glaciaire Cambrien a été réalisée à partir d'une approche géomatique (SIG) incorporant un contexte paléogéographique datant de l'intervalle 7 ka de la déglaciation (marge glaciaire et paléo-surface). Celle-ci démontre que le Lac glaciaire Cambrien s'est développé dans la partie méridionale du bassin actuel du Lac Cambrien et s'est étendu à l'est dans le bassin des lacs voisins, avec une étendue totale d'environ 2500 km^2 et un volume de 105 km^3.

L'application de la datation par isotopes cosmogéniques a fourni les premiers âges absolus sur la déglaciation du nord-central de l'Ungava. Les âges ^{10}Be indiquent que le Lac glaciaire Cambrien existait il y a environ 7500 ans BP, avant de se drainer suite au retrait du barrage de glace, laissant place à une invasion marine vers 7200 ans BP. Le retrait des eaux marines dans la vallée de rivière Caniapiscau s'est achevé vers 4400 ans BP. Cette étude est la première à dater l'émergence du territoire après l'incursion marine de la Mer d'Iberville, précisant ainsi le modèle de retrait glaciaire.

Les données géomorphologiques, stratigraphiques et géochronologiques indiquent que la position de la marge glaciaire des reconstructions paléogéographiques existantes devraient être modifiée afin de permettre de former un barrage de glace situé à environ 50 km au nord de la position actuellement suggérée, à la hauteur de la rivière Châteauguay. De plus, la position de la marge glaciaire à 7000 ans BP devrait plutôt être revue et assignée à un âge autour de 7500-7200 BP à la lumière des âges ^{10}Be obtenus dans cette étude. De tels travaux soulignent la nécessité d'accroître l’acquisition de données de terrain et de données géochronologiques afin de peaufiner les schémas de retrait glaciaire pour ce secteur de l’inlandsis.

Les données géochronologiques indiquent que le Lac glaciaire Cambrien était probablement l'un des derniers lacs glaciaires importants à s'être formé et à s'être drainé dans le secteur du Québec-Labrador. Malgré que le celui-ci soit trop jeune pour avoir contribué au refroidissement climatique de 8,2 ka BP, ces résultats et des études récentes suggèrent que collectivement, les lacs glaciaires de l'Ungava pourraient avoir eu un potentiel significatif dans les événements de forçage par les eaux de fonte de la dernière déglaciation, notamment en raison de leur proximité avec la mer du Labrador.

Finalement, des travaux archéologiques menés la région des Lacs Cambrien (*Mistisiipuw*) et Nachicapau (*Nachacapau*) ont révélé la présence de sites archéologiques d’importance sur les rivages marins présents dans le bassin du Lac Cambrien. Ces derniers témoignent d’une occupation pré-contact à historique du territoire par les ancêtres des Naskapis. Les artéfacts et vestiges d’habitations retrouvés indiquent que ces grandes formes littorales continues ont servi de campements ou encore de voies de déplacements. Les datations cosmogéniques présentées ici fournissent ainsi un âge maximal à l’établissement humain du nord-central de l’Ungava. Nous espérons que les résultats présentés dans ce mémoire contribueront à l’effort collectif entrepris dans le cadre de l’établissement d’un projet d’aire protégée des Lacs Cambrien et Nachicapau.

Ensemble, ces résultats renforcent le schéma et le timing du retrait glaciaire du sud de la baie d’Ungava pendant la dernière déglaciation, en fournissant un cadre géochronologique cohérent et robuste pour ce secteur. Ces nouvelles datations cosmogéniques affinent également les reconstructions paléogéographiques du secteur, en plus d’apporter des précisions sur le rôle et la magnitude des décharges d'eau de fonte de cette région durant la dernière déglaciation et le début de l'Holocène.

ANNEXE A

ÉLÉVATIONS CORRIGÉES DES FORMES MARINES MESURÉES AU GPS DIFFÉRENTIEL

Tableau A.1 Élévation des formes marines visitées sur le terrain

Site	Forme	Estant	Nordant	Élévation DGPS (m)	Élévation CDEM (m)	Déformation	Élévation Corrigée (m)
CAMB1	Terrasse	493991	6310590	115,70	105,84	189,92	-74,22
CAMB2	Terrasse	496057	6307456	130,30	116,25	190,09	-59,79
CAMB3	Terrasse	495703	6307799	109,80	98,26	190,10	-80,30
CAMB4	Rivage	496206	6305336	118,50	129,75	190,53	-72,03
CAMB5	Terrasse	495948	6305790	127,20	131,68	190,50	-63,30
CAMB6	Terrasse	495660	6305646	109,50	120,09	190,61	-81,11
CAMB7	Terrasse	492998	6294004	84,10	76,87	193,98	-109,88
CAMB8	Terrasse	495623	6302563	79,90	79,08	191,32	-111,42
CAMB9	Terrasse	499039	6300603	140,10	121,14	190,90	-50,80
CAMB10	Terrasse	499293	6300748	126,80	112,26	190,80	-64,00
CAMB11	Terrasse	499668	6300617	120,60	105,87	190,74	-70,14
CAMB12	Terrasse	499759	6300629	114,20	96,91	190,71	-76,51
CAMB13	Terrasse	494083	6306046	106,70	91,42	190,92	-84,22
CAMB14	Rivage	499687	6290183	125,60	111,74	193,16	-67,56
CAMB15	Terrasse	499349	6287348	106,00	90,66	193,91	-87,91
CAMB16	Terrasse	496956	6288068	130,10	112,63	194,35	-64,25
CAMB17	Terrasse	486298	6280719	133,60	111,00	198,67	-65,07
CAMB18	Terrasse	486124	6280563	120,30	92,95	198,75	-78,45
CAMB19	Terrasse	489747	6238441	88,70	98,62	206,42	-117,72
CAMB20	Rivage	495600	6251838	185,30	178,75	202,49	-17,19
CAMB21	Rivage	495550	6251884	178,90	173,64	202,49	-23,59
CAMB22	Rivage	495506	6251896	170,90	168,83	202,49	-31,59
CAMB23	Rivage	495567	6252549	188,80	189,68	202,35	-13,55
CAMB24	Rivage	494629	6252827	161,90	155,87	202,51	-40,61
CAMB25	Terrasse	488185	6242282	190,00	160,24	206,04	-16,04
CAMB26	Delta	488718	6242419	155,30	153,71	205,89	-50,59
CAMB27	Delta	488750	6242371	152,10	157,08	205,89	-53,79
CAMB28	Delta	489151	6242022	119,40	111,25	205,87	-86,47
CAMB29	Rivage	491139	6242449	189,80	193,00	205,34	-15,54
CAMB30	Rivage	491100	6242492	175,90	182,72	205,34	-29,44
CAMB31	Rivage	491039	6242494	169,00	177,07	205,35	-36,35
CAMB32	Delta	480217	6278069	182,10	166,98	200,78	-18,68
CAMB33	Terrasse	488833	6282023	88,20	88,21	197,75	-109,55
CAMB34	Delta	481206	6278072	168,40	147,20	200,53	-32,13
CAMB35	Delta	481053	6278135	172,40	152,27	200,55	-28,15
CAMB36	Rivage	489691	6269400	104,60	79,62	200,26	-95,66
CAMB37	Rivage	493409	6239389	184,80	196,94	205,41	-20,61
CAMB38	Rivage	493331	6239394	181,50	190,22	205,43	-23,93
CAMB39	Rivage	493280	6239333	172,40	174,78	205,46	-33,06
CAMB40	Terrasse	506594	6220018	99,60	87,03	206,17	-106,57
CAMB41	Terrasse	508241	6217835	127,10	109,41	206,22	-79,12

CAMB42	Rivage	506468	6228735	183,20	172,86	204,56	-21,36
CAMB43	Rivage	506434	6228724	179,00	167,27	204,57	-25,57
CAMB44	Terrasse	491615	6240265	135,20	131,61	205,65	-70,45

En raison du volume du tableau présentant toutes les élévations (1034) dérivées du CDEM, celui-ci est fourni sur demande à l'adresse : vallee.arianne@courrier.uqam.ca

ANNEXE B

INFORMATIONS RELATIVES AUX SITES ET ÉCHANTILLONS POUR LA DATATION AU ^{10}BE

Tableau B.1 Informations relatives aux sites d'échantillonnage

Sample ID	Latitude	Longitude	Élévation (m)
CAMB14-001	56.754836	-69.003664	121
CAMB14-002	56.754233	-69.004089	122
CAMB14-003	56.754233	-69.004089	127
CAMB14-005	56.753704	-69.004252	127
CAMB25-002	56.324951	-69.190141	188
CAMB25-003	56.325901	-69.19199	190
CAMB25-005	56.325091	-69.193069	192
CAMB32-001	56.646181	-69.322472	188
CAMB32-002	56.646558	-69.322328	187
CAMB32-003	56.646267	-69.320664	188
CAMB40-001	56.125145	-68.895168	93
CAMB40-002	56.125145	-68.895168	95
CAMB40-004	56.125081	-68.893222	99
CAMB40-005	56.125027	-68.893093	100

Tableau B.2 Données brutes associées aux datations par ^{10}Be

SAMPLE	(Corrected for boron)		Uncertainty	Sample wt		Carrier		Nb Be10 atoms	+/-	%	Blank atoms	Blk corrected atoms/g	+/- atoms/g
ID	10Be/9Be ratio	Error			wt. g.	conc ug/g	9Be ug						
CAMB14-001	4,539E-14	1,139E-15	2,51%	20,0987	0,1830	1044,6	191,2	579 875	14555	0,025	4 562	28 624	718
CAMB14-002	4,834E-14	1,185E-15	2,45%	20,7833	0,1816	1044,6	189,7	612 780	15018	0,025	4 562	29 265	717
CAMB14-003	5,640E-14	1,132E-15	2,01%	20,3190	0,1843	1044,6	192,5	725 557	14567	0,020	4 562	35 484	712
CAMB14-005	3,647E-14	9,952E-16	2,73%	17,4807	0,1824	1044,6	190,5	464 309	12671	0,027	9 803	26 000	710
CAMB25-002	6,261E-14	2,132E-15	3,41%	20,1629	0,1827	1044,6	190,8	798 526	27191	0,034	9 803	39 118	1332
CAMB25-003	6,302E-14	1,347E-15	2,14%	20,2507	0,1823	1044,6	190,4	801 990	17147	0,021	9 803	39 119	836
CAMB25-005	6,309E-14	1,409E-15	2,23%	20,0087	0,1830	1044,6	191,2	805 910	17996	0,022	9 803	39 788	888
CAMB32-001	5,865E-14	1,283E-15	2,19%	20,8212	0,1831	1044,6	191,3	749 609	16399	0,022	4 562	35 783	783
CAMB32-002	6,470E-14	1,551E-15	2,40%	20,4526	0,1830	1044,6	191,2	826 469	19816	0,024	4 562	40 186	964
CAMB32-003	5,681E-14	1,090E-15	1,92%	20,1954	0,1832	1044,6	191,4	726 464	13944	0,019	4 562	35 746	686
CAMB40-001	3,593E-14	1,376E-15	3,83%	20,2745	0,1820	1044,6	190,1	456 411	17477	0,038	9 803	22 028	844
CAMB40-002	1,156E-13	2,158E-15	1,87%	20,1431	0,1827	1044,6	190,8	1 474 765	27525	0,019	9 803	72 728	1357
CAMB40-004	3,190E-14	1,027E-15	3,22%	20,1711	0,1827	1044,6	190,8	406 889	13096	0,032	9 803	19 686	634
CAMB40-005	3,413E-14	1,115E-15	3,27%	20,6652	0,1824	1044,6	190,5	434 535	14195	0,033	9 803	20 553	671

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