UNIVERSITÉ DU QUÉBEC À RIMOUSKI

Évolution tardi-quaternaire et morpho-stratigraphie des sédiments du cratère des Pingualuit : variation du niveau du lac, origine des mouvements de masse et influence de la glaciation wisconsinienne

Mémoire présenté

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PAR

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Prenez le plus rêveur des rêveurs, plantez-le sur ses pattes, faites marcher ses pieds... il vous mènera sûrement à l'eau si l'eau existe dans ce pays.

Moby-Dick – Herman Melville

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Je souhaiterais en premier lieu remercier mon directeur, Guillaume St-Onge, pour la confiance qu'il m'a accordée en m'offrant ce projet de maîtrise. Je suis très reconnaissant pour sa grande disponibilité, son soutien, sa passion communicative et ses efforts pour offrir à ses étudiants un cadre de travail agréable. Je souhaiterais enfin le remercier pour les nombreuses opportunités de missions, de cours spéciaux et de congrès qui m'ont été offerts au cours de ces deux dernières années.

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Finalement, cette maîtrise représente deux ans et demi de conversations de lab, de pauses café, de soupers de colloques, de voyages, de soirées, de discussions plus ou moins

constructives, de découverte du Québec, de repas du midi à l'Auriculaire, d'apéro, de potluck, de fins de semaine en Gaspésie ... Alors comment ne pas avoir une pensée pour Gab, Flo, Audrey, Eliott, Paul, Évou, PJ, Mich-mich, Charles, Elissa, Kat, Aline, Éva, Lauris, Mathieu, Lotus, Fanny, Yves, Quentin, Val, Sylvain, David, Mélany ...

RÉSUMÉ

Le cratère des Pingualuit, situé dans la péninsule d'Ungava (Nunavik, Canada), est un cratère d'impact de 1.4 Ma renfermant un lac de 246 m de profondeur. Le lac est un système fermé, uniquement alimenté par les précipitations atmosphériques depuis la dernière déglaciation. La présence d'un lac sous-glaciaire dans le cratère lors du dernier maximum glaciaire exclut l'érosion par les glaces des sédiments de fond. Ces caractéristiques ont potentiellement permis au cratère des Pingualuit des enregistrements sédimentaires paléo-climatiques et paléo-écologiques des derniers cycles glaciaires/interglaciaires au niveau de la partie terrestre de l'Arctique canadien. Dans l'optique de définir la stratigraphie au fond du lac et de reconstruire l'histoire glaciaire tardi-quaternaire du cratère des Pingualuit, cette étude s'appuie sur des données provenant de trois expéditions conduites en mai 2007 (carotte sédimentaire d'une longueur d'environ 9 m), en août 2010 (~ 50 km de lignes sismiques) et en septembre 2012 (topographie à haute-résolution des parois internes à l'aide d'un LiDAR terrestre). Malgré la faible pénétration (~10 m) du profileur de sous-surface de 3.5 kHz causée par la présence de blocs dans la colonne sédimentaire, les données sismiques couplées à la stratigraphie de la carotte permettent l'identification de deux unités glacio-lacustres déposées lors des dernières étapes du retrait de l'Inlandsis laurentidien au cratère. Deux dépôts postglaciaires associés à des mouvements de masse ont également été identifiés sur les pentes et dans la partie profonde du bassin du cratère. La topographie à haute-résolution des pentes internes du cratère générée à partir des données LiDAR a permis de mettre en évidence un ancien niveau de lac à 545 m et de déterminer les altitudes des exutoires à l'origine de drainage. De plus, la cartographie des formes glaciaires à partir de l'interprétation de photos aériennes a rendu possible le paramétrage d'un nouveau modèle présentant la déglaciation et le drainage du lac du cratère des Pingualuit. Le modèle suggère trois phases principales de drainage en fonction de l'activation de sept exutoires suite au retrait vers le sud-ouest de l'Inlandsis laurentidien. Finalement, par opposition à d'autres lacs de cratère de haute latitude à l'image du lac El'gygytgyn (nord-est de la Sibérie) et de Laguna Potrok (secteur méridional de la Patagonie) dans lesquels des enregistrements paléo-climatiques à haute résolution ont été reconstitués grâce à un taux d'accumulation sédimentaire élevé, les données sismiques du lac du cratère des Pingualuit suggèrent un taux de sédimentation très faible suite au retrait de l'Inlandsis laurentidien en raison de l'absence d'affluents dans le lac.

Mots clés : Lac de cratère; Déglaciation; LiDAR terrestre; Modelés glaciaires; Variations du niveau de lac; Paléo-rivages; Profiles de sismique réflexion; Ungava

ABSTRACT

The Pingualuit Crater, located in the Ungava Peninsula (Northern Québec, Canada) is a 1.4 Myr old impact crater hosting a 246 m deep lake. The lake is a closed system, fed only by atmospheric precipitation since the last deglaciation. The existence of a subglacial lake in the crater during the Last Glacial Maximum (LGM) precluded glacial erosion of the bottom sediments. These characteristics have potentially allowed the Pingualuit Crater Lake to preserve paleoclimatic and paleoecological sedimentary records of the last glacial/interglacial cycles in the terrestrial Canadian Arctic. In order to define the stratigraphy in the lake and to reconstruct the Late-Quaternary glacial history of the Pingualuit Crater, this study investigates data from three expeditions carried out in May 2007 (~9 m long sediment core), in August 2010 (~ 50 km of seismic lines) and in September 2012 (high-resolution terrestrial LiDAR topography of the inner slopes). Despite the weak penetration (~10 m) of the 3.5 kHz sub-bottom profiling caused by the presence of blocks in the sedimentary column, seismic data coupled with stratigraphy from the sediment core enabled the identification of two glacio-lacustrine units deposited during the final stages of Laurentide Ice Sheet (LIS) retreat in the crater. Two postglacial mass movement deposits were also identified on the slopes and in the deep basin of the crater. The high-resolution topography of the internal slopes of the crater generated from the LiDAR data permitted the confirmation of a paleo-lake level at 545 m and determination of the altitudes of drainage outlets. Furthermore, the mapping of glacial and deglacial landforms from air photo interpretation of the area allowed the setting of a new model for the deglaciation and drainage of the Pingualuit Crater Lake. The model proposes three main phases of lake drainage, based on the activation of seven outlets following the retreat of the LIS front towards the south-west. Finally, as opposed to other high-latitude crater lakes such as Lake El'gygytgyn (northeastern Siberia) or Laguna Potrok (southern Patagonia) where high-resolution paleoclimatic records were reconstructed due to high sediment accumulation rates, the seismic data from the Pingualuit Crater Lake suggest very low sedimentation rates after the retreat of the LIS owing to the absence of tributaries in the lake.

Keywords : Crater Lake; Deglaciation; Terrestrial LiDAR; Glacial Landforms; lake-level variations; Paleo-shorlines; Seismic reflection profiles; Ungava

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INTRODUCTION GÉNÉRALE

Problématique

L'Arctique est actuellement le théâtre de bouleversements climatiques majeurs dont l'échelle et les conséquences avérées sur le système climatique global sont encore peu connues (e.g., ACIA, 2005; Otto-Bliesner et al., 2006; Overpeck et al., 2006). La compréhension des changements climatiques en Arctique nécessite de connaitre les variations des conditions environnementales dans cette région au cours du temps. Dans cette optique, les enregistrements sédimentaires des lacs de haute latitude représentent des archives exceptionnelles pour retracer ces variations de conditions environnementales en raison des indicateurs physiques, chimiques et biologiques qu'ils renferment (Pienitz et al., 2004). Cependant, de nombreux lacs de l'hémisphère Nord, notamment en Arctique, se révèlent inexploitables pour les reconstructions paléo-climatique. En effet, une grande partie de ces lacs sont trop jeunes, leur mise en place lors du retrait des glaciers remontant seulement à l'Holocène. De plus, les sédiments de lacs plus anciens ont été érodés et remobilisés par le passage des glaces lors des dernières glaciations (Pienitz et al., 2008). Ainsi malgré leurs qualités singulières, les études basées sur des enregistrements sédimentaires continentaux lacustres ne représentent qu'une faible proportion de la recherche paléo-climatique et paléo-environnementale en comparaison aux nombreux travaux effectués sur des carottes prélevées dans le milieu marin (e.g. Helmke et al., 2002; Spielhagen et al., 2004; de Vernal et Hillaire-Marcel, 2008).

Durant le dernier maximum glaciaire, le lac du cratère des Pingualuit, Nunavik (Figure 1 et 2), formé par un impact météoritique il y a environ 1,4 millions d'années, était également recouvert par un glacier atteignant près de deux kilomètres d'épaisseur dans ce secteur, l'Inlandsis laurentidien (Grieve et al., 1991; Dyke et al., 2002; Marshall et al., 2002). Cependant, la morphologie du cratère, ses parois abruptes, sa grande profondeur (246 m), et sa localisation proche du centre de dispersion du glacier, limitant ainsi le déplacement des glaces, auraient permis la formation d'un lac sous glaciaire dans le cratère lors de la dernière glaciation. Les sédiments présents au fond du lac auraient ainsi été préservés de l'action érosive des glaces (Bouchard, 1989b; Guyard et al., 2011). Ces caractéristiques confèrent au lac du cratère des Pingualuit un grand potentiel pour l'enregistrement et l'étude de la dynamique climatique, notamment les dernières successions de périodes glaciaires/interglaciaire dans la péninsule d'Ungava depuis 1,4 millions d'années (Bouchard, 1989b). Ainsi, au cours des dernières années, une carotte d'environ 9 m a été prélevée et plusieurs recherches ont été conduites dans le cadre du projet international dirigé par le professeur Reinhard Pienitz (U. Laval) et intitulé " *The Pingualuit Crater Lake Project* " afin de déterminer les variations paléoclimatiques au Nunavik à partir des sédiments du cratère des Pingualuit (Black et al., 2010; Girard-Cloutier, 2011; Guyard et al., 2011; Luoto et al., 2013).

Figure 1. Photographie du cratère des Pingualuit prise lors de la mission en septembre 2012; crédit photo : Pierre-Arnaud Desiage.

Figure 2. Localisation du cratère des Pingualuit (Adapté de nunavik-tourism.com).

Objectifs généraux

Dans ce contexte, le premier objectif de cette maîtrise était d'améliorer les connaissances concernant la géomorphologie et l'histoire tardi-quaternaire de la région du cratère des Pingualuit afin de fournir un contexte géologique et climatique aux archives paléo-climatiques prélevées dans le lac. Dans le secteur du cratère, le dernier évènement glaciaire a été documenté et décrit à l'aide de l'identification et de la cartographie des structures et des formes glaciaires engendrées par l'avancée et le retrait de l'Inlandsis laurentidien. Les phases de déglaciation successives du cratère et les brusques évènements de vidange des eaux du lac qui leurs sont associées, suggérées dans un premier temps par Bouchard et Saarnisto (1989), ont été discutées et actualisées. Ainsi, un nouveau modèle de déglaciation du cratère a été élaboré à l'aide des nouvelles connaissances provenant de la première carte géomorphologique centrée sur ce secteur et de la topographie LiDAR (*Light Detection And Ranging*) à haute résolution des pentes internes du cratère des Pingualuit. Le second objectif de ce projet était de présenter pour la première fois une étude détaillée de la stratigraphie par sismique réflexion sur l'ensemble du lac du cratère. L'identification et la caractérisation des faciès sismiques nous permettant d'affiner la compréhension de la sédimentation et la distribution des mouvements de masse au fond du lac du cratère des Pingualuit.

Expéditions et méthodologie

La base de réflexion de ce projet de maîtrise s'appuie principalement sur une dizaine d'articles compilés dans le livre " *L'histoire naturelle du Cratère du Nouveau Québec* " publié en 1989. Les études présentées dans cet ouvrage ont été menées consécutivement à une expédition scientifique conduite par Michel A. Bouchard (Université de Montréal) au cours de l'été 1988. Le but de cette mission pluridisciplinaire était d'étudier divers aspects du cratère, tel que sa genèse et son histoire, sa morphologie, la stratigraphie des sédiments du lac ou la faune et la flore qu'il héberge (Bouchard, 1989c). L'étude présentée dans ce mémoire de maîtrise est fondée sur des données provenant de trois expéditions scientifiques effectuées au cratère des Pingualuit lors des sept dernières années. En mai 2007, une équipe internationale a récupéré la carotte sédimentaire d'environ 9 m à l'aide d'un carottier à gravité UWITEC installé sur le lac gelé (Figure 3A). La seconde mission, conduite en août 2010 par une équipe de l'Université Laval et de l'ISMER-UQAR, a permis l'acquisition d'une cinquantaine de kilomètres de profils sismiques à partir du profileur de sous-surface Knudsen Chirp 3212 d' une fréquence de 3.5

kHz (Figure 3B). L'analyse et l'interprétation détaillée de ces données sismiques ont été réalisées pour la première fois au cours de ce projet de maîtrise. Ces résultats ont également été couplés à l'étude stratigraphique (Guyard et al., 2011) de la carotte prélevée en 2007 afin d'extrapoler cette stratigraphie aux unités sismiques identifiées dans les sédiments du lac. Finalement, une dernière expédition a été effectuée dans le cadre de cette maîtrise sur le cratère en septembre 2012 afin de réaliser des levés des pentes internes à l'aide d'un système de télédétection par laser (LIDAR) (Figure 3C). Durant cette expédition dirigée par Guillaume St-Onge (ISMER-UQAR), 35 levés ont été enregistrés à partir de 19 sites sur l'ensemble de la couronne du cratère permettant de modéliser et générer en 3D la totalité des parois internes du cratère des Pingualuit.

Par ailleurs, le parc national des Pingualuit (Figure 2) a vu le jour en janvier 2004 dans l'optique de protéger et mettre en valeur le cratère et plus de 11 000 km² du Plateau de l'Ungava. Le lac Pingualuk, considéré comme le joyau du parc, bénéficie d'une protection extrême interdisant l'accès à ce secteur à l'exception d'équipes éducatives et scientifiques soumises à des réglementations techniques et environnementales strictes. Dans ces conditions, les trois dernières expéditions menées au cratère ont été réalisées avec des précautions environnementales accrues, incluant notamment l'utilisation de moteurs électriques dans l'enceinte du cratère et le maintien des moteurs thermiques sur des plate-formes adaptées à l'extérieur de la couronne. L'organisation et la réalisation de ces expéditions ont également été effectuées en collaboration et avec le soutien remarquable des responsables du parc des Pingualuit, des guides du Parc et de la communauté inuit de Kangiqsujuaq.

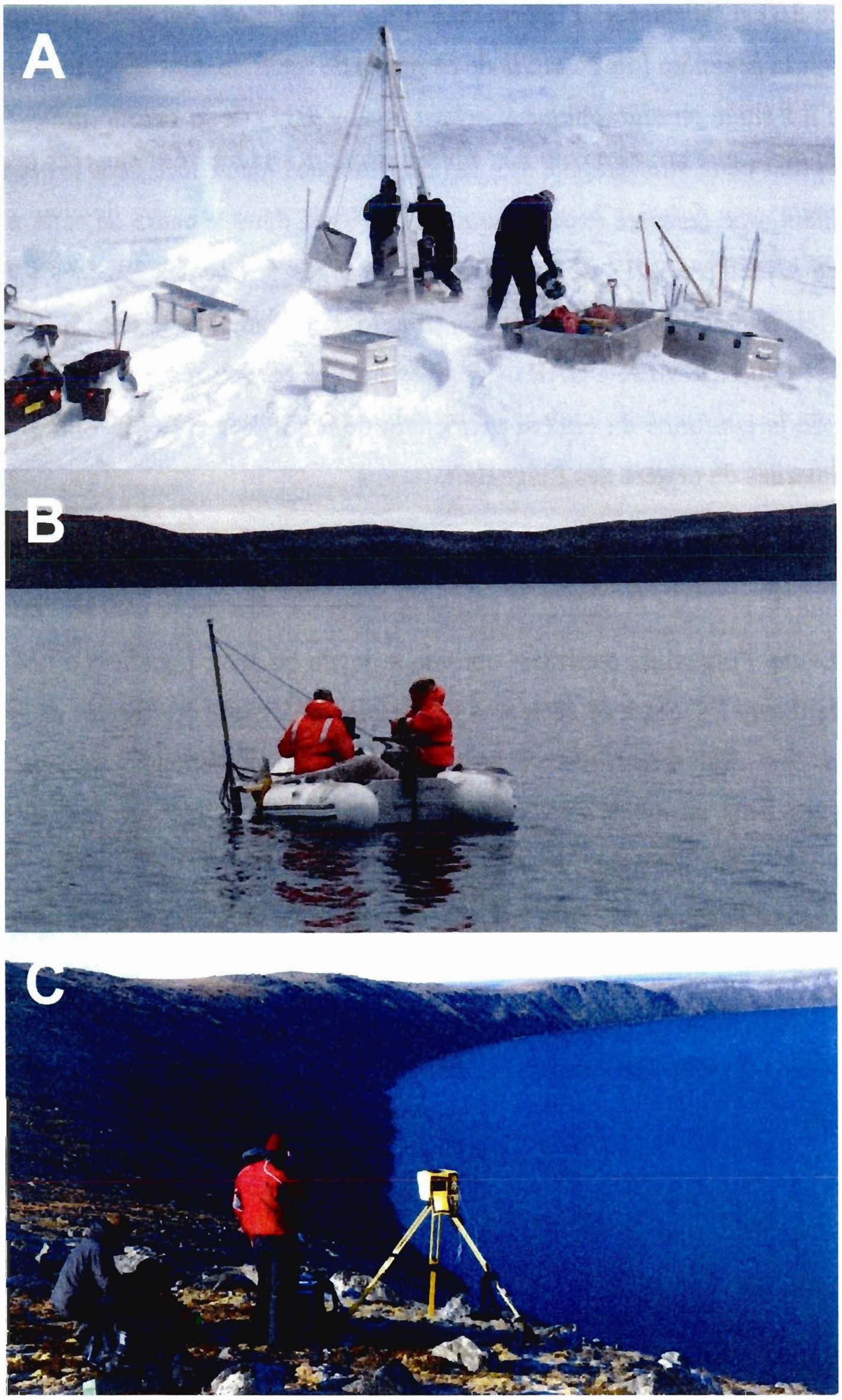

Figure 3. Photographies des trois expéditions conduites au cratère en 2007 (A), 2010 (B) et 2012 (C); crédit photo : Richard Niederreiter, Grégoire Ledoux et Pierre-Arnaud Desiage.

Organisation du mémoire et contribution

Ce mémoire est présenté sous la forme d'un article scientifique rédigé en anglais présentant la morphologie du cratère des Pingualuit et une reconstitution de son histoire glaciaire depuis la dernière glaciation. L'article devrait être soumis prochainement à la revue *Geomorphology* ou *Earth Surface Processes and Landforms.*

Desiage, P-A., Lajeunesse, P., St-Onge, G., Normandeau, A., Ledoux, G., Guyard, H., Pienitz, R., (sera soumis prochainement). Morphology and Late-Quaternary evolution of the Pingualuit Crater Lake basin, northern Québec (Canada). *Geomorphology* ou *Earth Surface Processes and Landforms.*

La réalisation de ce projet de recherche m'a conduit à participer à la troisième expédition au cratère des Pingualuit. Durant les 15 jours sur le terrain, mon rôle, en collaboration avec les autres participants de la mission et co-auteurs de l'article, Guillaume St-Onge et Alexandre Normandeau, consistait à sélectionner les sites de levés, manipuler le LiDAR et vérifier la qualité et le bon recouvrement des données. J'ai réalisé la numérisation et l'interprétation des photographies aériennes principalement à l'Université Laval en collaboration avec Patrick Lajeunnesse et le Laboratoire de Géomorphologie marine. Le traitement des données géophysiques et l'analyse de la stratigraphie ont été effectués à ISMER-UQAR à partir des travaux préliminaires de Grégoire Ledoux et d'Hervé Guyard. J'ai également généré et interprété la topographie à haute résolution des parois internes du cratère à partir des données LiDAR avec le soutien d'Alexandre Normandeau, Guillaume St-Onge et Patrick Lajeunesse. La rédaction et la majorité des figures de l'article ont été réalisées par mes soins et révisées par mes deux co-directeurs et co-auteurs de cet article Patrick Lajeunesse et Guillaume St-Onge.

Présentations lors de congrès

De plus, dans le cadre de ce projet de maîtrise, j'ai eu la chance de participer aux congrès/colloques ci-dessous.

Desiage, P-A., St-Onge, G., Lajeunesse, P., 2013. Morphostratigraphic study of Pingualuit crater lake: Lake level variations and mass movements influence. Présentation orale lors du congrès annuel des étudiants du GEOTOP, 1-3 février 2013, Wentworth-Nord (QC) Canada.

Desiage, P-A., St-Onge, G., Lajeunesse, P., Normandeau, A., 2013. Morphostratigraphic study of Pingualuit crater lake, Nunavik: Initial LiDAR results. Poster lors du *43rd Annual International Arctic Workshop*, 11-13 mars 2013, Amherst (MA) USA.

Desiage, P-A., St-Onge, G., Lajeunesse, P., Normandeau, A., Pienitz, R., Guyard, H., 2013. Le cratère des Pingualuit: comprendre son histoire géologique pour retracer le climat quaternaire arctique. Présentation orale lors du colloque de vulgarisation scientifique *La nature dans tous ses états*, 21-23 mars 2013, Rimouski (QC) Canada.

CHAPITRE 1
MORPHOLOGY AND LATE-QUATERNARY EVOLUTION OF THE PINGUALUIT CRATER LAKE BASIN, NORTHERN QUÉBEC (CANADA)

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1. Introduction

In recent years, the Pingualuit Crater Lake, Nunavik (Fig.4), has sparked a renewed interest in palaeoclimatology research in the Ungava Peninsula (Black et al., 2010; Girard-Cloutier, 2011; Guyard et al., 2011; Luoto et al., 2013). High-latitude lakes are excellent archives of past climatic and environmental variations due to the sediments they can preserve (Pienitz et al., 2004). Despite the presence of the Laurentide Ice Sheet during the Last Glacial Maximum (~21,000 years ago; Clark et al., 2009), the morphology of the crater favored the existence of a subglacial lake in the Pingualuit Crater, precluding glacial erosion of the bottom sediments (Bouchard, 1989b; Guyard et al., 2011). These characteristics give the Pingualuit Crater Lake sediments the potential to record successions of glacial/interglacial periods in the Ungava Peninsula since 1.4 Ma (Bouchard, 1989b). Furthermore, the Pingualuit Crater Lake has similar characteristics to lakes recently studied in the context of International Continental scientific Drilling Program (ICDP) projects for their potential in paleoclimatic research, such as the El'gygytgyn Crater Lake in 2008/09 and Laguna Potrok Aike in 2008 (Melles et al., 2012; Zolitschka et al., 2013 and papers in the special issue). El'gygytgyn Crater Lake, also located in the Artic (67.5°N, 172°E) and formed by a meteoritic impact, escaped Northern Hemisphere glaciation due to its location in the center of Beringia (Brigham-Grette et al., 2007). Laguna Potrok Aike, located in south-eastern Patagonia (Argentina), and the Pingualuit Crater Lake have a similar morphology with a high depth-to-area ratio, allowing the potential accumulation of long sedimentary record (Bouchard 1989a; Anselmetti et al., 2009).

This study aims to reconstruct the Late-Quaternary glacial and deglacial history of the Pingualuit Crater Lake basin based on recently acquired seismic and LiDAR data. This new information will contextualize the paleoclimatic archives recovered in the lake (Guyard et al., 2011) and allow reconstructing successive stages of crater deglaciation and the resulting rapid drainage events of the lake, first suggested by Bouchard and Saarnisto (1989).

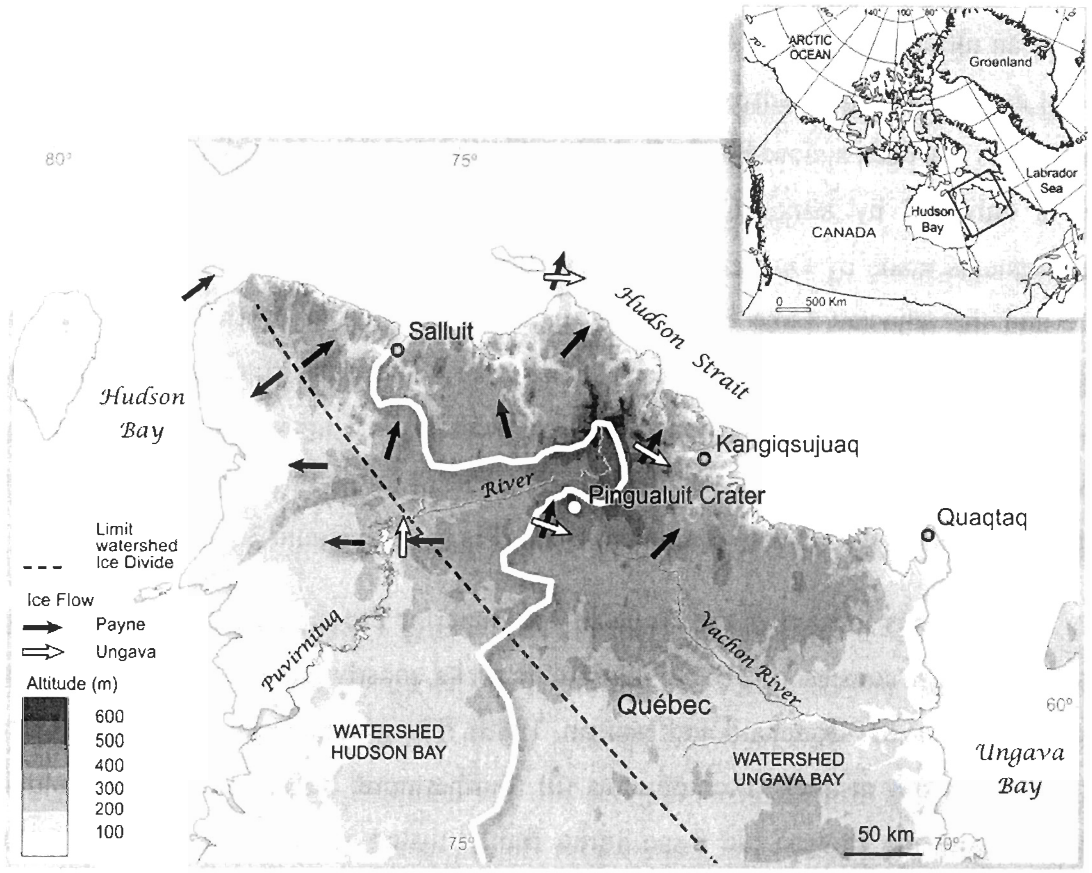

Figure 4. Location of the Pingualuit Crater Lake in the Ungava Peninsula. Black and white arrows show the main ice flow directions (Payne and Ungava) determined from accumulation and erosional features (Bouchard and Marcotte, 1986; Daigneault and Bouchard, 2004). The dashed line illustrates the ice divide (Daigneault and Bouchard, 2004) and the white line marks the limit between the Ungava Peninsula and Hudson Bay watersheds. Realisation: Département de Géographie, Université Laval, 2013.

2. Study area

The Pingualuit Crater, located in the Ungava Peninsula (Nunavik, Canada; Fig.4) is a simple crater created by a meteoritic impact ca. 1.4 million years ago as determined by Ar-dating of impactites collected nearby (Bouchard and Marsan, 1989; Grieve et al. 1991). The crater is a 410 m deep (rim-to-basin) and 3.4 km wide (rim-to-basin) near circular depression whose rim reaches a maximum altitude of 657 m above sea level (a.s.l), which is one of the highest peak in Ungava. This summit rises to 163 m above the surface (494 m a.s.l) of an ultraoligotrophic 246 m deep and 2.8 km wide lake hosted by the crater. Since the last deglaciation this transparent water lake (33 m Secchi depth in August 2010; Guyard et al., 2011) has been a closed hydrological and sedimentary basin with no tributaries as the lake is only fed by atmospheric precipitation (Guyard et al., 2011). However, $\delta^{18}O$ measurements made by Ouellet et al. (1989) from water from (into) the Pingualuit Crater Lake and the adjacent Lake Laflamme suggest a potential cryptorheic drainage system across a fault plan linking both lakes (Currie, 1965). The water flowing of the Pingualuit crater area are drained by the Vachon River across the Ungava Bay catchment basin. However, the northernmost part of this area is adjacent to the Puvirnituq River, one of the main rivers of the Hudson Bay catchment basin (Fig.4; Daigneault, 2008).

The crater is located in the Archean-age Superior Province of the Canadian Shield. Bedrock geology consists of a blend of plutonic rocks, mostly granitoids, cut by some basic dykes (Currie, 1965; Bouchard and Marsan, 1989). The ground surface consists of blocks, gravels and a 0-2 m-thick discontinuous till. Furthermore, dozens of erratic boulders of dolomite from the Proterozoic Cape-Smith Belt, situated about 40 km north, have been counted in the crater area (Bouchard et al., 1989). The rim and steep inner slopes (26-35°) are also strewn with boulders and rocks strongly mineralized with epidote and hematite, and altered with sericite (Currie, 1965). These slopes terminate on an asymmetric basin constituted by a plateau in the south-west part of the lake and a deep basin in the north-east part of the lake (Bouchard and Marsan, 1989). Bouchard (1989a) accounts for this morphology by intense sediment inputs from the south-west during the last deglaciation. Interpretation of seismic data, acquired during a 1988 expedition, by Moussawi and Tessier (1989), suggests thick deposits of till and/or gravels intersected by fine clay layers (thickness between 1 and 2 m). The chaotic seismic signal furthermore reveals the presence of blocks throughout the sediments with the exception of the upper 25 m of the deep basin, where sediments are finer. Reflectors indicate a potential accumulation of at least 73 m of sediments on the plateau and 93 m in the deep basin (Moussawi and Tessier, 1989; Bouchard, 1989a). Bouchard (1989a) explained the presence of thick and coarse till deposits in the crater by a rain-out and reworking of sediments from melting ice and/or by dense flows originating from glacial retreat. The stratigraphy of a ~ 9 m-long core retrieved in 2007 from the deep basin reveals subglacial, and proglacial lacustrine depositional conditions during the last deglaciation and organic-rich intervals corresponding to ice-free conditions during postglacial times (Guyard et al., 2011). This stratigraphy will be integrated with the discussion of seismic surveys hereinafter.

Regional glacial/deglacial history

During the last glaciation, northern Ungava remained glaciated from the end of the Sangamonian (marine isotopic substage 5e; ~123,000 years ago; Lisiecki and Raymo, 2005) to the Holocene deglaciation (Daigneault, 2008). In the Pingualuit Crater Lake basin, two distinct glacial movements have characterized the last glaciation: the Ungava and Payne flows (Gray and Lauriol, 1985; Bouchard and Marcotte, 1986). The first one originated from the Ungava center in the central part of the Ungava Peninsula and was oriented south-east (azimuth 110°) in the study area, whereas the second originating from the Payne center was oriented north-east (azimuth 45°) (Fig.4; Currie, 1965; Bouchard et al., 1989a; Daigneault and Bouchard, 2004). During this second glacial movement, the Payne flow covered the main part of the Ungava peninsula. This relative chronology is supported in the crater area, by the greatest abundance of geomorphological features being associated with the Payne flow (Bouchard et al., 1989a; Daigneault and Bouchard, 2004).

Deglaciation of the Ungava peninsula began on the southern coast of the Hudson Strait between 10.5 kyr BP and 7 kyr BP, and progressed toward the Ungava plateau (Gray and Lauriol, 1985; Dyke and Prest, 1987; Lauriol and Gray, 1987; Bruneau and Gray, 1997; Gray, 2001; Daigneault and Bouchard, 2004; Saulnier-Talbot and Pienitz, 2010). In the Pingualuit Crater, a sediment sequence from a 14 cm-long grab sample gathered in August 1986 presents the postglacial environment of the area (Richard et al., 1989). Characteristics at the base of the sample, dated at 5780 ± 135 cal BP (5030 ± 70 yr BP), indicate ice-free lake conditions at this time (Bouchard et al., 1989b; Richard et al., 1989; Grönlund et al., 1990; Guyard et al., 2011). Furthermore, AMS ^{14}C dating and multiproxy paleoenvironmental reconstruction performed by Guyard et al. (2011) on the ~9 m sediment core collected in the deep basin in 2007 suggests the retreat of the Laurentide Ice Sheet (LIS) from the crater area around 6844 ± 100 cal BP.

The Pingualuit Crater Lake has sustained several rapid drainage events during the last deglaciation as revealed by the three paleo-shorelines on the internal slopes of the crater and the outwash channels on the external slopes and on the neighbouring grounds of the crater (Bouchard et Saarnisto, 1989). According to Bouchard and Saarnisto (1989), the drainages have occurred through ten crater rim channels (outlets) in the crater rim during four main phases of glacial retreat in the area (Fig. 5). During the first phase, the U-shaped and highest channels 6 and 7 (respectively 608 m and 596 m a.s.l.) were cleared of ice and drained small volumes of the lake waters. As the glacial retreat progressed to phase 2, the opening of outlets 5 and 8 reduced the lake level by about 20 m (Fig. 5). Outflows through channels 5 and 8 were torrential, with a strong erosive power causing the development of outflow systems at the base of the crater. The highest paleo-shoreline (574 ± 5m) observed by Bouchard and Saarnisto (1989) on the northern half of the crater was formed during this second phase. The glacial retreat to phase 3 caused the draining of outlets 5 and 8 and the freeing of the western channels 4 and 3 and eastern channels 9 and 10 (Fig. 5). However, channels 9 and 10 do not appear to have been affected by drainage events owing to their high altitudes (601 ± 5m) precluding contact with lake-waters (between 574 and 544 ± 5 m a.s.l. during phase 3). Bouchard and Saarnisto (1989) have explained the existence of outflow system indicator at the base of the crater near outlet 10 by a sub- and pro- glacial drainage system independent of the crater lake during the glacial retreat. During the phase 4, the lake was totally ice-free but the southern channels 2 and 1 were not affected by drainage, their altitudes being higher than that of channel 3. Torrential outflows through channel 3 persisted during and after phase 4, allowing a connection with Lake Laflamme. Finally, the link was interrupted when the lake level lowered beneath that of the second paleo-shoreline (544 ± 5 m a.s.l.), abandoning the lowermost outlet (channel 3 at 553 ± 5 m a.s.l.). This paleo-shoreline is the most pronounced with a level of washed boulders visible all around the crater. The third paleo-shoreline (around 509-514 m a.s.l.) is poorly developed and barely observable in some parts of the internal slopes (Bouchard and Saarnisto, 1989).

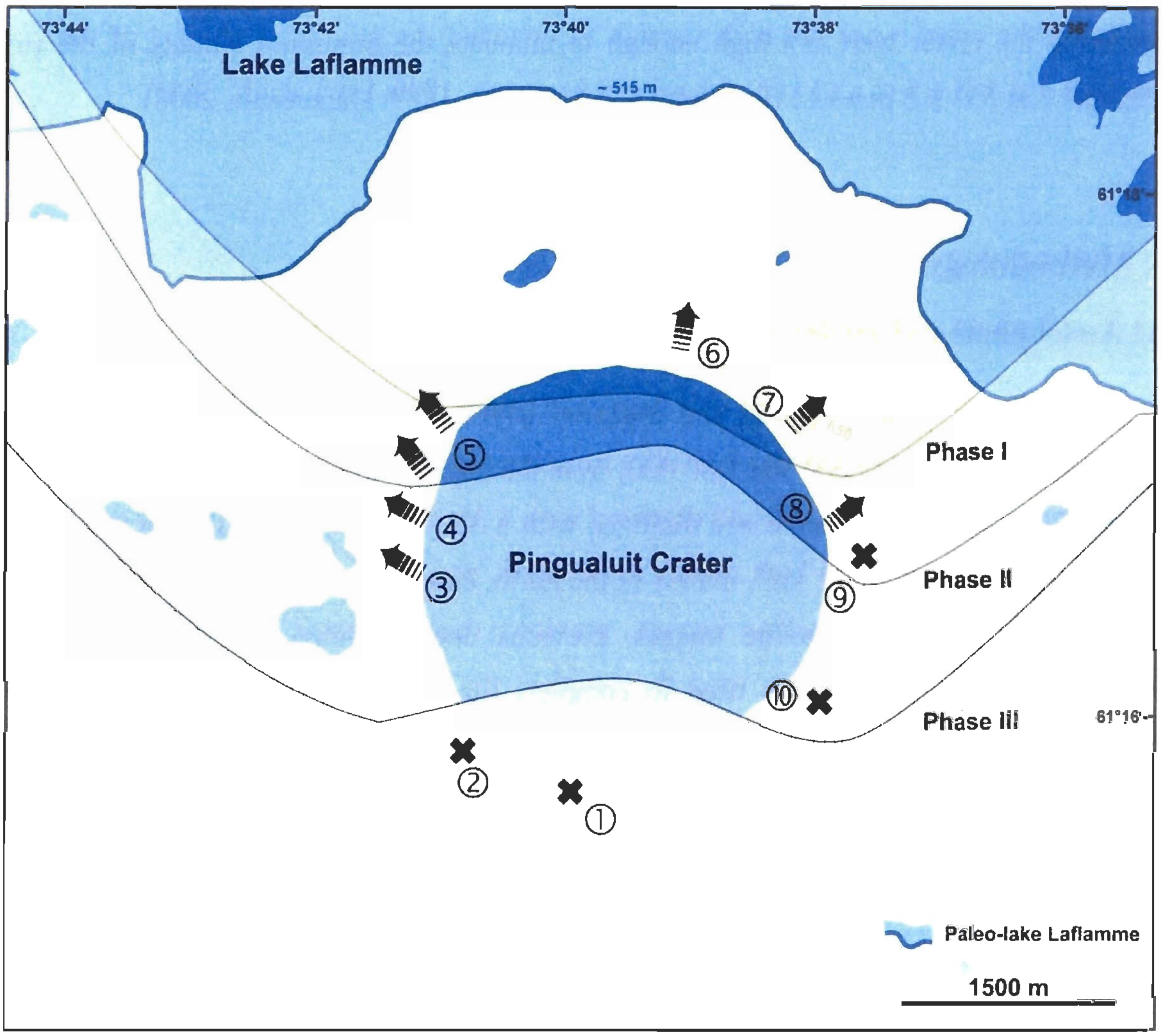

Figure 5. Conceptual model for deglaciation of the Pingualuit Crater Lake suggested by Bouchard and Saarnisto (1989). Black arrows show the crater rim channels hosting outflows, whereas black crosses illustrate channels not affected by drainage. The numbers indicate the ten channels in the crater rim according to Bouchard and Saarnisto (1989). Also illustrated is the proglacial Lake Laflamme at its maximal level (~ 515 m a.s.l.) (Bouchard and Saarnisto, 1989).

During deglaciation, part of the territory around the crater was covered by proglacial lakes adjoining the ice front (Daigneault, 2008). These were located especially upstream of the Vachon and Puvirnituq Rivers (Prest, 1972; Daigneault, 1993; Daigneault, 2008). Nevertheless, none of these lakes appear to have reached a sufficient altitude to allow an overflow in the Pingualuit Crater Lake. Indeed, the maximal levels of proglacial lakes Saint-Germain and Laflamme (respectively around 520 m and 515 m a.s.l.) (Fig. 5) bordering the crater were not high enough to inundate the minimum altitude of the rim (channel 3 at 553 ± 5 m a.s.l.) (Bouchard and Saarnisto, 1989; Daigneault, 2008).

3. Methodology

3.1 Aerial-photo and satellite imagery mapping of landforms

In order to identify glacial and deglacial landforms, three series of medium scale aerial photographs (1:20 000 and 1:30 000) from the *GéoStat* Center (Université Laval) and *Géomathèque* ®, were selected and digitized with a 350 dpi resolution. The 26 air photos used cover an area of ~ 455 km², mainly in the north, east and west parts of the crater area. Analysis of Landsat 7 satellite images, previous documentation and 2012 fieldwork observations (see below) were used to complete the aerial photography interpretation. Landsat images (spectral band 1 and composite 7-4-3) from the *GeoBase* database (http://www.geobase.ca; Natural Resources Canada) round out the study of uncovered area with air photos but allow the mapping of large-scale landforms only (Lajeunesse, 2008). All the landforms related to glacial and deglacial processes were identified on a map of a DEM of the Pingualuit crater area generated from elevation data of the *GeoBase* database.

3.2 Terrestrial LiDAR mapping

In September 2012, a survey was conducted to record the high-resolution topography of the internal slopes of the crater using a terrestrial LiDAR. A total of 35 surveys were completed with the *ILRIS-3D* laser scanning system from *Optech Inc*. These scans were recorded from 19 different sites around the crater ring on the top of the internal slopes; the coordinates of each site were measured by GPS (Fig. 6). Spacing among sites is at most 600 m to maximize overlap between scans for the merge step. The scanning range of a survey covers up to 1500 m of the slope in the highest reflectivity conditions (Optech Inc., 2008). The three-dimensional point clouds acquired with the terrestrial LiDAR were imported and merged with *Polyworks* CAD (Computer Aided Design) software from *Innovmetric Inc*. To facilitate the merging process, a site was selected to generate an absolute coordinate (i.e., 0; 0; 0) and all others sites coordinates were transformed accordingly. A scan recorded from this selected site was employed as a base for merging the other scans. The point clouds were manually aligned and then merged using the *Best-Fit* function from the *IMAlign Polyworks* software to achieve the highest convergence. The large ASCII file generated during this process was converted to LAS (LASer) file format to create a ground surface (DEM) of 0.5 m resolution using *LP360* from the *QCoherent* software (Fig. 7). The resulting DEM was then exported in ArcGIS® software to analyse the internal slopes of the crater and to determine the elevation of various outlets.

3.3 Bathymetry and seismic acquisition-stratigraphy

About 50 km of sub-bottom profiles (Fig. 6) were collected on the Pingualuit Crater Lake in August 2010 using a Knudsen Chirp 3212 system with a frequency of 3.5 kHz (Ledoux et al., 2011). The sub-bottom profiler data were integrated and analysed using The Kingdom Suite® software (IHS). Identified seismic horizons were exported into ArcGIS® to generate isopach maps for each horizon. The acoustic travel times was converted into depth using p-wave velocities of 1420 $m.s^{-1}$ and 1500 $m.s^{-1}$ for the determination of lake floor and thickness horizons, respectively (Moussawi and Tessier, 1989; Guyard et al., 2011). Interpretation of the units observed was completed using the correlation between seismic transects and stratigraphy of the ~9 m sediment core described by Guyard et al. (2011). The ~ 300 m meshing (Fig. 6) was used to produce a mid-resolution bathymetric map of the lake. This bathymetry was coupled with the high-resolution topography of the internal slopes from LiDAR data to produce for the first time the entire inner part of the Pingualuit Crater (Fig. 7).

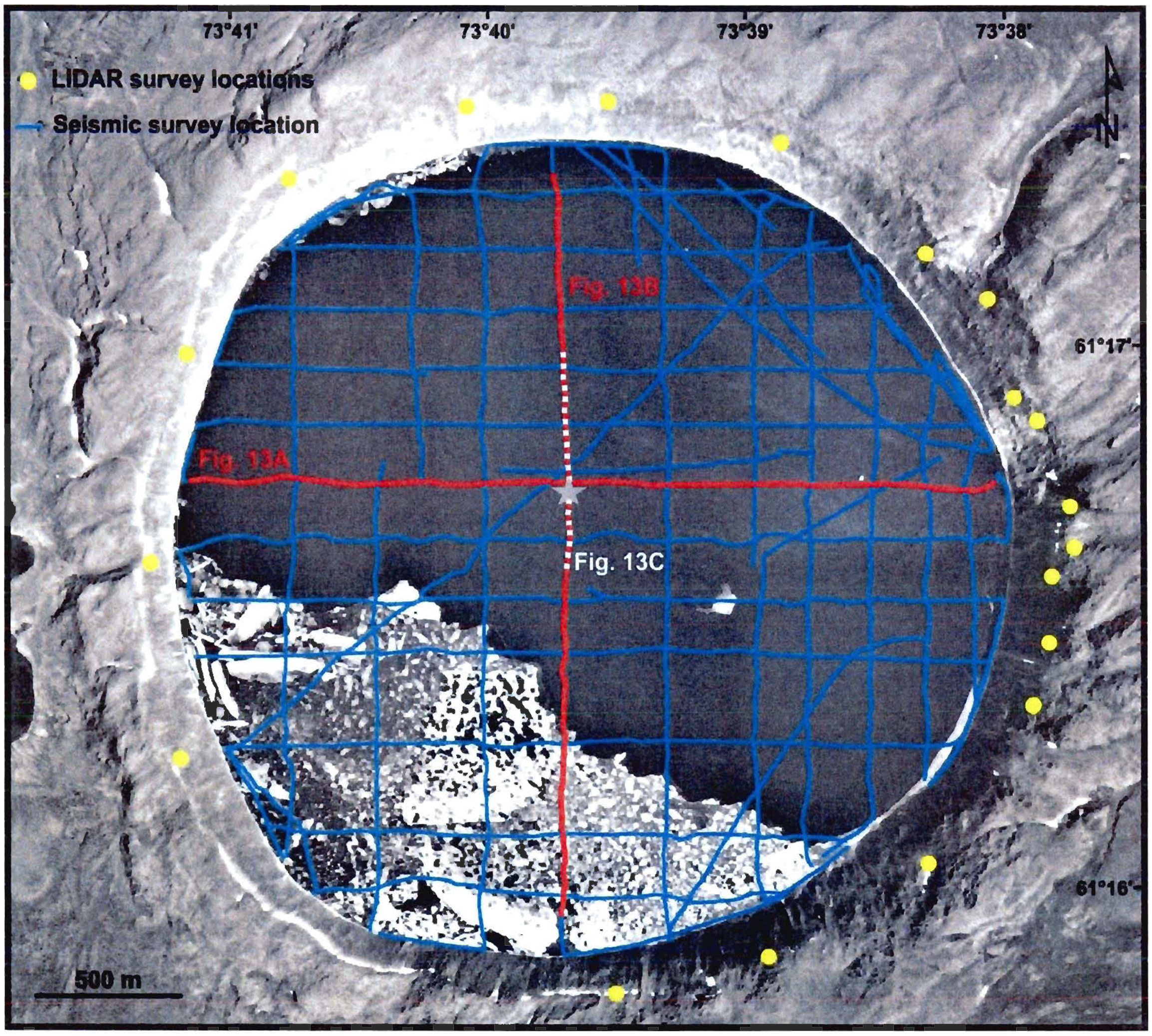

Figure 6. Location on an aerial photography (1:20 000) of seismic-reflection profiles collected in August 2010 (Ledoux et al., 2011), the sediment core collected in May 2007 (grey star) and LiDAR survey sites accomplished in September 2012.

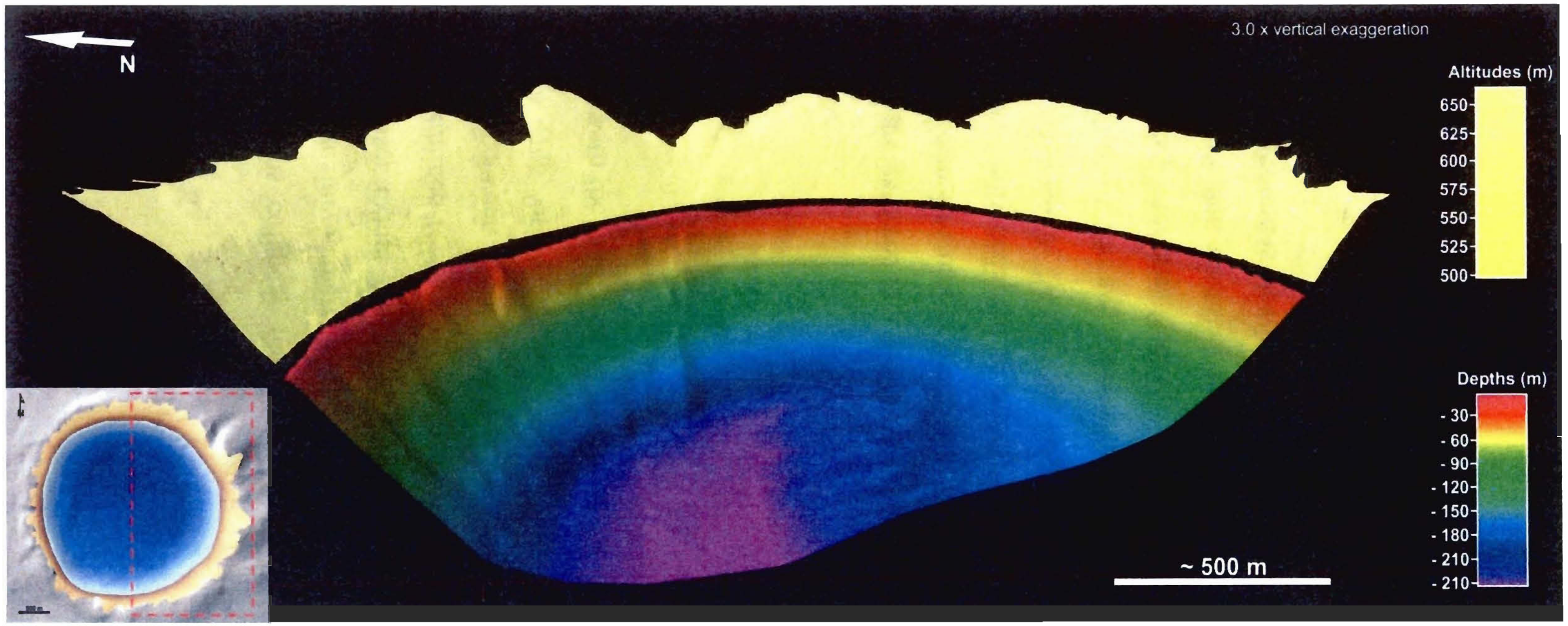

Figure 7. A coupled topography-bathymetry model of the eastern part of the Pingualuit Crater (dashed red frame). Mid-resolution bathymetry obtained by interpolation between seismic transects and high-resolution topography generated from LiDAR data.

4. Results

4.1 Glacial geomorphology

4.1.1 Streamlined forms

Several streamlined forms compose the landscape in the Pingualuit Crater area (Daigneault, 1997). They are mainly gathered in the eastern sector of Lake St-Germain and Vachon River, and to a lesser extent NE of Pingualuit Crater (Fig. 8). According to Daigneault (2008), the streamlined forms are principally drumlins and drumlinoids in the study area. Their size varies between 350 and 1000 m long and 100 and 400 wide, with a maximum height of 10 m (Fig. 9B; Daigneault, 2008). The overall orientation of the streamlined forms matches with the main axis of the Payne ice flow (Fig 4; Bouchard and Marcotte, 1986).

4.1.2 Hummocky moraine

Hummocky moraines are gathered in a sector 1 km NE of the Pingualuit Crater (Fig. 9A). Hummocky moraines form irregular mounds or small ridges of till interrupted by depressions, which are occasionally occupied by ponds. The mounds never exceed 250 m in width and 5 m in height (Daigneault, 2008). This morphology extends over less than 25 km^2 with a maximum length of ~9 km and a maximum width of ~3 km (Fig. 8). In the central part of the hummocky moraines sector, the hummocks are less marked and abundant whereas in the eastern and western part of the area, the boundary between the moraine and the neighbouring ground is clearly defined.

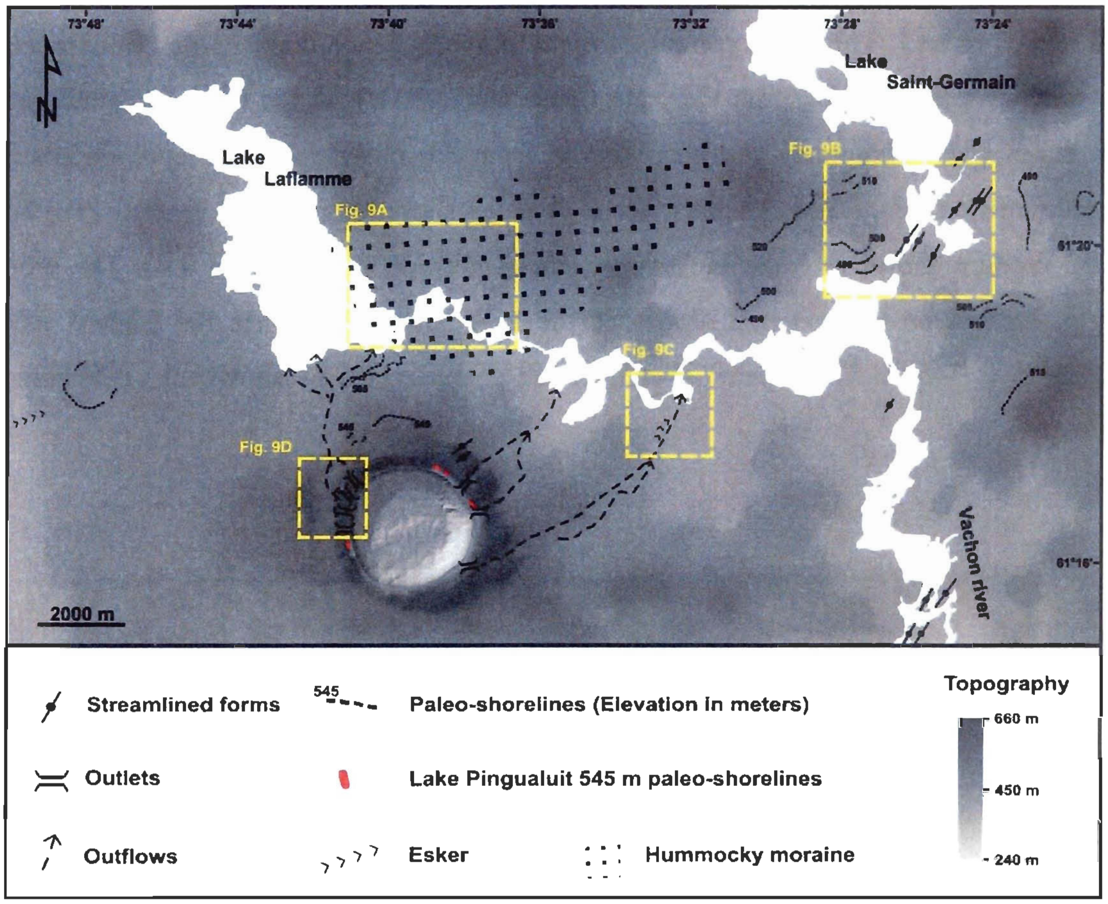

Figure 8. Geomorphological map of the Pingualuit Crater Lake basin illustrating the identified glacial/deglacial landforms and hydrological features (see text for details).

4.1.3 Proglacial lake paleo-shorelines

Numerous paleo-shorelines have been identified on the aerial photos in a small stretch located between the southern part of Lake St-Germain and the northernmost part of the Vachon River (Fig. 8). Paleo-shorelines are also noticeable to a lesser extent at the foot and on the external slopes of the northern part of the Pingualuit Crater, near Lake Laflamme (Daigneault, 2008). Paleo-shorelines appear as linear sections, parallel to contour lines, marking a break in slope (Fig. 9B). The linear section can occasionally be observed on aerial photos by change in tones due to the scarp created by the erosive action of swash on the shore. In the Lake St-Germain area, paleo-shorelines altitudes vary from

490 to 520 m a.s.l. This level comprises many gravelly beach deposits on both slopes of the southern part of Lake Saint-Germain (Daigneault, 2008). In the Lake Laflamme area, two major paleo-shorelines can be observed from the observation of aerial photos and measurements of the DEM. The first group of paleo-shorelines, located in close proximity to the modern shores of Lake Laflamme, has an altitude about 505 m a.s.l. The second group, located on the external slopes of the Pingualuit Crater, has the highest paleo-shorelines at 545 m. These paleo-shorelines are characterised by snowbanks persisting in the scarps.

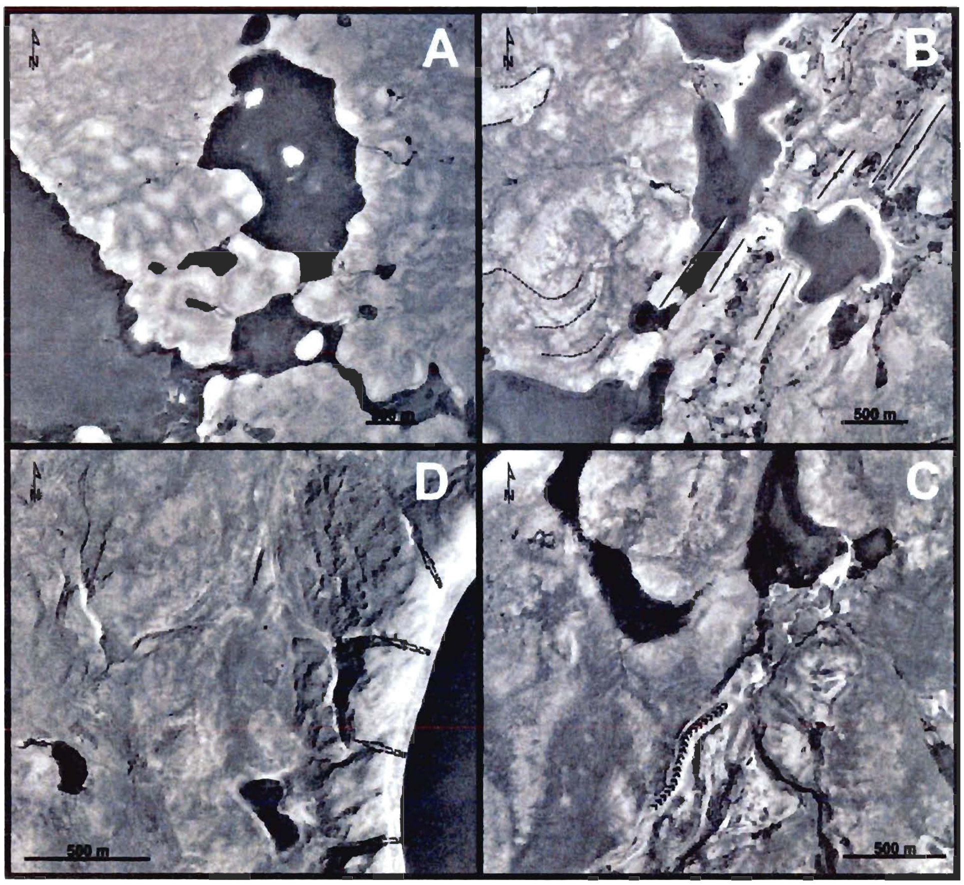

Figure 9. Aerial photographs of glacial/deglacial landforms and hydrological features in the Pingualuit Crater Lake basin. A) Hummocky moraines in the sector of Lake Laflamme; B) Streamlined forms (black lines) and paleo-shorelines (dashed lines) in the southern part of Lake St-Germain; C) Esker (multiple black arrows) and terminal part of outflow channel linked to outlet 10 (Fig. 12); D) North-East outlets (black arrow) of the Pingualuit Crater Lake and associated outflow channels.

4.1.4 Esker

One short esker can be mapped about 3 km north-east of the crater (Fig. 9C). While esker segments of the eastern coast of Hudson Bay can reach lengths of 40 km (Lajeunesse, 2008), the segment observed in the area is less than 700 m long. The esker-appears to have a north-east direction, i.e., parallel to the direction of the Payne ice-flow (Bouchard et al., 1989).

4.2 Deglacial hydrology of Pingualuit Crater Lake

4.2.1 Pingualuit Crater Lake paleo-shorelines

The LiDAR data allow the observation of paleo-shorelines along the internal slopes of the crater. Among the four paleo-shoreline segments identified, three of them are located in the north-eastern sector of the crater, while a fourth is located in the western sector (Fig. 10). The slope break and notches typical of paleo-shorelines is distinctly observable on the DEM processed from the LiDAR data (Fig. 11). The longest identifiable segment (Fig. 11b) measures ~ 150 m and the shortest is less than 50 m. All four paleo-shorelines have the same altitude of 545 m a.s.l. within a margin of error of 1 m (twice the DEM resolution). Existence of several paleo-shorelines with the same altitudes at different sites (north-east and west sectors) attests to a paleo-lake level at 545 m.

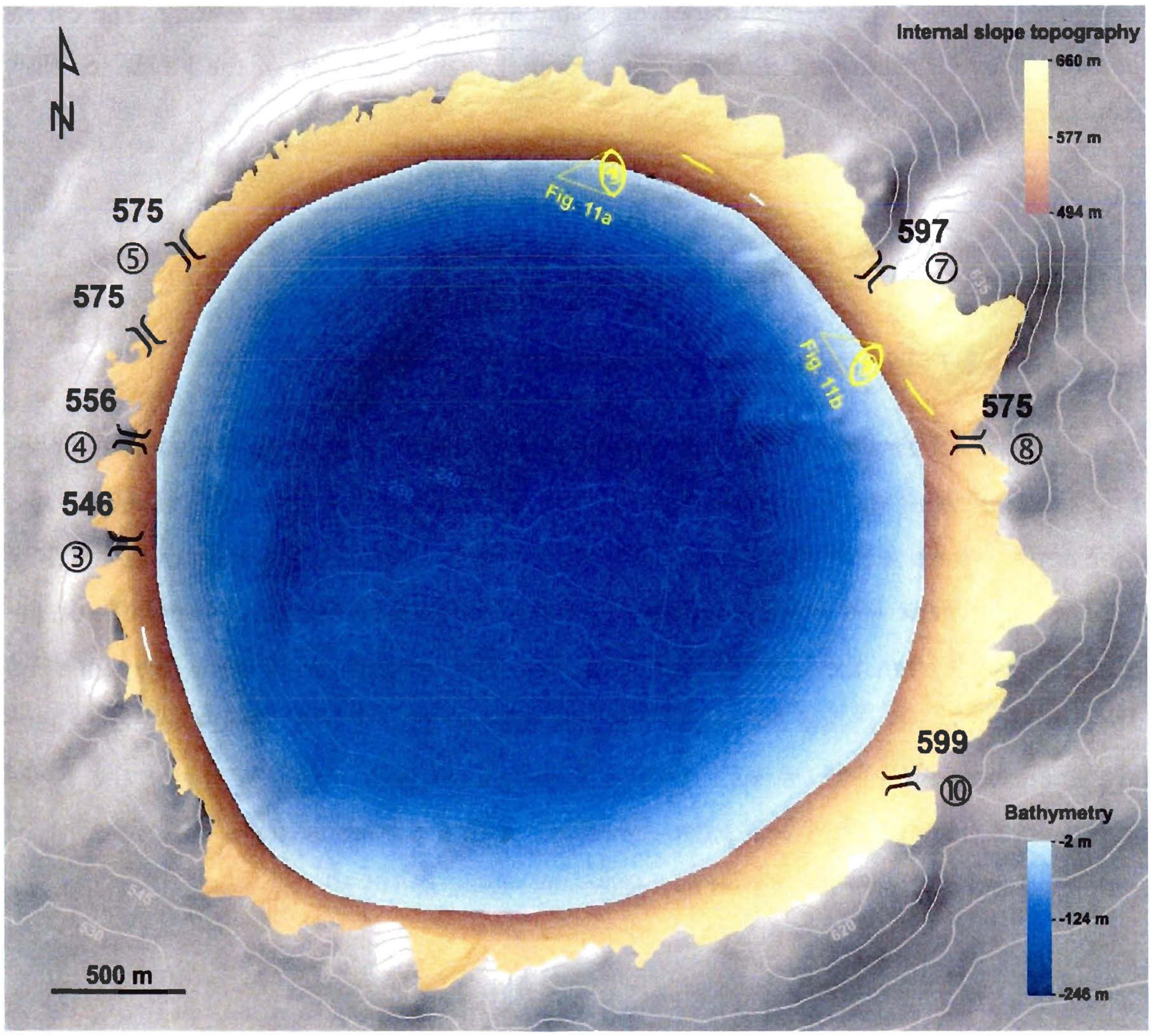

Figure 10. DEM of the Pingualuit Crater using high-resolution topography of the internal slopes and mid-resolution bathymetry. Elevation of the crater rim channels are indicated in meters (a.s.l.) (black brackets) and paleo-shorelines at 545 m a.s.l. are highlighted with white and yellow lines. The yellow eyes represent the field of view illustrated in figures 11a and b.

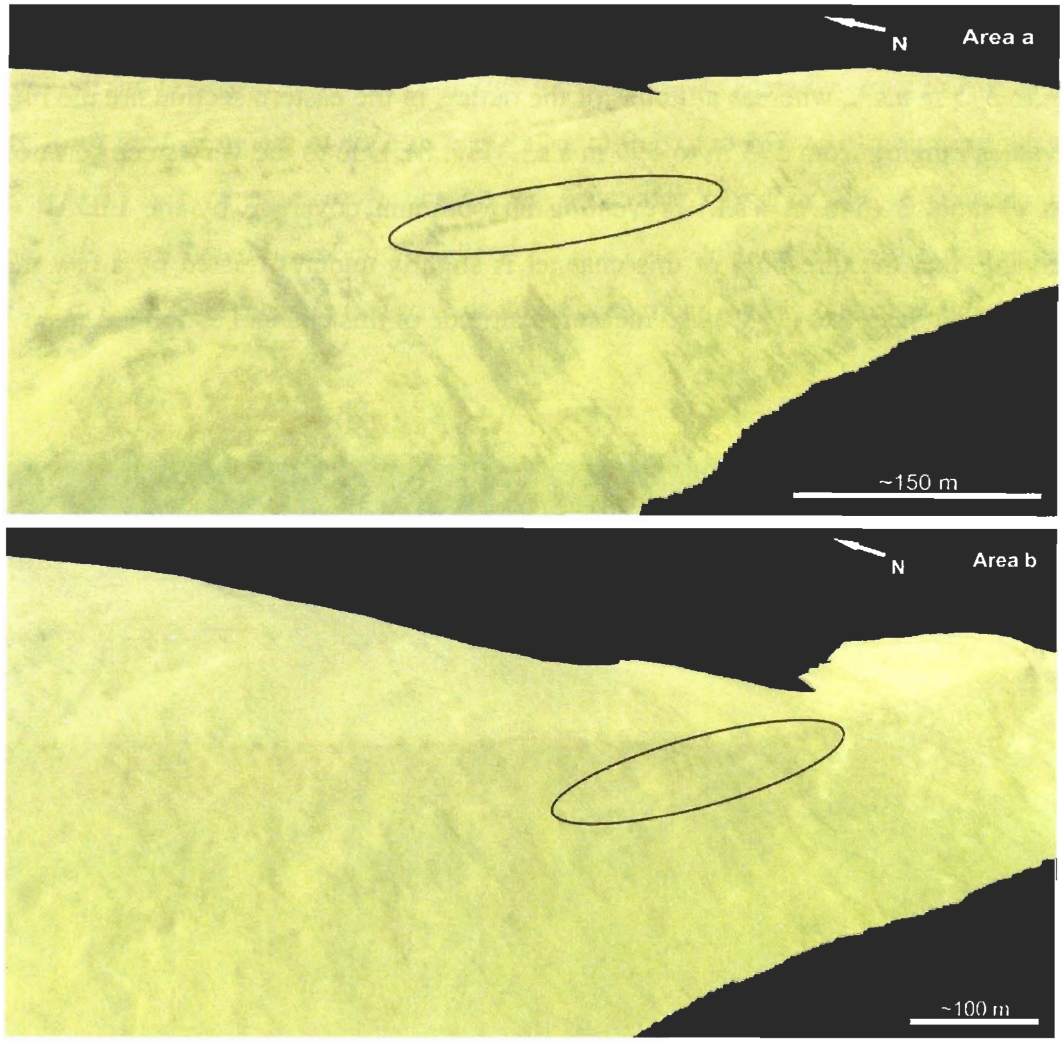

Figure 11. Paleo-shorelines at the altitude of 545 m a.s.l. (black circles). The location of the two sites is indicated in Fig. 10.

4.2.2 Characterization of the outlets

The outlets form U or V shaped channels cutting the rim of the crater. About ten outlets are recognizable around the rim (Fig. 5). Nonetheless, only seven are described in this study according to the criterion that they were potentially active during the last glacial retreat (Fig. 8). These outlets have the most pronounced channels profiles and are associated with traces of outflow on the external slopes of the crater (Fig. 12). The channels located in the western sector of the crater are the lowest with values ranging from 546 m to 575 m a.s.l., whereas altitudes of the outlets in the eastern section are the highest with values ranging from 575 m to 599 m a.s.l. (Fig. 8). Due to the very steep form of the lowest channel 3 (546 m a.s.l.) preventing an optimum coverage by the LiDAR, it is conceivable that the threshold of this channel is slightly underestimated by a few meters (Bouchard and Saarnisto (1989) had measured altitude of this channel at 553 ± 5 m a.s.l.).

Figure 12. Photograph presenting the mouth of outlet 10 with boulders washed and grouped by outflows. Photo credit: Alexandre Normandeau.

4.2.3 Pingualuit crater lake-deglaciation outflow marks

Interpretation of the aerial photographs allowed the identification of three outflow systems formed by channels linked with outlets from the crater (Fig. 9). The first channel system, located in the western sector of crater, connects western outlets with Lake

Laflamme (Fig. 9D). Closer to the crater, the system appears to be made up by two paleo-tributaries linked to outlets. The first poorly demarcated and flared, is linked with the outlet 3 at 546 m a.s.l. and partially linked to the outlet 4 at 556 m a.s.l. Outlet 4 also flows into the second tributary with the western outlets 5 at 575 m a.s.l. Indeed, in the downstream section of the outlet 4, the outflow divides into two parts. The second tributary, more marked, incises alongside the external slope of the crater then diverges at the level of the southern outlet 5. The two paleo-tributaries merge to form a ~2 km long narrow channel. At just under 1 km from the present shoreline of Lake Laflamme, this channel disperses and divides into several small channels joining the lake. The surface affected by these outflow channels has a delta form with a low difference in altitude. This sector also hosts impactites used to date the meteoritic impact (Bouchard and Saarnisto, 1989).

The second channels system, located in the north-east part of crater area, connects 597 and 575 m a.s.l. eastern outlets (respectively the 7 and 8 outlets) with the upstream part of the Vachon River. A well-traceable channel starts at each outlet. A few hundred meters from the external slopes, traces of outflow become more difficult to identify. The connection between the outlet 8 and the channel is marked on the external slopes by an important depression covered by washed boulders. Then, the channel disperses and the flow paths appear to move northward to reach the second channel, connected to the outlet 7, and the Vachon River.

The last channel is located in the south-eastern sector of the crater at the mouth of the outlet 10 at 599 m a.s.l. At the end of the outlet, the outflows facing toward the north-east are characterized over 1 km by a channel, segmented by several break in slope, covered by washed boulders (Fig. 12). These boulders, also described at the base of outlet 8, have been washed and grouped by the surge of waters during activation and drainage of the lake through outlets. At the base of the crater, this channel widens and divides into numerous distinct channels. The channel network enlarges with distance from the crater to reach a maximum width of ~700 m. Here the bedrock appears clearly on aerial photos as a white striated area. Flows have washed-out the till-covered bedrock and eroded it to form furrows on its surface. About 4 km from the crater, traces made by flows converge over 2 km to reach the Vachon River with a width of ~200 m. In this area, the boundaries between the parts affected and unaffected by flows can be clearly visible owing to extremely straight breaks in slope between them. The channels of this area are in contact with the esker (Fig. 9C).

5. Description and interpretation of the seismic survey

Seismic reflection data enabled the identification of three seismic units and two types of mass movements (Fig. 13B). Nonetheless, the seismic data do not represent the entire sedimentary sequence due to the weak penetration of the signal in very coarsed deposits and the impossibility of using a higher energy seismic source because of strict environmental regulations for this extreme protected area of the Pingualuit National Park (Fig. 13A and B; Guyard et al., 2011). The three seismic units have been observed only in the deep basin of the crater (Fig. 14A and B). The surface of slopes and the plateau is characterized by very low acoustic penetration with mid-amplitude reflection on top followed by a rapid deterioration of the signal. The very low penetration indicates the presence of many blocks and/or boulders (Moussawi and Tessier, 1989) derived from rockfalls along the crater walls. Blocks and boulders present on the slopes of the crater also cover the submerged slopes and the plateau in the lake (Fig. 15). The three units and two mass movements described below are labeled from oldest to newest (Fig. 13C). The generic mass movement terminology used indicates deposits or traces related to mass wasting according to their seismic signature (e.g. Schnellmann et al., 2005 and references therein). The interpretation of the seismic units relies on the deep basin core description and discussion (Guyard et al., 2011).

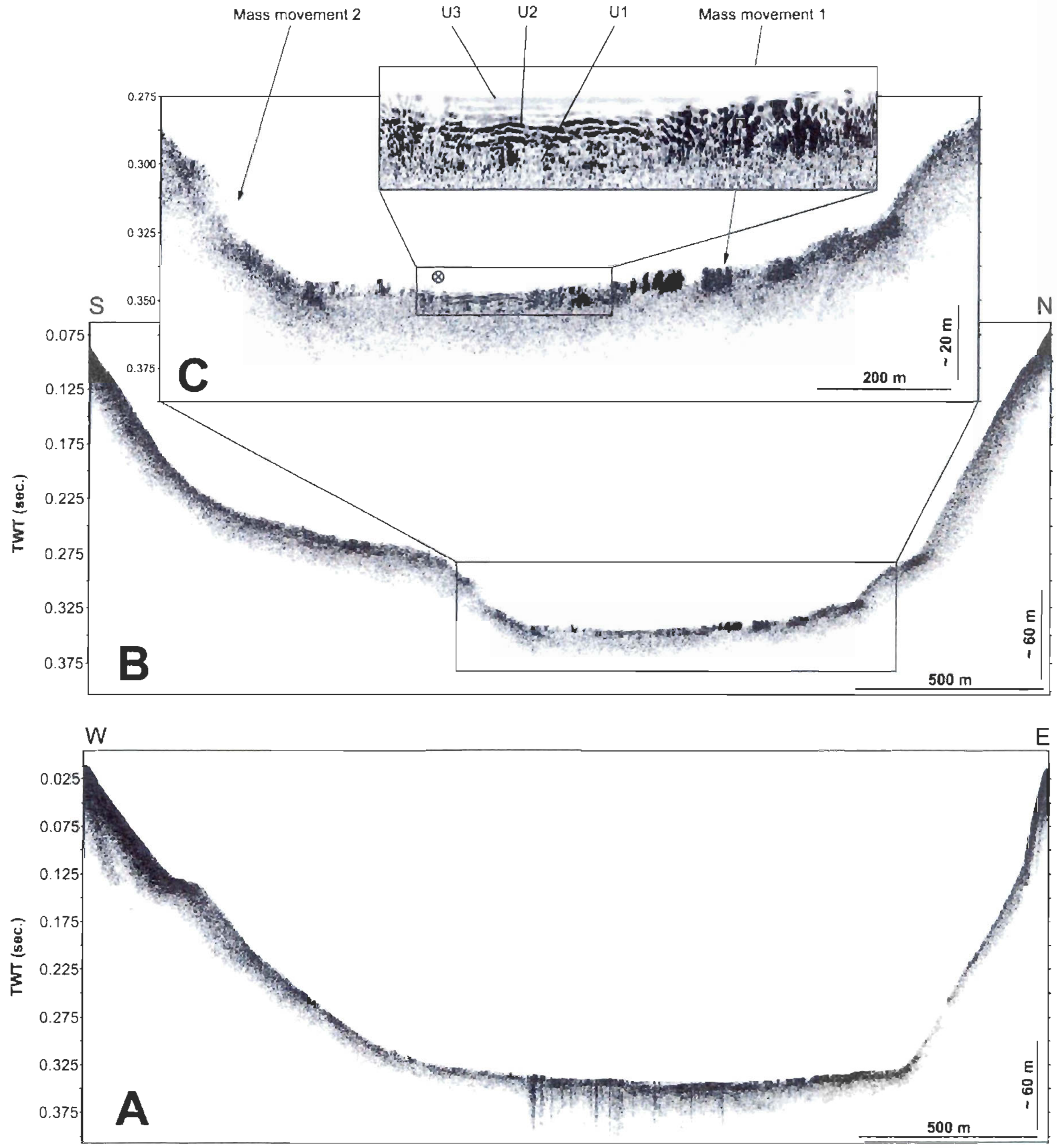

Figure 13. Seismic lines (location in Fig. 6) from an East-West (A) and a North-South (B) profile illustrating in A and B typical profiles of the seismic reflection of the crater with the very low acoustic penetration; and in C the two mass movement deposits (mass movements 1 and 2) and the three seismic units (U1, U2 and U3) identified in the deep basin of the Pingualuit Crater. The cross indicates the coring site.

5.1 Units 1 and 2 – glacio-lacustrine deposits

Unit 1 is the lowest sequence, and is characterized by low acoustic penetration and the absence of reflections. High-amplitude touches are identifiable locally. The base of Unit 1 is not defined due to the weak penetration of the signal. This unit is observed only in the deepest part of deep basin and mainly where other units are visible. The maximal depth of the top of this unit attained ~ 5.75 m below the lake floor (Fig. 13C).

Unit 2 is characterized by high amplitude parallel reflections with lateral limits poorly defined. This unit is also observed only in the deeper part of deep basin (Fig. 14A). The thickness of Unit 2 varies from less than 1 m to 4 m. In the sector where the 2007 core was recovered, the thickness of this unit reaches ~1 m and is present from ~ 3 m below the lake floor (Fig. 13C).

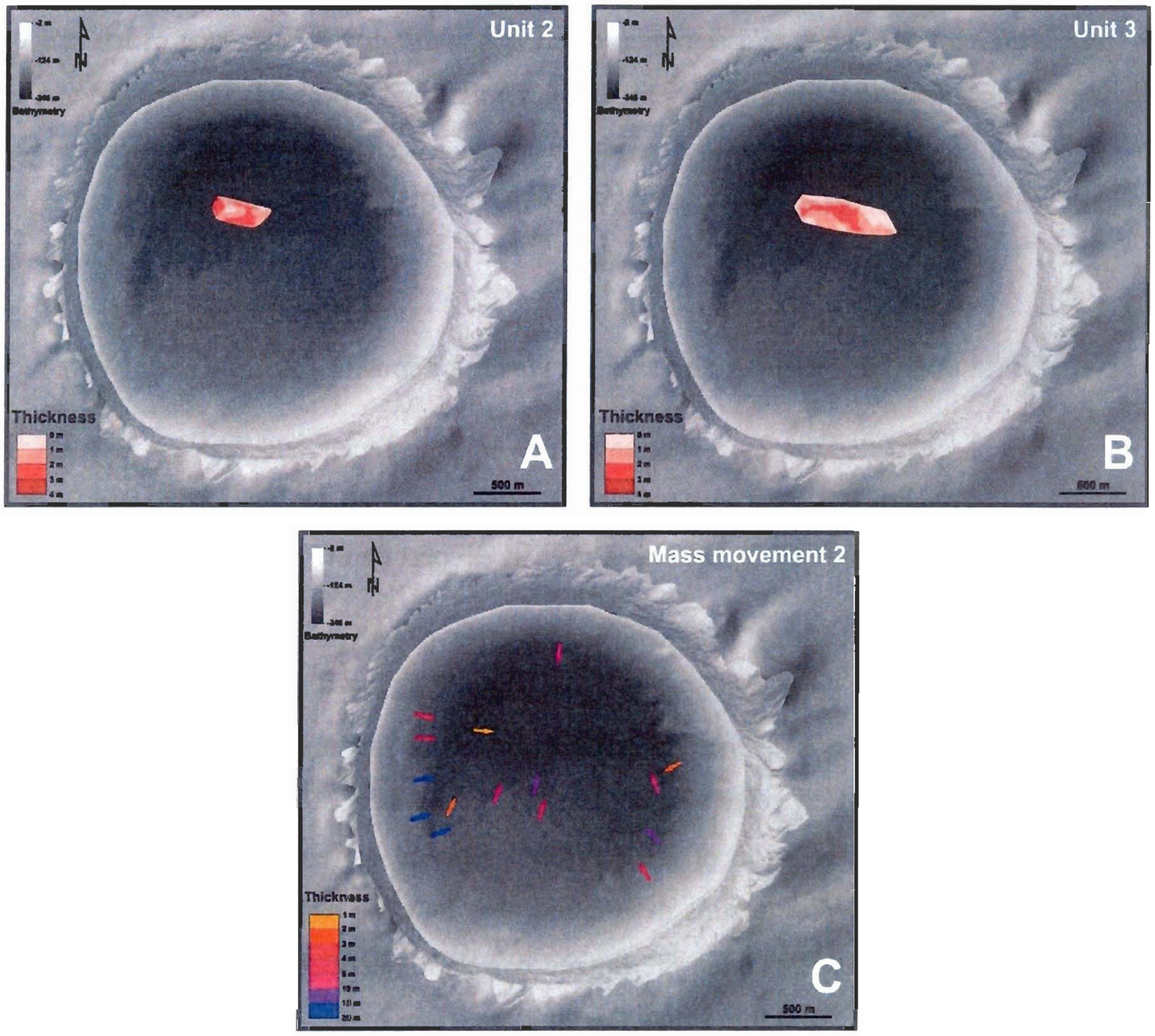

Figure 14. Isopach maps from the Pingualuit Crater Lake. Maps A and B illustrate the thickness of units 2 and 3 in the deep basin. Map C is showing the estimated orientation and maximum thickness of multiple mass movements linked to mass movement 2.

Based on previous interpretation of similar acoustic facies and detailed sedimentology analyses, units 1 and 2 suggest a glacio-lacustrine sedimentation associated with a decrease in discharge linked with the retreat of the LIS (Eyles and Mullins, 1997; Van Rensbergen et al., 1999; Guyard et al., 2011). According to their depths, units 1 and 2 coincide with finely laminated silts with few dropstones intercalated by a massive sand layer interval from 270 to 710 cm. This facies and its glacigenic sediments are interpreted as indicating high meltwater and sediment discharge with a lower influence of ice sheet-detritic inputs at the top, corresponding to Unit 2. Units 1 and 2 probably correspond to the last stages of ice sheet retreat with a semi-permanent ice covered lake still supplied by residual ice from the disintegrating glacier (Black et al., 2010; Guyard et al., 2011).

5.2 Unit 3 and mass movement 1 and 2: mass wasting deposits

Unit 3 is characterized by a low amplitude seismic facies and appears as a thick transparent and chaotic sedimentary sequence. Sediments of Unit 3 cover a large part of the basin but reach a maximum thickness of 3-4 m in its deepest part (Fig. 14B).

Mass movement 1 (MM1) constitutes the most chaotic and scarcely describable acoustic facies. This mass movement is characterized by high amplitude chaotic and discontinuous sedimentary sequences laterally disrupted by low amplitude and transparent sedimentary sequences. Few meters below the top of this unit, it is no longer observable due to the chaotic configuration of the sediments causing a weakening of the acoustic signal (Fig. 13C). According to this description, this unit has acoustics characteristic of debris flows (Prior et al., 1984), but the limited correlation between acoustic profiles and the weak penetration of the signal limits this interpretation. MM1 is present mainly in the northern and eastern parts of the crater at foot of the slopes and in the deep basin. Due to the characteristics of this unit, it is impossible to observe other units under MM1. However, the contact between MM1 and units 1 and 2 indicate that mass movements have affected and probably eroded these horizons.

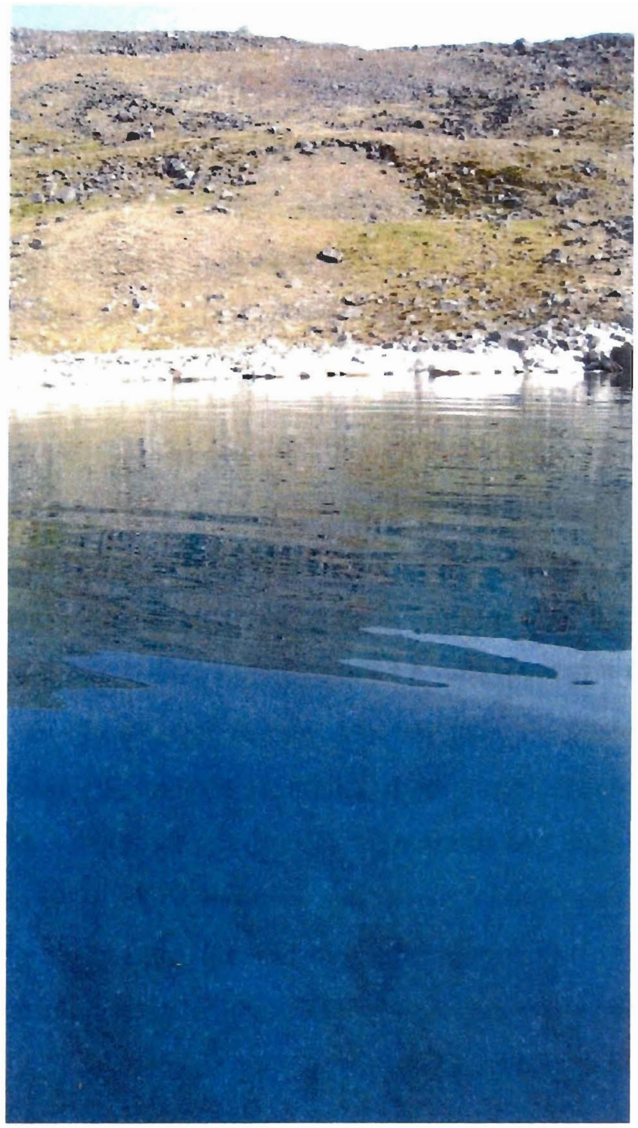

Figure 15. Photograph illustrating the steep internal subaerial and subaqueous slopes covered by large blocks and boulders. Photo credit: Grégoire Ledoux.

Mass movement 2 (MM2) consists of a chaotic to transparent seismic facies. Its surface is fairly smooth but appears occasionally slightly hummocky when transects laterally cross the mass movement. Its surface is also more irregular than the top of the underlying layer. Furthermore, MM2 overlays none of the other horizons, only the surface of slopes and the plateau. MM2 is observed in three kinds of bathymetric configurations

(Fig. 14C): (1) it is visible at the toe of steep slopes at the level of the plateau and in the deep basin mainly in the eastern part of the crater; (2) south of the central part of the crater, it is present on the shallower slopes between the plateau and the deep basin; (3) it is discernable on the steep slopes in the western sector of the crater. In this area, MM2 reaches a maximum thickness of ~20 m, but elsewhere it ranges between 1 and 15 m in thickness. MM2 was not observed in contact with the other identified units (Fig. 13). However, in several parts at the toe of the slopes it partially overlapped MM1.

Description of mass movements 1 and 2 indicates two distinct mass wasting events in the Pingualuit Crater Lake. The first one preceded MM2 and occurred after the deposition of seismic units 1 and 2, as indicated by the erosional contact between the mass wasting and these units. Unit 3 is probably the most recent deposit in the lake, though it could be concomitant with MM2. Indeed, Unit 3 coincides with a mass wasting deposit composed of folded and reworked glacigenic material and characterized by an erosive contact at its base (Guyard et al., 2011). Furthermore, both units have seismic characteristics with important similarities: low amplitude and transparent seismic facies. Finally, MM2 and Unit 3 may be linked to a single depositional event that occurred about 4200 cal BP (Guyard et al. 2011). Guyard et al. (2011) suggested a translational slide based on the observation of preserved internal sedimentary organisation, but the indistinct failure surface weakens this hypothesis (Mulder and Cochonat, 1996).

6. Discussion

Aerial photography focused on the Pingualuit Crater Lake basin reveals glacial streamlined forms and hummocky moraines, which reflect, respectively, the orientation and deglacial conditions of the last glaciation in the study area. The overall north-east direction of all the observed streamlined forms attests to a main glacial Payne flow (azimuth 45°) subsequent to the Ungava flow (azimuth 110°) in the crater area during the last glaciation (Bouchard, 1989b; Daigneault and Bouchard, 2004).

Hummocky moraines are generally deposited at the margins of the Laurentide Ice Sheet and have been mainly observed in the Great Plains of North-America (Gravenor and Kupsch, 1959; Parizek, 1969; Clark et al., 1996; Mollard, 2000; Boone and Eyles, 2001; Evans et al., 2013). In the Ungava Peninsula, the majority of hummocky moraines are located and gathered in the western part of the peninsula around the presumed position of ice divide line (Daigneault, 2008). According to Daigneault (2008), these moraines correspond to the locations of the last remnants of ice. Furthermore, hummocky moraines are evidence of supraglacial or subglacial depositional processed tied to the stagnation of ice during ice-sheet retreat (Gravenor and Kupsch, 1959; Stalker, 1960; Parizek, 1969; Johnson et al., 1995; Boone and Eyles, 2001; Daigneault, 2008). In the Pingualuit Crater area, hummocky moraines are relatively isolated, faintly extended and located farther away from the presumed position of the ice divide line (Fig. 4 and 8; Daigneault, 1997). This organization of moraines suggests the development of a stagnation zone during a rapid overall deglaciation of the Ungava Peninsula caused by the presence of glaciolacustrine waters (Evans, 2003; Daigneault, 2008). However, hummocky terrain being limited to the north-eastern sector of the study area (Fig. 8), it is likely that this stagnation did not occur on and immediately around Pingualuit Crater.

The paleo-shorelines observed in the southern sectors of Lake St-Germain and Lake Laflamme confirm the presence of a proglacial lake in the study area during the glacial retreat. Paleo-shorelines identified at different elevations between 490 and 520 m a.s.l. (Fig. 8) provide futher evidence for several periods of relative stable water level during the development and the emptying of the proglacial lake. At that time, the ice front prevented drainage of glacio-lacustrine waters to the south by the Vachon River, allowing the development of proglacial lakes (Daigneault, 2008). In the Lake Saint-Germain area, the elevations of the highest paleo-shoreline indicate a proglacial lake with a maximum level of 520 m a.s.l.. The elevation of the paleo-delta generated by outflows from the Lake Pingualuit spread in the southern part of the Lake Laflamme area show a proglacial lake with a maximum level of 515 m a.s.l. (Fig.16; Bouchard and Saarnisto, 1989). Nevertheless, the paleo-shorelines observed on the external slopes of the Pingualuit Crater at 545 m a.s.l. (Fig. 8), corroborated by paleo-shorelines at ~ 540 m a.s.l. identified by Daigneault (1997) near a lake located a few kilometers east of the Vachon River, may indicate the presence of a higher altitude proglacial lake. According to these altitudes, the proglacial lake in the Pingualuit area could have reached 545 m a.s.l., approximately 45 m above the current level of Lake Laflamme (Fig. 16).

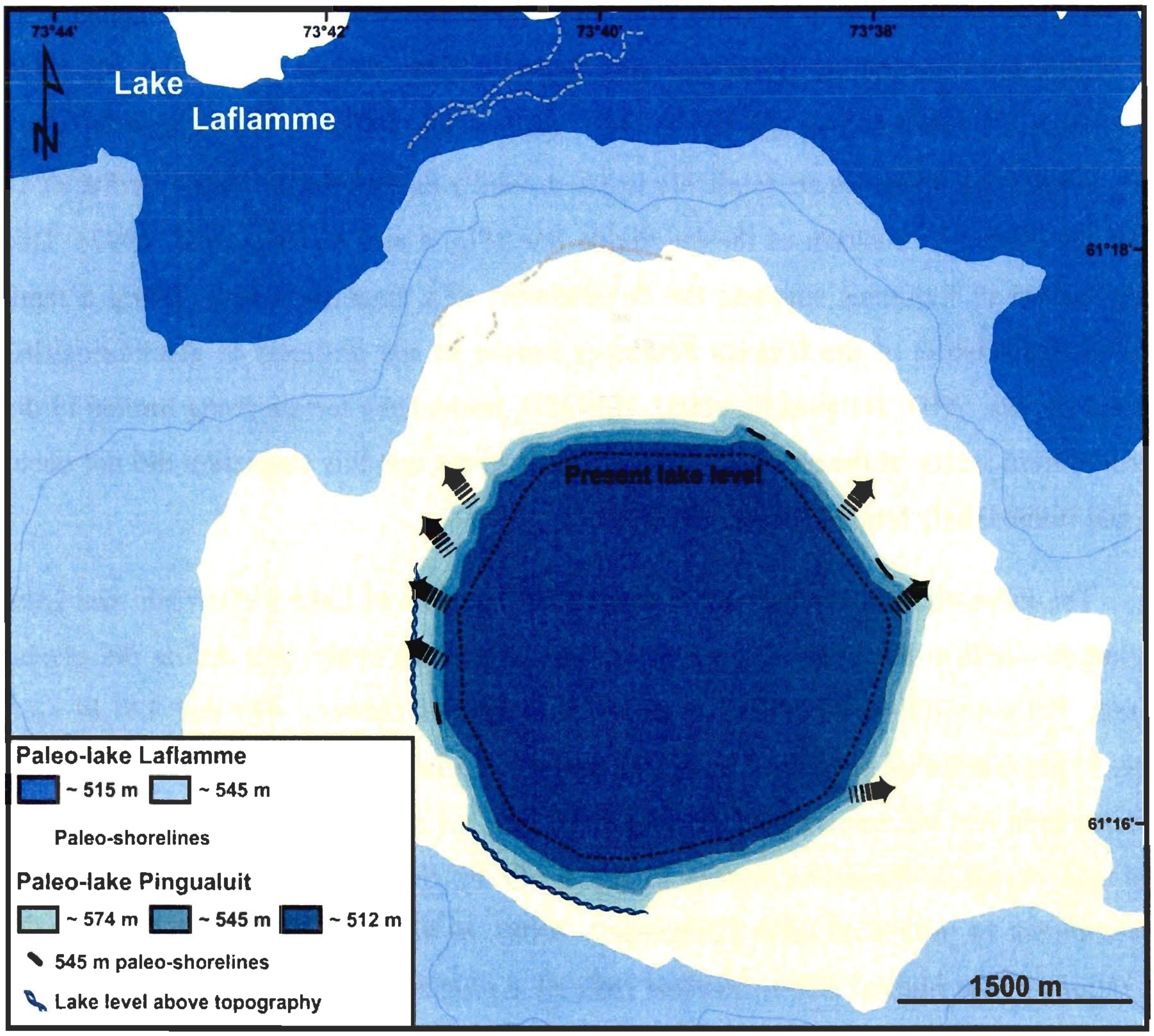

Figure 16. Topographical map of the Pingualuit Crater Lake basin presenting the potential paleo hydrology since the beginning of the deglaciation of the crater. The black arrows are showing the crater rim channels involved in the lake drainage.

Identifications of outflow marks, characterization of outlets and identification of the paleo-shorelines on the internal slopes of the crater allowed the establishment of a new model of deglaciation of the Pingualuit crater (Fig. 17). The deglaciation model is presented in three main phases according to the three major lake drainage events associated with the release and the activation of outlets. The model is based on a rapid glacial retreat occurring towards the south-west with the main axis of the ice front oriented north-west-south-east. The direction of the glacial is inferred from the Ungava regional pattern of deglaciation suggested by Daigneault (2008) and confirmed in the crater area by the estimated north-east direction of the noticeable esker (Fig. 9C). Furthermore, orientation of the ice front is strongly suggested and confirmed in the area by altitudes of the outlets. The three phases discussed below do not correspond to periods of stagnation of the ice front, but to characteristic snapshots of each main phases of the Pingualuit crater deglaciation.

During the first phase (Fig. 17) of deglaciation, phase I, glacial retreat affected the eastern sector of the crater, freeing a narrow band of the lake along the east coast. The eastern crater rim channels 7, 8 and 10 became ice-free and active as shown by outflow marks at their bases. Outlets 7 and 10 were probably fed for a reduced period of time on account of their high altitudes, 597 and 599 m a.s.l. respectively. Despite this short-lived activity, outlets 7 and 10 appear to have drained a significant amount of water into the proglacial lake Laflamme and/or the Vachon River, as revealed by well-defined outflow channels at the base of each outlet. Furthermore, the esker observed in the downstream section of the channel system linked to outlet 10 indicates a subglacial and proglacial drainage system independent of and prior to the drainage of the Pingualuit Crater Lake (Bouchard and Saarnisto, 1989). The channel system generated by subglacial drainage probably received outflow from outlet 10, causing an intensification of erosion in the area between the crater and the esker. In this way, the short and poorly-defined esker has been affected and eroded by outflow from channel 10. Outlet 8 received continuous overflow throughout phase I due to its lower altitude (575 m a.s.l.). Lake levels were higher than the altitude of channel 10 (599 m a.s.l.) at the beginning of phase I, and remained higher than the altitude of channel 8 (575 m a.s.l.) by the end of it, maintaining continuous drainage of the lake.

The ice front retreated towards the south-west until reaching the position shown in phase II, leading to the opening of crater rim channels 5 (Fig. 17). During phase II, equal-altitude outlets 8 and 5 (575 m a.s.l.) function simultaneously and drain supercritical highly erosive flows, as revealed by distinctively marked outflow channels linked to outlets on the external slopes of the crater (Bouchard and Saarnisto, 1989). Outflows toward outlets 5 allow, for the first time, drainage of the lake by the western part of the crater, leading to the supply of drainage waters to the proglacial lake Laflamme. Furthermore, the less pronounced channels linked to outlet 8 could indicate a precocious desertion of this channel and a concentration of the drainage toward outlets 5 in the north-west sector of the crater (Bouchard and Saarnisto, 1989). Finally, the end of phase II sees the drying-up of these outlets and leads to the development of the highest and most poorly-developed paleo-shoreline (574 ± 5m) observed by Bouchard and Saarnisto (1989) in the northern part of the crater (Fig. 16).

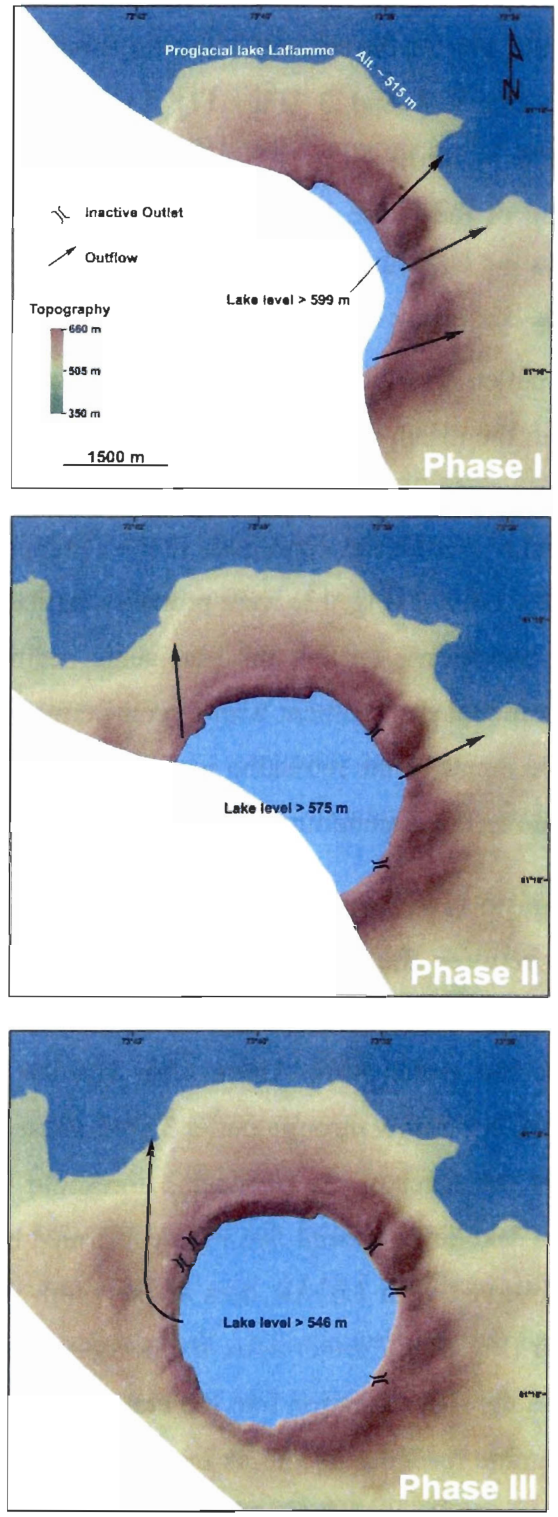

Figure 17. Conceptual model for the deglaciation of the Pingualuit Crater Lake. The lake level indicated is the lowest lake level to maintain the exoreic drainage during each phase.

During phase III, the glacial retreat maintains its motion towards the south-west successively releasing channels 4 and 3 (Fig. 17). Low-elevation channels 4 and 3 (respectively 556 and 546 m a.s.l.) allow the drainage of the lake waters from their elevation at the beginning of the phase III to approximately 574 m. Runoff from these outlets is transported from the base of the external slopes to the north-west and flows into proglacial lake Laflamme. Lowering of the lake level below the threshold of channel 4 causes desertion of this outlet, with the lower channel 3 becoming the last active crater outlet. Phase III ends with the disappearance of the last remnants of the LIS in the crater perimeter, implying the cessation of glacial inputs to the lake. Guyard et al. (2011) dated the change from proglacial to postglacial conditions in the Pingualuit Crater Lake basin at 6850 cal BP. Seismic Units 1 and 2 (Fig. 13) were probably settled during phase III before the onset of postglacial conditions. Indeed, the glacigenic sediments of these horizons show quite clearly a depositional environment with a semi-permanent ice-covered lake still affected by the last detritic inputs of the retreating ice-sheet. The lessening influence at the top of these units foreshadows the impending postglacial conditions (Guyard et al., 2011).

Bouchard and Saarnisto (1989) suggested the maintenance of a temporary surface hydrological connection between the Pingualuit crater lake and Lake Laflamme at the transition between proglacial and postglacial conditions to explain the presence of the single fish population in the crater lake, Arctic Char (Delisle and Roy, 1989). This connection requires a constant outflow through outlet 3 after phase III, requiring in turn the upkeep of lake waters at the level of the channel 3 threshold (Fig. 16; 546 m a.s.l.). Prolonged maintenance of lake level around 546 m is confirmed by the paleo-shoreline at 545 m a.s.l. distinctly observed with LiDAR data at the south of channel 3 and in the northern part of the crater (Fig. 11). Furthermore, the postglacial hydrological connection between the two lakes and the fish migration into the crater could have been facilitated by the proglacial Lake Laflamme reaching 545 m as mentioned above (Fig. 16). Finally, the postglacial exoreic phase of the Pingualuit Crater Lake ends when the lake level descends below the threshold of channel 3, potentially giving way to a cryptorheic drainage phase and the current hydrologic context (Bouchard and Saarnisto, 1989).

Since the end of the exoreic phase, the lake continually declined to reach its current level (494 m a.s.l.), as revealed by the absence of distinct intermediate paleo-shorelines. The poorly developed paleo-shoreline around 514 m a.s.l. constitutes nonetheless an exception to this uninterrupted lowering (Fig. 16; Bouchard and Saarnisto, 1989). The decline of the lake within the cryptorheic regime could be explained by the drainage of the proglacial lake north of the Pingualuit Crater. Indeed, the glacial retreat in the southern part of the study area causes the release of the Vachon River, which had been obstructed and thus responsible for the development of the proglacial lake. The release leads the drainage of the proglacial lake to the Ungava Bay through the Vachon River and the lowering of Lakes Laflamme and St-Germain to present levels (~ 500 m a.s.l.) (Daigneault, 2008). As the Pingualuit Crater Lake and Lake Laflamme were probably linked by a North-South oriented fault plane allowing cryptorheic drainage between both lakes, the lowering of proglacial Lake Laflamme would have modified the hydrostatic equilibrium (Ouellet et al., 1989). This destabilisation has led to increased outflow through the fault plane from the crater lake to Lake Laflamme, consequently lowering the Pingualuit Crater lake level. Regardless of the exact mechanism of lake lowering, the lake level dropped by 51 m since the end of the exoreic phase.

The two mass movement events identified on the seismic data (Fig. 13) were probably triggered during or following the deglacial phase of the crater. The chronology of these events indicates that deposition of MM1, preceding the depositional event linked to MM2 and Unit 3 and dated around 4200 cal BP by Guyard et al. (2011), occurred after sedimentary units 1 and 2 settled during phase III. The two mass movement events could have been triggered by similar mechanisms. First, the steep basin walls (26-35°) contribute greatly to the instability of the slopes, causing sediment redistribution through sliding and slumping (Dearing, 1997). Indeed, several models and studies, notably in small lakes, use and/or show instability or very low accumulation on the slopes beyond about 15 % (~9°) (e.g. Hakanson, 1977; Hilton, 1985; Bennett, 1986). In the context of deglaciation, the retreat and disappearance of the ice-sheet above the subglacial lake caused the reduction of water pressure in the lake and increased the inner crater surface's exposure to erosion.

These conditions, coupled with a rapid drop of lake levels and the activation of outlets through the rim, might have favor instabilities of aerial and subaqueous slopes (Guyard et al. 2011). The combination of these mechanisms and the increase of glaciolacustrine deposits associated with crater lake deglaciation can explain acceptably the enactment of MM1 limited to the northern and eastern part of the crater. Earthquake can also be referred as a possible trigger mechanism for mass wasting in lakes (e.g., Schnellmann et al., 2002; Monecke et al., 2004; Normandeau et al., 2013). Observation of multiple MM2 deposits at the level or at the foot of slopes at many sites (Fig. 14C) could indicate a simultaneous triggering generated by an earthquake. Indeed, the area is seismically active and a $M_S = 6.3$ earthquake was recorded around 120 km southwest of the crater (60.12°N; 73.60°W) in 1989 (Adams et al., 1991). Furthermore, the seismic activity could be exacerbated by glacio-isostatic rebound following deglaciation in Ungava (Guyard et al., 2011).

7. Conclusions

The high-resolution topography of the internal slopes of the crater generated from LiDAR data permitted the identification of four paleo-shorelines with the same altitudes of 545 m a.s.l., proving the presence of a paleo-lake level at 545 m. Furthermore, the altitudes of various channels cutting the rim of the crater and serving as outlets for the drainage of lake waters have also been identified on the LiDAR data. These observations obtained from the interpretation of aerial photographs allowed the establishment of a new deglaciation model for the Pingualuit crater. The model proposes three main phases of lake drainage as channels opened following the retreat of the LIS front towards the south-west. The progressive activation of the seven outlets led to a decrease of lake levels from elevations higher than 599 m (altitude of the highest outlet) to 545 m (altitude beneath the lowest outlet). The decline of the lake to its present level (494 m a.s.l.) can be explained by an intensification of groundwater flow in a cryptorheic connection between the Pingualuit crater Lake and the neighboring Lake Laflamme. This intensification was possibly caused by permafrost degradation during the postglacial warming period and/or the modification of hydrostatic equilibrium between the two lakes following the drainage of the proglacial lake north of the crater.

Seismic reflection data of Pingualuit Crater Lake allowed the identification of two glacio-lacustrine units deposited during the final stages of deglaciation, as well as two postglacial mass movement deposits. Interpretation of seismic profiles revealed faintly diversified sedimentary records at a low temporal resolution. Indeed, all the deposits identified in this study appear to derive from sedimentation during deglaciation and sediment reworking linked to postglacial sublacustrine mass wasting events. In the Pingualuit Crater Lake, contrary to the Lake El'gygytgyn and the Lake Potrok Aike which are supplied by small streams and periodic inflow (Zolitschka et al., 2006; Nolan and Brigham-Grette, 2007), the absence of tributaries has greatly restricted the accumulation of a high-resolution paleoenvironmental record since the retreat of the LIS. Furthermore, a large number of blocks and/or boulders are present on the submerged slopes and in the sedimentary deposits observed. The lack of seismic information beneath these units (the 3.5 kHz sub-bottom profiler is expected to image the sedimentary column beyond the ~ 10 m obtained given the configuration of the crater) seems indicate the presence of blocks under the glacio-lacustrine units that does not allow deeper signal penetration. The presence of these blocks might be explained by slope movements, which may have resulted from the balancing of slopes following impact cratering.

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CHAPITRE 2
CONCLUSION

Ce projet de maîtrise a permis de fournir une approche actualisée et étoffée de l'histoire glaciaire du cratère des Pingualuit et de sa région au cours de la période tardi-quaternaire. En effet, l'orientation des formes glaciaires (moraine de décrépitude, formes fuselées, esker, etc ...) mises en évidence lors de l'analyse des photographies aériennes, a montré une mise en place de l'Inlandsis laurentidien dominée par le flot glaciaire de Payne (azimut 45°) subséquent au flot d'Ungava (azimut 110°) lors de la dernière glaciation. Un nouveau modèle de déglaciation du cratère et de vidange des eaux du lac Pingualuk en trois phases principales a ainsi été proposé, basé sur l'orientation des écoulements glaciaires couplée aux altitudes des exutoires du cratère et à l'identification d'un paléo-rivage à 545 m d'altitude déterminées à partir des données LiDAR. Au cours de la première phase, le retrait glaciaire, dirigé vers le sud-ouest, permet la libération des vallées orientales du cratère entraînant un drainage des eaux du lac Pingualuk, dont le niveau était alors situé au-dessus de 599 m d'altitude, vers la rivière Vachon à l'est. Durant la seconde phase de déglaciation, le retrait du front de glace conduit au dégagement de vallées dans la partie nord-ouest de la couronne, les exutoires permettaient alors des vidanges conjointement vers la rivière Vachon et le lac Laflamme situé au nord. À la fin de cette phase, le niveau du lac s'est stabilisé à une altitude de 574 m après l'assèchement des vallées libres de glace les moins élevées. Lors de la dernière phase, le glacier continue de se retirer permettant la libération des vallées occidentales dont les seuils possèdent la plus faible élévation de toutes les vallées de la couronne. Ces exutoires ont permis la vidange des eaux du lac vers le nord-ouest jusqu'au lac Laflamme. Le modèle proposé présente ainsi clairement les trois phases successives de drainage ayant conduit au déclin du niveau du lac jusqu'à 545 m (altitude sous l'exutoire le moins élevé) et de nouvelles pistes ont également été évoquées afin d'expliquer le niveau actuel des eaux du lac à 494 m.

Les données LiDAR et la photo-interprétation ont fourni de nouvelles informations concernant la géomorphologie de la région du cratère des Pingualuit. Ainsi, le modèle numérique de terrain des pentes internes, généré à partir des données LiDAR, a permis de déterminer avec une grande précision (résolution de 1 m) l'altitude des exutoires du cratère et du paléo-rivage à 545 m, jusqu'alors estimé par Bouchard et Saarnisto (1989) avec une résolution de seulement ± 5 m. Ce modèle a également apporté le niveau de résolution nécessaire pour l'identification, dans plusieurs secteurs du cratère, des empreintes du paléo-rivage à 545 m. De plus, le couplage de la topographie à haute résolution avec la bathymétrie de la partie submergée du cratère permet pour la première fois de visualiser et d'étudier la morphologie du cratère des Pingualuit dans un système en 3D. Ces travaux ont également permis d'étoffer et d'actualiser les connaissances de l'histoire glaciaire tardi-quaternaire dans ce secteur de l'Ungava. Les futures études paléo-climatiques sur les sédiments du lac du cratère des Pingualuit possèderont ainsi un contexte géologique et climatique de la région mieux documenté.

Ce projet a également permis de mettre en évidence et de cartographier des unités sédimentaires et des mouvements de masse au fond et sur les pentes du lac du cratère des Pingualuit à partir de l'interprétation des données sismiques et d'une étude stratigraphique réalisée par Guyard et al. (2011). Deux unités glacio-lacustres déposées lors des dernières phases de retrait du glacier ont ainsi été identifiées dans le secteur le plus profond du lac. Deux dépôts postglaciaires associés à des mouvements de masse ont également été référencés. Les travaux réalisés sur ces données sismiques ont cependant été fortement limités par la faible pénétration du signal acoustique en raison d'un nombre important de blocs rocheux sur les pentes, le fond et potentiellement sous les unités sédimentaires identifiées dans cette étude. La capacité du lac du cratère des Pingualuit à préserver des enregistrements sédimentaires de plusieurs cycles glaciaires/interglaciaires et la possibilité d'extraire de plus longues séquences sédimentaires pourraient ainsi être remises en question si la forte présence de blocs rocheux, sous les unités cartographiées, était avérée. Pour confirmer ou infirmer cette hypothèse une nouvelle campagne sismique pourrait être conduite au lac du cratère à l'aide d'une source sismique à plus basse fréquence d'émission (e.g. *Boomer* ou *sparker*) afin d'améliorer la pénétration du signal dans les sédiments du cratère. Cependant, une campagne sismique de cette ampleur nécessite une logistique difficile à mettre en place au cratère en raison de son isolement et des normes environnementales très strictes appliquées au cratère des Pingualuit, le joyau du parc national des Pingualuit.

RÉFÉRENCES BIBLIOGRAPHIQUES

Adams, J., Wetmiller, R.J., Hasegawa, H.S., Drysdale, J., 1991. The first surface faulting from a historical intraplate earthquake in North America. Nature 352, 617–619.

Anselmetti, F.S., Ariztegui, D., De Batist, M., Catalina Gebhardt, A., Haberzettl, T., Niessen, F., Ohlendorf, C., Zolitschka, B., 2009. Environmental history of southern Patagonia unravelled by the seismic stratigraphy of Laguna Potrok Aike. Sedimentology 56, 873–892.

Arctic Climate Impact Assessment (ACIA), 2005. Arctic Climate Impact Assessment scientific report. Cambridge University Press, Cambridge, United Kingdom. 1042 pp.

Bennett, K.D., 1986. Coherent slumping of early postglacial lake sediments at Hall Lake, Ontario, Canada. Boreas 15, 209–215.

Black, J.L., Hausmann, S., Pienitz, R., St-Onge, G., Guyard, H., Salonen, V.-P., Lavoie, M., Girard-Cloutier, A.-M., Luoto, T., 2010. Reconstruction of paleoenvironmental changes from Pingualuit Crater Lake sediments during glacial-interglacial cycles MIS 1 to MIS 8: a long-term terrestrial record from the Canadian Arctic. European Geophysical Union, Vienna, Austria.

Boone, S.J., Eyles, N., 2001. Geotechnical model for great plains hummocky moraine formed by till deformation below stagnant ice. Geomorphology 38, 109–124.

Bouchard, M.A., 1989a. Stratigraphie et sédimentation sous- et pro-glaciaire au lac du cratère du Nouveau-Québec. In: Bouchard, M.A. (Ed.), L'histoire naturelle du Cratère du Nouveau-Québec. Collection Environnement et Géologie, vol. 7. Université de Montréal, 225–235.

Bouchard, M.A., 1989b. Englaciation et glaciation du cratère du Nouveau-Québec, un modèle théorique. In: Bouchard, M.A. (Ed.), L'histoire naturelle du Cratère du

Nouveau-Québec. Collection Environnement et Géologie, vol. 7. Université de Montréal, 139–163.

Bouchard, M.A., 1989c. Introduction. In: Bouchard, M.A. (Ed.), L'histoire naturelle du Cratère du Nouveau-Québec. Collection Environnement et Géologie, vol. 7. Université de Montréal, 1–17.

Bouchard, M.A., Marcotte, C., 1986. Regional glacial dispersal patterns in Ungava, Nouveau-Québec. Geological Survey of Canada, Paper 86-1B, 295–304.

Bouchard, M.A., Marsan, B., 1989. Description générale du cratère du Nouveau-Québec. In: Bouchard, M.A. (Ed.), L'histoire naturelle du Cratère du Nouveau-Québec. Collection Environnement et Géologie, vol. 7. Université de Montréal, 37–58.

Bouchard, M.A., Saarnisto, M., 1989. Déglaciation et paléo-drainages du cratère du Nouveau-Québec. In: Bouchard, M.A. (Ed.), L'histoire naturelle du Cratère du Nouveau-Québec. Collection Environnement et Géologie, vol. 7. Université de Montréal, 165–189.

Bouchard, M.A., Marsan, B., Péloquin, S., Fortin, G., Saarnisto, M., Shilts, W.W., David, P.P., Fliszár, A., 1989a. Géologie glaciaire du cratère du Nouveau-Québec. In: Bouchard, M.A. (Ed.), L'histoire naturelle du Cratère du Nouveau-Québec. Collection Environnement et Géologie, vol. 7. Université de Montréal, 101–138.

Bouchard, M.A., Péloquin, S., Fortin, G., 1989b. L'échantillonnage des sédiments au fond du lac du cratère - 1986. In: Bouchard, M.A. (Ed.), L'histoire naturelle du Cratère du Nouveau-Québec. Collection Environnement et Géologie, vol. 7. Université de Montréal, 191–198.

Brigham-Grette, J., Melles, M., Minyuk, P., 2007. Overview and significance of a 250 ka paleoclimate record from El'gygytgyn Crater Lake, NE Russia. Journal of Paleolimnology 37, 1–16.

Bruneau, D., Gray, J.T., 1997. Ecoulements glaciaires et déglaciation hâtive (ca 11 ka BP) du nord-est de la péninsule d'Ungava, Québec, Canada. Canadian Journal of Earth Sciences 34, 1089–1100.

Clark, P.U., Licciardi, J.M., MacAyeal, D.R., Jenson, J.W., 1996. Numerical reconstruction of a soft-bedded Laurentide Ice Sheet during the last glacial maximum. Geology 24, 679–682.

Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W., McCabe, A.M., 2009. The Last Glacial Maximum. Science 325, 710-714.

Currie, K.L., 1965. The geology of the New Quebec crater. Canadian Journal of Earth Sciences 2, 141–160.

Daigneault, R.A., 1993. Quaternary geology. In: Geology of the eastern Cape Smith Belt: Parts of the Kangiqsujuaq, cratère du Nouveau-Québec, and lacs Nuvilik map areas, Québec. Comission géologique du Canada, mémoire 438, 96–99.

Daigneault, R.A., 1997. Géologie des formations en surface, région du cap de Nouvelle-France, du cratère du Nouveau-Québec et de Kangiqsujuaq, Québec-Territoires du Nord-Ouest. Comission géologique du Canada, carte 1863A.

Daigneault, R.A., 2008. Géologie du Quaternaire du nord de la péninsule d'Ungava, Québec. Comission géologique du Canada, bulletin 533, 115.

Daigneault, R.-A., Bouchard, M.A., 2004. Les écoulements et le transport glaciaires dans la partie septentrionale du Nunavik (Québec). Canadian Journal of Earth Sciences 41, 919–938.

de Vernal, A., Hillaire-Marcel, C., 2008. Natural variability of Greenland climate, vegetation, and ice volume during the past million years. Science 320, 1622–1625.

Dearing, J.A., 1997. Sedimentary indicators of lake-level chnages in the humid temperate zone: a critical review. Journal of Paleolimnology 18, 1–14.

Deslisle, C.E., Roy, L., 1989. L'Omble chevalier (Salvelinus alpinus) du lac du cratère du nouveau Québec.. In: Bouchard, M.A. (Ed.), L'histoire naturelle du Cratère du Nouveau-Québec. Collection Environnement et Géologie, vol. 7. Université de Montréal, 261–276.

Dyke, A.S., Prest, V.K., 1987. Late Wisconsinan and Holocene history of the Laurentide ice sheet. Géographie physique et Quaternaire 41, 237–263.

Dyke, A.S., Andrews, J.T., Clark, P.U., England, J.H., Miller, G.H., Shaw, J., Veillette, J.J., 2002. The Laurentide and Innuitian ice sheets during the last glacial maximum. Quaternary Science Reviews 21, 9–31.

Evans, D.J.A. (Ed.), 2003. Glacial landsystems. Arnold Publisher, London. 532pp.

Evans, D.J.A., Young, N.J.P., Ó Cofaigh, C., 2013. Glacial geomorphology of terrestrial-terminating fast flow lobes/ice stream margins in the southwest Laurentide Ice Sheet. Geomorphology.

Eyles, N., Mullins, H.T., 1997. Seismic-stratigraphy of Shuswap Lake, British Columbia, Canada. Sedimentary Geology 109, 283–303.

Girard-Cloutier, A.-M., 2011. Reconstitution paléobotanique et paléoclimatique en Ungava: analyse pollinique des sédiments du Cratère des Pingualuit. M.Sc thesis, Université Laval, Département de Géographie, 68 pp.

Gravenor, C.P., Kupsch, W.O., 1959. Ice-disintegration features in western Canada. Journal of Geology 67, 48–64.

Gray, J.T., 2001. Patterns of ice flow and deglaciation chronology for southern coastal margins of Hudson Strait and Ungava Bay. In: MacLean, B.S. (Ed.), Marine Geology of Hudson Strait and Ungava Bay, Eastern Arctic Canada: Late Quaternary Sediments, Depositional Environments, and Late Glaciale-deglacial History Derived from Marine and Terrestrial Studies. Geological Survey of Canada Bulletin, 31–55.

Gray, J.T., Lauriol, B., 1985. Dynamics of the Late Wisconsin Ice Sheet in the Ungava Peninsula interpreted from geomorphological evidence. Arctic and Alpine Research 17, 289–310.

Grieve, R.A.F., Bottomley, G., Guilbault, J.-P., Bouchard, M.A., Saarnisto, M., 1990. Diatoms and arcellaceans from Lac du Cratère du Nouveau-Québec, Ungava, Québec, Canada. Canadian Journal of Botany 68, 1187–1200.

Grönlund, T., Lortie, R.B., Bouchard, M.A., Robertson, P.B., Orth, C.J., Attrep, M., 1991. Impact melt rocks from New Quebec crater, Quebec, Canada. Meteoritics 26, 31–39.

Guyard, H., St-Onge, G., Pienitz, R., Francus, P., Zolitschka, B., Clarke, G.K.C., Hausmann, S., Salonen, V.-P., Lajeunesse, P., Ledoux, G., 2011. New insights into Late Pleistocene glacial and postglacial history of northernmost Ungava (Canada) from Pingualuit Crater Lake sediments. Quaternary Science Reviews 30, 3892–3907.

Hakanson, L., 1977. The influence of wind, fetch and water depth on the distribution of sediments in Lake Vanem, Sweden. Canadian Journal of Earth Sciences 14, 397–412.

Helmke, J.P., Schulz, M., Bauch, H.A., 2002. Sediment-color record from the Northeast Atlantic reveals patterns of millennial-scale climate variability during the past 500,000 years. Quaternary Research 57, 49–57.

Hilton, J., 1985. A conceptual framework for predicting the occurrence of sediment focusing and sediment redistribution in small lakes. Limnology and Oceanography 30, 1131–1143.

Johnson, M.D., Mickelson, D.M., Clayton, L., Attig, J.W., 1995. Composition and genesis of glacial hummocks, western Wisconsin, USA. Boreas 24, 97–116.

Lajeunesse, P., 2008. Early Holocene deglaciation of the eastern coast of Hudson Bay. Geomorphology 99, 341–352.

Lauriol, B., Gray, J.T., 1987. The decay and disappearance of the late Wisconsin ice sheet in the Ungava Peninsula, northern Québec, Canada. Arctic and Alpine Research 19, 109–126.

Ledoux, G., Lajeunesse, P., Philibert, G., Sinkunas, B., Guyard, H., St-Onge, G., Hausmann, S., Pienitz, R., 2011. Morpho-stratigraphy of Pingualuit Crater Lake, Ungava Peninsula, Nunavik. 41th Arctic Workshop. Montréal, Canada, p. 179.

Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic D18O records. Paleoceanography 20, PA 1003.

Luoto, T.P., Salonen, V.-P., Larocque-Tobler, I., Pienitz, R., Hausmann, S., Guyard, H., St-Onge, G., 2013. Pro-and postglacial invertebrate communities of Pingualuit Crater Lake, Nunavik (Canada), and their paleoenvironmental implications. Freshwater Science 32, 951–963.

Marshall, S.J., James, J.T.S., Clarke, G.K.C., 2002. North American ice sheet reconstructions at the last glacial maximum. Quaternary Science Reviews 21, 175–192.

Melles, M., Brigham-Grette, J., Minyuk, P.S., Nowaczyk, N.R., Wennrich, V., DeConto, R.M., Anderson, P.M., Andreev, A.A., Coletti, A., Cook, T.L., Haltia-Hovi, E., Kukkonen M., Lozhkin, A.V., Rosén, P., Tarasov, P., Vogel, H., Wagner, B., 2012. 2.8 million years of Arctic climate change from Lake El'gygytgyn, NE Russia. Science 337, 315–320.

Mollard, J.D., 2000. Ice-shaped ring-forms in Western Canada: their airphoto expressions and manifold polygenetic origins. Quaternary International 68, 187–198.

Monecke, K., Anselmetti, F.S., Becker, A., Sturm, M., Giardini, D., 2004. The record of historic earthquakes in lake sediments of Central Switzerland. Tectonophysics 394, 21–40.

Moussawi, A., Tessier, G., 1989. L'épaisseur des sédiments au fond du Lac du Cratère du Nouveau-Québec: relevés géophysiques. In: Bouchard, M.A. (Ed.), L'histoire naturelle du Cratère du Nouveau-Québec. Collection Environnement et Géologie, vol. 7. Université de Montréal, 199–222.

Mulder, T., Cochonat, P., 1996. Classification of offshore mass movements. Journal of Sedimentary Research 66, 43–57.

Nolan, M., Brigham-Grette, j., 2007. Basic hydrology, limnology, and meteorology of modern Lake El'gygytgyn, Siberia. Journal of Paleolimnology 37, 17–35.

Normandeau, A., Lajeunesse, P., Philibert, G., 2013. Late-Quaternary morphostratigraphy of Lake St-Joseph (southeastern Canadian Shield): Evolution from a semi-enclosed glacimarine basin to a postglacial lake. Sedimentary Geology 295, 38–52.

Optech Inc. 2008. ILRIS-3D intelligent laser ranging and imaging systems [online]. Available from www.optech.ca/i3dtechoverview-ilris.htm.

Otto-Bliesner, B.P., Marshall, S.J., Overpeck, J.T., Miller, G.H., Hue, A., CAPE Last Interglacial Project members, 2006. Simulating Arctic climate warmth and icefield retreat in the Last Interglaciation. Science 311, 1751–1753.

Ouellet, M., Pagé, P., Bouchard, M.A., 1989. Quelques aspects limnologiques du lac du cratère du Nouveau-Québec, Ungava. In: Bouchard, M.A. (Ed.), L'histoire naturelle du Cratère du Nouveau-Québec. Collection Environnement et Géologie, vol. 7. Université de Montréal, 238–259.

Overpeck, J.T., Otto-Bliesner, B.P., Miller, G.H., Muhs, D.R., Alley, R.B., Kiehl, J.T., 2006. Paleoclimatic evidence for future ice-sheet instability and rapid sea-level rise. Science 331, 1747–1750.

Parizek, R.R., 1969. Glacial ice-contact rings and ridges. In: United States Contributions to Quaternary Research. Geological Society of America Special Papers 123, 49–102.

Pienitz, R., Douglas, M.S. V, Smol, J.P., 2004. Long-term environmental change in Arctic and Antarctic lakes. In: Pienitz, R., Douglas, M.S.V., Smol, J.P. (Eds.), Long-term Environmental Change in Arctic and Antarctic Lakes. Developments in Paleoenvironmental Research, vol. 8. Springer, Dordrecht.

Prest, V.K., 1975. Géologie du Quaternaire au Canada. In: Chap. XII de Géologie et ressources minérales du Canada. Commission géologique du Canada, Série de la géologie économique 1, 752–852.

Prior, D.B., Bornhold, B.D., Johns, M.W., 1984. Depositional characteristics of a submarine debris flow. The Journal of Geology 92, 707–727.

Richard, P.J.H., Larouche, A.C., Morasse, N., 1989. Études floristiques et paléo-phytogéographiques au Cratère du Nouveau-Québec.. In: Bouchard, M.A. (Ed.), L'histoire naturelle du Cratère du Nouveau-Québec. Collection Environnement et Géologie, vol. 7. Université de Montréal, 315–342.

Saulnier-Talbot, E., Pienitz, R., 2010. Postglacial chironomid assemblage succession in northernmost Ungava Peninsula, Canada. Journal of Quaternary Science 25, 203–213.

Schnellmann, M., Anselmetti, F., Giardini, D., McKenzie, J., 2005. Mass movement induced fold- and thrust-belt structures in unconsolidated sediments in Lake Lucerne (Switzerland). Sedimentology 52, 271–289.

Schnellmann, M., Anselmetti, F., Giardini, D., McKenzie, J., Ward, S.N., 2002. Prehistoric earthquake history revealed by lacustrine slump deposits. Geology 30, 1131–1134.

Speilhagen, R.F., Baumann, K.H., Erlenkeuser, H., Nowaczyk, N.R., Nørgaard-Pedersen, N., Vogt, C., Weiel, D., 2004. Arctic Ocean deep-sea record of northern Eurasian ice sheet history. Quaternary Science Reviews 23, 1455–1483.

Stalker, A.M., 1960. Ice-pressed drift forms and associated deposits in Alberta. Geological Survey of Canada Bulletin 57, 1–38.

Van Rensbergen, P., De Batist, M., Beck, C., Chapron, E., 1999. High-resolution seismic stratigraphy of glacial to interglacial fill of a deep glacigenic lake: Lake Le Bourget, Northwestern Alps, France. Sedimentary Geology 128, 99–129.

Zolitschka, B., Schäbitz, F., Lücke, A., Corbella, H., Ercolano, B., Fey, M., Haberzettl, T., Janssen, S., Maidana, N., Mayr, C., Ohlendorf, C., Oliva, G., Paez, M.M., Schleser, G.H., Soto, J., Tiberi, P., Wille, M., 2006. Crater lakes of the Pali Aike Volcanic Field as key sites for paleoclimatic and paleoecological reconstructions in southern Patagonia, Argentina. Journal of South American Earth Sciences 21, 294–309.

Zolitschka, B., Anselmetti, F., Ariztegui, D., Corbella, H., Francus, P., Lücke, A., Maidana, N., Ohlendorf, C., Schäbitz, F., Wastegard, S., 2013. Environment and climate of the last 51,000 years – new insights from the Potrok Aike maar lake sediment archive drilling project (PASADO). Quaternary Science Reviews 71, 1–12.