UNIVERSITÉ DU QUÉBEC À MONTRÉAL

ÉVOLUTION DU LAC GLACIAIRE OJIBWAY AU COURS DES PHASES TARDIVES DE LA DÉGLACIATION À PARTIR DES ENREGISTREMENTS GÉOMORPHOLOGIQUES ET SÉDIMENTAIRES DE L'ABITIBI ET DE LA JAMÉSIE (QUÉBEC ET ONTARIO)

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À mon grand-père.

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TABLES DES MATIÈRES

LISTE DES FIGURES x

LISTE DES TABLEAUX xix

LISTE DES SYMBOLES, UNITÉS ET ABRÉVIATIONS xx

RÉSUMÉ xxiii

ABSTRACT xxv

INTRODUCTION 27

0.1 Objectifs et approches méthodologiques 33

0.2 Contexte physiographique et géologique 34

0.3 Méthodologie 37

0.3.1 Géochronologie de l'inondation glaciolacustre Ojibway 37

0.3.2 Analyses compositionnelles et chronologie de séquences de varves Ojibway 40

0.3.3 Reconstruction des niveaux glaciolacustres et identification des phases Ojibway 42

CHAPITRE I
COSMOGENIC ^{10}BE DATING OF RAISED SHORELINES CONSTRAINS THE TIMING OF LAKE LEVELS IN THE EASTERN LAKE AGASSIZ-OJIBWAY BASIN 45

1.1 Introduction 47

1.2 History of Lake Ojibway stages 49

1.3 Geomorphic setting of Ojibway shorelines 52

1.4 Methods 53

1.5 Results 54

1.6 Discussion 56

1.6.1 The 9.9 ka ages and the chronology of lake levels 56
1.6.2 The 16 ka ages and the regional deglaciation 58

1.7 Conclusion 60

1.8 Supplementary material 69

CHAPITRE II
HIGH-RESOLUTION VARVE SEQUENCES DOCUMENT THE TIMING OF LATE-GLACIAL ICE READVANCE AND DRAINAGE EVENTS IN THE EASTERN LAKE AGASSIZ-OJIBWAY BASIN 76

2.1 Introduction 79

2.2 Physiographic setting and deglacial history of the Ojibway basin 83

2.3 Methods 85

2.3.1 Sites and sediment sampling 85
2.3.2 Varve counting and thickness measurements 85
2.3.3 Loss on ignition and grain-size analyses 86
2.3.4 Compositional analyses 87

2.4 Results 88

2.4.1 General physical and geochemical characteristics of varves 88
2.4.2 Matagami varve sequence 90
2.4.3 La Reine varve sequence 94
2.4.4 Varve thickness correlations 98

2.5 Discussion 101

2.5.1 The Matagami varve sequence 101
2.5.2 La Reine varve sequence 102
2.5.3 Timing of ice readvance, Connaught deposition and drainage events .. 108

2.6 Conclusions 111

CHAPITRE III
RECONSTRUCTING THE LAKE-LEVEL HISTORY OF THE EASTERN LAKE AGASSIZ-OJIBWAY BASIN USING A LIDAR-BASED INVENTORY OF SHORELINES 121

3.1 Introduction 123

3.2 Lake Ojibway background 126

3.3 Methods 130

3.3.1 Sources of shoreline data 130
3.3.2 Paleotopographic reconstruction and model vertical accuracy 130
3.3.3 GIS and lake level reconstruction 131

3.4 Results 132

3.4.1 Shoreline data set 132
3.4.2 Shoreline selection for lake level reconstructions 133

3.5 Discussion 135

3.5.1 High-elevation lake levels 136
3.5.2 Interval 1: the Kinojévis-type lake stage 136
3.5.3 Interval 2: the La Sarre lake stage 137
3.5.4 Interval 3: the Palmarolle lake stage 139
3.5.5 Paleogeographic implications 140

3.6 Conclusions 143

3.7 Supplementary material 156

CONCLUSIONS 159

REFERENCES 167

LISTE DES FIGURES

Figure Page

0.1 A) Carte schématique montrant l'étendue du Lac Agassiz-Ojibway et de l'inlandsis laurentidien dans le contexte de la déglaciation il y a ~8.6 cal ka BP (Dyke, 2004). L'encadré montre la localisation générale de la région à l'étude. B) Carte de la région à l'étude montrant la topographie du territoire dans les tons de gris (d'après le Modèle numérique de surface du Canada). Les éléments géomorphologiques principaux (moraines) dans le bassin sont représentés en orange d'après Veillette et al. (2003), Veillette et al. (2017b) et Fulton (1995). La limite atteinte par la Mer de Tyrrell est délimitée en vert (Dredge and Cowan, 1989; Vincent, 1989). Les lignes rouges délimitent les sous-bassins de drainage modernes situés au nord de la ligne de partage des eaux continentale entre les bassins du fleuve Saint-Laurent et de la Baie d'Hudson (surimpression pointillée noire). La flèche située le long de cette ligne de partage des eaux montre l'exutoire principal du Lac Ojibway vers le sud (Vincent and Hardy, 1979). Le soubassement rocheux de la région est majoritairement composé des roches ignées et métamorphiques du Bouclier canadien, à l'exception d'une zone au nord-ouest où des roches sédimentaires paléozoïques (trame de brique) et mésozoïques (trame pointillée) sont présentes (Wheeler et al., 1997). Les cercles montrent les cinq sites échantillonnés pour la datation par isotopes cosmogéniques des rivages érosifs glaciolacustres (Chapitre 1) et les carrés correspondent aux deux endroits où ont été prélevées des séquences de varves qui documentent les événements survenus durant les stades tardifs du Lac Ojibway (Chapitre 2). L'encadré noir montre la couverture LiDAR qui a été utilisée pour inventorier les rivages glaciolacustres Ojibway et mesurer précisément leur altitude afin d'identifier et reconstruire les niveaux et les différentes phases du lac (Chapitre 3). 36

1.1 A) Schematic extent of Lake Agassiz and Lake Ojibway in the context of the Laurentide Ice Sheet at ~8.5 cal yr BP (Dyke, 2004); location of the study area (red star). B) Study area and main physiographic features of the Ojibway basin in Ontario and Québec. Note that the red box covers the area shown in Fig. 1.3. Triangles show the location of the outlet system related to the main stages of Lake Ojibway (orange: Angliers; blue: early Kinojévis; white: late Kinojévis; after Vincent and Hardy, 1979). 62

1.2 Schematic representation of the main lake levels reported in the Lake Ojibway basin, with the corresponding uplift gradients (1: Veillette, 1994; 2: Vincent and Hardy, 1979; 3: Roy et al., 2011). Full and dotted horizontal lines represent well- and poorly-defined lake levels, respectively. The timing and duration of each lake level is unknown; elevations are approximate and based on a crude projection of these lake levels in the southern Lake Abitibi region. Time span for the lake comes from a varve chronology (4: Antevs, 1925; Breckenridge et al., 2012), while its termination is given by the chronology of meltwater discharges associated with the final lake drainage (5: Jennings et al., 2015). Shaded areas correspond to calibrated ages reported for the lake drainage (with 1σ error bars): pink is from marine sediment cores (Barber et al., 1999); orange is from continental sediment sequences (Roy et al., 2011). Red bar corresponds to the 8.2 ka event documented in the Greenland ice-core records (Rasmussen et al., 2006). The lower rectangles show proposed drainage pathways for meltwater overflow/discharges for the lake. 63

1.3 A) Location of the study area (red star) with respect to Lakes Agassiz and Ojibway and the Laurentide Ice Sheet margin at ~9.5 cal ka BP (Dyke, 2004). B) Digital elevation model showing the physiography of the study area. The low-lying areas (green colors) correspond to the flat-lying Ojibway clay plain, which is broken in places by hills (brown colors) where raised erosional shorelines of the Angliers lake level developed. Yellow lines show the isobases associated with the inclined water plane formed by the Angliers lake level (Veillette, 1994). White boxes show ^{10}Be ages and sample numbers (see Fig. 1.5; Table 1.1 and Supplementary Table 1.2 for details). The high-rise terrains to the south of Lake Abitibi mark the continental drainage divide that encompasses the Kinojévis River outlet system. The outlet at the time of the Angliers lake stage was located ~40 km to the south of the river identified by the white arrow (see Fig. 1.1 for location). 64

1.4 A) Schematic model showing the development of lakeshore erosional shorelines known as washing limits (see text for details). B) Photograph of Michel Lake site showing an oblique aerial view of wave-washed bedrock rim (tree-less areas with whitish colors) formed by the lakeshore erosion. Note the presence of a capping of untouched sediments that marks the upper limit reached by the wave erosion. C) Google Earth satellite image of the washing limit exposed at the Nissing Hills site. D) Example of a bedrock surface sampled for ^{10}Be surface exposure dating (Nissing Hills; rock saw width is 75 cm). Pictures of the three other sites sampled are showed in Supplementary Figure 1.7. 65

1.5 Probability density functions (PDF) plots for ^{10}Be surface exposure ages and associated uncertainties [68% (1σ) confidence interval in black; 2σ given in red and 3σ in green]. The blue vertical line denotes the arithmetic mean value of the age population; thin curves represent individual ages within 1-σ uncertainties (see Table 1.1 and Supplementary Table 1.2 for data). A) Distributions of all 15 ages obtained from 5 sites in this study. Note that the two oldest ages from Preissac Hill are considered as outliers (see text for details). B) PDF for the ages forming Group 1 seen in A. C) PDF for the older ages forming Group 2. D) PDF for the population of younger ages composed by the samples forming Group 1 and the younger age obtained at Preissac Hill. We used the arithmetic mean ages (blue line) of this PDFs as formation age of the Angliers lake level. Reported errors for these ages are calculated by quadratic propagation of the standard deviation of the respective arithmetic mean and the production rate error given by Young et al. (2013). 66

1.6 Schematic model showing the deglacial thinning mechanism proposed as an explanation for the small group of ^{10}Be ages centered at ~16 ka. A) Cross section depicting the ice cover during the full glacial conditions (ice thickness not to scale, unlike the underlying topography). B) As the deglaciation proceeds, significant ice-mass loss is thought to occur through surface melting, causing the high-elevation terrains to be exposed to subareal conditions and cosmic rays. C) Submersion by meltwater as the ice margin retreats north of the continental drainage divide. Several geological considerations indicate that this model cannot be retained (see discussion for details). 68

1.7 Google Earth images showing the erosional shorelines sampled at the East Deloge Hill, Joe Lake and Preissac Hill (see Fig. 1.2 for the two other sites). 70

1.8 Photographs showing general and detailed views of the erosional shorelines sampled at the East Deloge Hill site. 71

1.9 Photographs showing general and detailed views of the erosional shorelines sampled at the Joe Lake site. 72

1.10 Photographs showing general and detailed views of the erosional shorelines sampled at the Nissing Hills site. 73

1.11 Photographs showing general and detailed views of the erosional shorelines sampled at the Michel Lake site. 74

1.12 Photographs showing general and detailed views of the erosional shorelines sampled at the Preissac Hill site. 75

2.1 A) Schematic map showing the extent of Lake Agassiz-Ojibway and the Laurentide Ice Sheet at the time of the Cochrane readvance (orange arrows) (Dyke et al., 2003; Dyke, 2004). Pink star shows the general location of the study area. B) General map of the study area showing the location of the Matagami and La Reine varve sections (pink stars) and the main geomorphic (moraine) features in the basin (grey) (Fulton, 1995; Veillette et al., 2003; Veillette et al., 2017b). Other varve localities are also showed in pink, where diamonds refer to Antevs sites (Antevs, 1925; 1928); triangles correspond to localities where the Connaught sequence was originally described (Hughes, 1959; 1965); circles refer to other sites with Connaught varves were identified (Breckenridge et al., 2012); and squares correspond to the recently cored Frederick House Lake sequence (Greg Brooks, *pers. comm.*). The thick white line shows the southern limit of the Cochrane ice readvance (grounding line) and the white shaded areas correspond to the extent related surge deposits where an ice-rafted debris-rich layer (*gritty clay*) is present at the top of the Ojibway sequence (Boissonneau, 1966; Veillette and Pomares, 2003; Thibaudeau and Veillette, 2005; Paradis, 2007a; 2007b; Veillette, 2007a; 2007b; Veillette and Thibaudeau, 2007; Paradis et al., 2017; Veillette et al., 2017d). The limit of the Cochrane II ice extent is also presented (Hardy, 1976). Shorter thick white lines show the southward progression of the Cochrane ice front in Ontario (Breckenridge et al., 2012). The red line outlines the Tyrrell Sea limit (Dredge and Cowan, 1989; Vincent, 1989) The maroon line correspond to the present-day drainage divide separating the St. Lawrence River and the Hudson Bay watersheds. The white arrow along the divide corresponds to the late Kinojévis outlet with an elevation of 300 m (Vincent and Hardy, 1979). The area is underlain by igneous and metamorphic rocks of the Canadian Shield, except to the north, where Paleozoic and Mesozoic sedimentary rocks (brick pattern) are present (Wheeler et al., 1997). 114

2.2 Sample sites. A) Lake Matagami stratigraphic section, B) close view of this section and C) close view of the sampled varves. D) drainage varve in the region of La Reine (Daubois et al., 2014), E) close view of the drainage varve at the La Reine site, and F) close view of the sampled varves. 116

2.3 Particle size distribution for the Matagami varves are expressed as surface plots of grain-size data (Beierle et al., 2002) with the D50 or median (white dots) values. Varve thickness data (white line) are superimposed on the grain-size data. High-resolution RGB and CT-scan images are also shown along with the magnetic susceptibility (MS) and loss on ignition (LOI) data. High-resolution elemental ratios are shown by the blue lines. Note that the apparent lighter color of the summer layers upward from 1.87 cm is not linked to sedimentological changes, but to the sampling conditions of the sediments that were desiccated towards the top of the section. 117

2.4 Particle size distribution for the La Reine varves are expressed as surface plots of grain-size data (Beierle et al., 2002) with the D50 or median (white dots) values. Note that the color scale is the same as the one used in Fig.2.3. Varve thickness data (white line) are superimposed on the grain-size data. High-resolution RGB and CT-scan images are also shown along with the magnetic susceptibility (MS) and loss on ignition (LOI) data. High-resolution elemental ratios are shown by the blue lines. Red dashed boxes refer to the close-up views presented in Fig. 2.5. 1: Daubois et al. (2014); 2: Antevs (1925); 3: Hughes (1959; 1965) and 4: Breckenridge et al. (2012). 118

2.5 Close-up views of RGB and CT images for the two coarse sediment intervals present in the La Reine varve sequence. The coarse rhythmites forming the lower interval was interpreted as an unconformity while the silt bed at the top was documented as a drainage varve (Daubois et al., 2014). The D50 or median grain-size values are shown along the Zr/kcps and Ca/Sr high-resolution profile to document these two layers (see text for details). 119

2.6 Correlated varves thicknesses records related with the Lake Ojibway late-stages according to the varve number. Present study Lake Matagami data (green) and La Reine (red) compared with the Lake Matagami Series (yellow) from Hardy (1976), Site 138 and Temiskaming D series (maroon) from Antevs (1925; 1928), Twin Falls (orange) data from Hughes (1959; 1965), and late-stage sequences from Breckenridge et al. (2012) (dark blue) and Brooks (*pers. comm.*) (light blue). Modified from Breckenridge et al. (2012). 1: Breckenridge et al. (2012); 2: Daubois et al. (2014). 120

3.1 A) Schematic map showing the extent of Lake Agassiz-Ojibway and the Laurentide Ice Sheet during the last ~300 years of the lake's existence at the time of the Cochrane readvance (orange arrows) based on Dyke et al. (2003). Star shows the general location of the study area. B) General map of the study area showing the CDSM topography in shades of black. The LiDAR coverage is outlined in black where the elevation measurements on wave-cut scarps (small turquoise dots) and raised shorelines and lake limits are respectively symbolized by orange and red dots. The white dots refer to recent measurements (Roy et al., 2015) in the La Sarre area and the green ones to new field measurements presented in this study. The reds dots correspond to Vincent and Hardy (1979) shoreline data while the yellow ones correspond to maximum lake levels recorded at 145 sites by Veillette (1994) using photogrammetry and/or altimetry, including 25 sites compiled by Vincent and Hardy (1979), 33 sites from Veillette (1983; 1988) and 1 site from Prichonnet et al. (1984). The regional tilt axis of N 17°E is represented by the thick black line starting at Mattawa. The main geomorphic (moraine) features in the basin (orange) are depicted according to Veillette et al. (2003), Veillette et al. (2017b) and Fulton (1995). The thick white line shows the southern limit of the Cochrane ice readvances (grounding line) obtained from surficial geology maps (Boissonneau, 1966; Veillette and Pomares, 2003; Thibaudeau and Veillette, 2005; Paradis, 2007a; 2007b; Veillette, 2007a; 2007b; Veillette and Thibaudeau, 2007; Paradis et al., 2017; Veillette et al., 2017d) while the Cochrane II limit is mapped accordingly to Hardy (1976). The Tyrrell sea limit is outlined by a red line (Dredge and Cowan, 1989; Vincent, 1989). The elevation above sea level (asl) of the outlets associated with the Angliers (260 m), early Kinojévis (275 m) and late Kinojévis (300 m) levels of Lake Ojibway are also shown (Vincent and Hardy, 1979). A maroon line marks the present-day drainage divide of the St. Lawrence River and Hudson Bay watersheds. 146

3.2 Distance-elevation diagram on a 600 km transect along the regional tilt axis (N 17°E) showing all the previous shoreline measurements recorded in the Lake Barlow-Ojibway basin. The elevation of the outlets is indicated with black (previous work) and white (proposed) squares along with their respective elevations. Lake levels from previous studies are shown with gray lines (see text for details). The red rectangular box corresponds to the limits of the LiDAR coverage used in this study. 1: Vincent and Hardy (1979); 2: Veillette (1994) and 3: Roy et al. (2015). 148

3.3 Examples of raised shorelines in the Ojibway basin, A) and B) are wave-cut scarps in the soft clayey Ojibway lake bed in the La Sarre area; the one shown in A is the same as the one exposed the upper middle portion of Fig. 3.4 B; C) Boulder beach resulting from the erosion of thick till on the western flank of Mt. Plamondon measured in the study. 149

3.4 Close-up LiDAR views of Ojibway shorelines. A) Wave-cut scarps (turquoise) and numerous beaches (orange) along a major esker ridge located 42 km NE of Val-D'Or; B) Wave-cut scarps in the Lake Abitibi clay plain 7.5 km NNW of La Sarre; and C) Wave-cut scarps and beaches (orange) in an area located 42 km SSE of Lebel-sur-Quévillon. Note the well-defined lake-limit (black dashed line) indicated by the red dots that marks the contact with the fluted terrains (white arrow). 150

3.5 Close-up view of the Fig.3.2 red box. The selected 2139 LiDAR shoreline-elevation data points are divided between wave-cut scarps and raised beaches and are compared to the lake limit and the Angliers level. The minimum elevation reached by the Hudson Bay erratics at Mt. Plamondon is indicated by the black dot and dashed line (Veillette et al., 1991), the early (white square) and late Kinojévis outlets (black square) are also shown. 1: Vincent and Hardy (1979) and 2: Veillette (1994). 151

3.6 Histogram representing the population of 2139 LiDAR shoreline-elevation data on the 8.5 ka paleotopography. The interval 1 corresponds to the Kinojévis-type lake stage, interval 2 to the La Sarre lake stage and interval 3 to the Palmarolle lake stage. The lake levels defining each stage are highlighted in red (see text for details). 152

3.7 Lake levels associated with the 3 intervals shown in Fig. 3.6 where the black lines represent the trend of the associated shorelines. 154

3.8 Distance-elevation diagram including the new field measurements and the lake levels described in this study. 155

3.9 Reconstruction of the Kinojévis-type lake stage in the Lake Abitibi region. The white shaded areas correspond to the extent related to Cochrane readvances deposits where an ice-rafted debris-rich layer (*gritty clay*) is present at the top of the Ojibway sequence (Veillette and Pomares, 2003; Thibaudeau and Veillette, 2005; Paradis, 2007a; 2007b; Veillette, 2007a; 2007b; Veillette and Thibaudeau, 2007; Paradis et al., 2017; Veillette et al., 2017d). 156

3.10 Reconstruction of the La Sarre lake stage in the Lake Abitibi region. 157

3.11 Reconstruction of the Palmarolle lake stage in the Lake Abitibi region. ... 158

LISTE DES TABLEAUX

Tableau Page

1.1 Samples information and surface exposure ages. 67

1.2 Analytical and procedural data. 69

3.1 Elevation data and uplift gradients of the reconstructed lake levels. 153

LISTE DES SYMBOLES, UNITÉS ET ABRÉVIATIONS

3D	Tridimensionnel
asl	Above sea level
Be	Béryllium
BP	Before Present
C	Carbone
Ca	Calcium
cal	Calibrated
CDSM	Canadian Digital Surface Model
cps	Coup par seconde
CT	Computed Tomography
δ	Delta
D50	Diamètre médian
DGPS	Differential Global Positioning Systems
DTM	Digital Terrain Model
Fe	Fer

GIA	Glacial isostatic adjustment
GIS	Geographic information system
IRD	Ice-rafted debris
K	Potassium
ka	*kilo annum*, milliers d'années
kcps	kilocoups par seconde
kV	Kilovolt
LiDAR	Light Detection and RAnging
LIS	Laurentide Ice Sheet
LOI	Loss on ignition
mA	Milliampère
Mo	Molybdénium
MS	Magnetic susceptibility
O	Oxygène
OC	Organic matter content
PDF	Probability density functions
ppm	Parties par million
PSD	Particle size distribution
R	Coefficient de corrélation de Pearson

Rb	Rubidium
RGB	Red, green and blue
RMSE	Root mean square error
RSL	Relative sea level
Si	Silicium
Sr	Strontium
SRTM	Shuttle Radar Topographic Mission
Ti	Titanium
WCS	Wave-cut scarps
XRF	X-Ray fluorescence
Zr	Zirconium

RÉSUMÉ

La fonte de l'inlandsis laurentidien lors de la dernière glaciation a entraîné la formation de grands bassins glaciolacustres qui ont considérablement varié en superficie et en volume. Le Lac Ojibway a recouvert une portion importante du nord-est de l'Ontario et du nord-ouest du Québec et s'est joint durant les stades tardifs de la déglaciation au Lac Agassiz qui a occupé de vastes territoires plus à l'ouest. Le drainage abrupt de ce grand lac de barrage glaciaire dans l'Atlantique Nord est considéré comme le principal mécanisme responsable du déclenchement d'un refroidissement majeur de courte durée vers 8,2 cal ka BP, via l'injection massive d'eau de fonte qui aurait vraisemblablement affecté la circulation thermohaline. Cependant, l'évaluation de l'impact des décharges massives d'eau de fonte sur le système climatique requiert des contraintes fiables sur les changements de configuration de ces lacs, sur la chronologie de leurs principales phases, ainsi que sur les mécanismes glacio-dynamiques ayant mené à leurs drainages. Or, les séquences de rivages glaciolacustres enregistrant les variations de l'étendue et de la profondeur du Lac Ojibway au cours des derniers stades de la déglaciation demeurent peu documentées. Beaucoup d'incertitudes persistent quant au nombre de différents niveaux du lac dont la chronologie demeure largement non contrainte, de même que sur le rôle joué par la dynamique glaciaire sur l'évolution du lac et sur les étapes ayant mené à son drainage final. L'objectif principal de cette thèse est de raffiner la configuration et la chronologie de la séquence d'événements ayant influencé l'évolution du Lac Ojibway au cours des stades tardifs de la déglaciation à partir de l'étude détaillée des enregistrements géomorphologiques et sédimentaires dans le bassin Ojibway. Cet objectif est abordé à l'intérieur de trois chapitres qui forment le cœur de la thèse.

Le premier chapitre décrit l'utilisation de la datation par isotopes cosmogéniques (^{10}Be) sur des surfaces rocheuses délavées qui forment des rivages érosifs surélevés marquant la limite maximale atteinte par le Lac Ojibway. Cette approche novatrice vise à évaluer l'applicabilité de cette méthode pour dater d'anciens rivages glaciolacustres afin d'obtenir la première chronologie directe sur une phase majeure du lac. Les nouvelles données géochronologiques présentées dans cette étude permettent de contraindre le début de l'épisode glaciolacustre Ojibway à un stade précoce de la déglaciation régionale. De plus, ces résultats constituent une étape importante vers l'amélioration des reconstructions paléogéographiques décrivant l'évolution des lacs glaciaires, lesquelles seront éventuellement utilisées pour calculer

les volumes d'eau de fonte contenus dans ces bassins durant des intervalles spécifiques de la dernière déglaciation.

Le second chapitre présente l'étude détaillée de deux séries de varves du Lac Ojibway prélevées dans le nord-ouest du Québec qui documentent la dynamique glaciaire et les événements de drainage dans le bassin lors des stades tardifs du lac. Ces sections de varves ont été corrélées avec d'autres séquences régionales à partir de l'analyse de l'épaisseur des varves, combiné avec des données sédimentologiques et géochimiques à haute résolution. La chronologie varvaire indique que la première séquence prélevée aux abords du Lac Matagami enregistre une réavancée glaciaire majeure survenue ~310 ans avant le drainage final du Lac Ojibway, tandis que la seconde séquence provenant de la région du Lac Abitibi suggère la présence de deux événements de drainage distincts – incluant le drainage final du lac – séparés par 65 ans. Ces données indiquent que la dynamique glaciaire (réavancée de Cochrane) a joué un rôle important dans l'évolution et le drainage du lac. Ces résultats permettent aussi d'établir pour la première fois un lien entre les données du domaine continental et celles provenant des enregistrements marins, lesquelles sont communément utilisées pour documenter les événements associés au drainage final du Lac Agassiz-Ojibway.

Finalement, le troisième chapitre présente une reconstruction de l'évolution des niveaux dans le bassin oriental du Lac Agassiz-Ojibway basée sur un inventaire exhaustif de mesures d'altitude de rivages Ojibway cartographiés à partir d'un modèle numérique de terrain LiDAR. Cette reconstruction est assistée d'un modèle de relèvement isostatique qui permet de prendre en compte les effets du gauchissement sur la géométrie du bassin, facilitant ainsi l'identification de populations distinctes de rivages qui témoignent de phases glaciolacustres majeures. Cette étude documente trois phases de stabilité, lesquelles sont entrecoupées de deux abaissements majeurs du plan d'eau Ojibway. Ces données établissent une nouvelle séquence de rivages qui regroupe le niveau maximal atteint par le Lac Ojibway durant la phase Angliers, les niveaux intermédiaires et ceux de basses altitudes récemment documentés dans le bassin. Globalement, ces travaux soulignent la nécessité de réévaluer la connexion présumée entre le bassin Ojibway à l'est et celui du Lac Agassiz à l'ouest, ainsi que de la surface du plan d'eau utilisée dans les calculs de volumes d'eau de fonte associés au drainage final du Lac Agassiz-Ojibway.

Mots clés : inlandsis laurentidien, Lac Agassiz-Ojibway, Lac Ojibway, événement de 8,2 ka, dernière déglaciation, chronologie ^{10}Be, varves, réavancées glaciaires, événements de drainage, rivages, niveaux glaciolacustres, LiDAR.

ABSTRACT

The retreat of the Laurentide Ice Sheet (LIS) led to the development of vast meltwater reservoirs that varied greatly in areal extent and volume during the last deglaciation. Lake Ojibway occupied large portions of northeastern Ontario and northwestern Québec and shared a common water plane with Lake Agassiz in late deglacial time. The abrupt drainage of this large ice-contact lake in the North Atlantic Ocean is considered the main mechanism responsible for the trigger of a short-lived major cooling event around 8.2 cal ka BP, which occured through the massive injection of freshwater that impeded the thermohaline circulation. Evaluating the impact of such massive meltwater discharges on the climate system requires reliable constraints on changes in the configuration of these glacial lakes, on the chronology of the main lake phases and on the mechanisms that led to the final deglaciation of the south-central sector of the Laurentide Ice Sheet. However, the sequences of raised shorelines recording the variations in extent and depth of Lake Ojibway during the last stages of deglaciation remain poorly documented, as is the number and chronology of the different lake levels and lake-surface drawdowns. In addition, many uncertainties persist regarding the effect of the ice dynamic on the evolution of Lake Ojibway and on the sequence of events that led to the final drainage. The main objective of this thesis is to refine the configuration and chronology of the events that influenced the evolution of the lake during the late-stages of deglaciation through the detailed study of geomorphological and sedimentary records from the Ojibway basin. This objective is addressed in three chapters forming the core of the thesis.

The first chapter presents the application of cosmogenic dating (^{10}Be) on bedrock surfaces forming raised erosional shorelines marking the maximum level reached by Lake Ojibway during deglaciation. This novel approach aims at evaluating the applicability of this method to date former glacial lake shorelines, and to obtain the first direct chronology on a major phase of Lake Ojibway. The new geochronological constraints obtained place the initiation of the Ojibway glaciolacustrine inundation during the early stages of the regional deglaciation. This forms an important step towards the improvement of the temporal reconstructions documenting the evolution of these glacial lakes, which will ultimately be used to evaluate the volume of meltwater contained in these basins during specific time intervals of the last deglaciation.

The second chapter documents two varve sequences from northwestern Québec that record changes in ice sheet dynamic and drainage events in the basin during the late-stages of the deglaciation. These two sequences are correlated to the main regional varve chronology template based on varve thicknesses and the high-resolution compositional and geochemical data. The first sequence sampled along the Lake Matagami records the occurrence of a single major ice readvance that preceded by ~310 years the drainage of Lake Ojibway. The second sequence contains a series of varves from the Lake Abitibi basin that record two distinct drainage events that are separated by 65 years, including the final one. These data outline the major role played by the ice dynamics (Cochrane readvance) on the lake evolution and drainage. These results also provide for the first time a direct link between data from the continental domain and those from marine records that are commonly used to document events associated with the final drainage of Lake Agassiz-Ojibway.

Finally, the third chapter presents a reconstruction of the lake level evolution during the late-stages of Lake Agassiz-Ojibway based on an exhaustive inventory of elevation measurements obtained from the mapping of shorelines on a LiDAR digital terrain model. The reconstruction of the basin geometry comprises a glacial isostatic adjustment model in order to account for the effect of the glacial isostatic deformation; an approach that allows robust shoreline correlations and the recognition of distinct shoreline populations that mark stable lake levels. This study documents three stable phases associated with two major drawdowns of the lake surface in the Ojibway basin. These data outline a new sequence of Ojibway shorelines that regroups the maximum lake level reached by Lake Ojibway during the Angliers phase, the lake levels of intermediate elevation and those of low elevation that were recently documented. Overall, these results point to a reevaluation of the presumed connection between the eastern Ojibway basin and the Agassiz basin in the west, as well as the lake-surface area used in the calculations of the meltwater volumes associated with the final drainage of Lake Agassiz-Ojibway.

Keywords : Laurentide Ice Sheet, Lake Agassiz-Ojibway, Lake Ojibway, 8.2 ka event, last deglaciation, ^{10}Be chronology, varves, ice readvances, drainage events, shorelines, lake levels, LiDAR

INTRODUCTION

Les archives paléoclimatiques de la dernière déglaciation et du début de l'Holocène indiquent que le climat terrestre est caractérisé par une grande instabilité, marquée notamment par des oscillations de température de fortes amplitudes à des échelles de temps décennales à millénaires (Bond et al., 1997; Alley and Ágústsdóttir, 2005; Rohling and Palike, 2005). L'un des mécanismes souvent évoqué afin d'expliquer certains de ces changements climatiques abrupts implique des décharges massives d'eau douce dans l'Atlantique Nord, lesquelles auraient perturbé la circulation thermohaline qui joue un rôle clé dans la redistribution de vastes quantités de chaleur dans l'Hémisphère Nord (Clark et al., 2002).

Les variations de volume et de superficie de l'inlandsis laurentidien lors de la déglaciation sont considérées comme des facteurs déterminants dans cette variabilité du climat global. En effet, les changements de configuration de l'inlandsis ont permis des décharges abruptes d'eaux de fonte qui s'étaient accumulées dans d'immenses lacs de barrage glaciaire via l'ouverture soudaine de nouvelles voies de drainage vers l'Atlantique Nord et l'Océan Arctique (e.g., Clark et al., 2001; Teller et al., 2002; Teller and Leverington, 2004). Cette influence est illustrée par un épisode important de refroidissement survenu il y a ~8200 ans et qui a brusquement interrompu le réchauffement du climat qui avait permis l'amorce du retrait des grandes masses de glace continentales après le dernier maximum glaciaire (Alley et al., 1997). L'événement de 8.2 ka coïnciderait avec le drainage soudain d'un grand lac glaciaire formé par la coalescence du Lac Agassiz et du Lac Ojibway (Barber et al., 1999). Malgré l'apparence d'un accord entre ce mécanisme de forçage et la réponse du climat,

des interrogations demeurent quant à l'impact précis de cette décharge d'eau douce sur le système climatique (e.g., Clarke et al., 2004).

Les deux lacs ont évolué indépendamment à la marge sud de l'inlandsis laurentidien pour la majeure partie de la déglaciation, jusqu'à ce que le retrait graduel de la glace dans le nord de l'Ontario permette vraisemblablement leur coalescence pour former le Lac Agassiz-Ojibway. Ce vaste plan d'eau aurait alors inondé entièrement les terrains de basse altitude entre le Manitoba et le Québec (Thorleifson, 1996; Leverington et al., 2002a). Traditionnellement, les reconstructions paléogéographiques basées sur les archives sédimentaires et géomorphologiques continentales ont toujours montré que le Lac Agassiz-Ojibway se serait drainé d'un seul coup dans la mer postglaciaire de Tyrrell suite à l'effondrement soudain de la masse de glace en décrépitude au sud de la baie d'Hudson (e.g., Dyke and Prest, 1987). Cependant, de récentes modélisations paléohydrauliques indiquent plutôt que le lac pourrait s'être drainé lors de multiples décharges générées par l'ouverture et la fermeture soudaine de conduits sous-glaciaires à la base de la calotte (e.g., Clarke et al., 2003; Clarke et al., 2004). Même si ce modèle est soutenu par la présence d'éléments géomorphologiques sur le plancher de la baie d'Hudson (Josenhans and Zevenhuizen, 1990; Lajeunesse and St-Onge, 2008), de nombreuses incertitudes persistent quant au nombre et à la chronologie de ces débâcles, l'emplacement des voies de drainage et la dynamique de la marge glaciaire précédant le drainage du lac (e.g., Teller et al., 2002; Clarke et al., 2004; Roy et al., 2015).

À ce jour, l'hypothèse de multiples drainages du lac est principalement soutenue par les enregistrements sédimentaires marins à haute résolution de l'Atlantique Nord. En effet, ces données indiquent que cet intervalle de la déglaciation est ponctué de plusieurs décharges d'eau de fonte de volumes considérables, dont notamment deux événements majeurs autour du refroidissement de 8,2 ka (Ellison et al., 2006; Hillaire-Marcel et al., 2007; Kleiven et al., 2008; Jennings et al., 2015). Ces

injections massives d'eau douce sont également documentées dans les enregistrements à haute résolution du niveau marin relatif, qui montrent plusieurs hausses au cours de cette période (Hijma and Cohen, 2010; Li et al., 2012; Törnqvist and Hijma, 2012; Lawrence et al., 2016). Ces données suggèrent que le Lac Agassiz-Ojibway s'est drainé de façon séquentielle par l'entremise d'au moins deux décharges majeures, ce qui implique des abaissements significatifs du niveau du lac ainsi qu'une évolution très complexe durant les stades tardifs.

En milieu continental, la mise en lumière d'un tel scénario est plus complexe qu'en milieu marin étant donné l'absence de données géochronologiques directes due à l'environnement de déglaciation des moyennes et hautes latitudes, lequel est pratiquement dépourvu de matériel organique rendant l'utilisation de la datation au radiocarbone impraticable. Les enregistrements sédimentaires et géomorphologiques pertinents aux stades tardifs des lacs glaciaires Agassiz et Ojibway sont également encore très peu documentés, limités entre autres par un contexte physiographique défavorable au développement de rivages et par la présence d'un épais couvert forestier qui complique tant le recensement de formes de terrain que l'accès au territoire. Ainsi, le drainage séquentiel du lac a été initialement proposé sur la base de l'identification de quelques rivages épars marquant un niveau tardif ("Fidler") présent dans le nord du bassin Agassiz qui se projetterait sous l'altitude de l'exutoire (Kinojévis) du Lac Ojibway qui contrôlait présumément la surface du plan d'eau Agassiz-Ojibway (Klassen, 1983; Thorleifson, 1996). La signification de la phase Fidler demeure cependant très peu comprise, de même que son extension vers l'est dans le bassin Ojibway (Dyke, 2004). Conséquemment, les étapes ayant mené à la déglaciation finale et au drainage du Lac Agassiz-Ojibway ont jusqu'à présent été en grande partie articulées autour d'une reconstruction du Lac Ojibway (Vincent and Hardy, 1979), bien que cette dernière découle d'une étude régionale s'appuyant sur un nombre limité de données géologiques, notamment en ce qui à trait aux nombres de phases du lac, leur étendue et leur chronologie.

Dans le bassin du Lac Ojibway, les stades finaux de la déglaciation sont complexes, marqués par des réavancées de la marge glaciaire, ce qui suggère des modifications importantes de la configuration du bassin peu de temps avant le drainage du lac dans la Mer de Tyrrell (Hardy, 1976; 1982). Les réavancées de Cochrane ont notamment occupé de larges territoires et sont caractérisées par de nombreuses formes fuselées qui s'entrecoupent et par un apport marqué en carbonates détritiques dans les sédiments du bassin Ojibway (e.g., Veillette et al., 1991). Cependant, malgré des signatures géomorphologique et sédimentaire distinctes, le nombre et le *timing* de ces crues glaciaires demeurent mal connus. Certaines régions présentent des indices de une à trois réavancées glaciaires (Prest, 1970; Hardy, 1976; Veillette, 1994; Thorleifson, 1996), compliquant ainsi grandement la reconstruction de la géométrie du bassin (Veillette et al., 2017a) et les estimations du volume d'eau de fonte (Veillette, 1994).

D'ailleurs, le manque de contraintes sur la position de la marge glaciaire qui maintenait les eaux du Lac Agassiz-Ojibway lors de son drainage final propage des incertitudes significatives dans les reconstructions utilisées pour estimer le volume prédrainage. À cet effet, les estimations de ~230 000 km^3 (Veillette, 1994), ~200 000 km^3 (Barber et al., 1999) et de 163 000 km^3 (Leverington et al., 2002a) s'équivalent lorsqu'on considère ces incertitudes, puisqu'en déplaçant la marge de 1° de latitude (environ 111 km) vers le nord, le volume d'eau de fonte contenu dans le lac double, tandis qu'en déplaçant la marge de 1° de latitude vers le sud, le volume d'eau contenu diminue de plus de la moitié, et ce malgré l'utilisation d'outils GIS pour supporter ces reconstructions (Leverington et al., 2002a). De plus, la dernière de ces réavancées coïnciderait avec le drainage final du lac, mettant en lumière la possibilité que les fluctuations de la marge glaciaire dans le bassin soient à l'origine du drainage final du Lac Ojibway (Roy et al., 2011).

Des travaux récents dans le bassin de la Baie-James ont permis de montrer que l'abaissement final du Lac Ojibway a été précédé par des épisodes de drainage sous-glaciaire (Roy et al., 2011). À cet endroit, les varves Ojibway sous-jacentes à une unité de drainage contiennent des ostracodes d'eau douce (*Candona* sp.) ainsi que des microfossiles marins (foraminifères). Ces derniers affichent des compositions en isotopes de l'oxygène ($\delta^{18}O$) fortement contrastées avec celles des ostracodes, suggérant des incursions des eaux de la Mer de Tyrrell dans le Lac Ojibway avant le drainage final et soulignant ainsi l'occurrence possible d'épisodes de drainage sous-glaciaires. La chronologie ^{14}C de l'unité de drainage suggère également que cet événement pourrait représenter le plus jeune des deux événements de drainage du lac documenté dans les enregistrements sédimentaires marins (e.g., Jennings et al., 2015). Ces résultats indiquent que le Lac Agassiz-Ojibway pourrait s'être drainé à quelques reprises à partir d'événements survenus principalement dans le bassin du Lac Ojibway.

La cartographie récente des formations en surface du NE de l'Ontario et du NO du Québec a également permis la reconnaissance de rivages de basses altitudes dans le secteur du Lac Abitibi (Thibaudeau and Veillette, 2005; Veillette et al., 2008). Des mesures d'altitude réalisées sur ces rivages ont soulevé la possibilité que des phases glaciolacustres tardives potentiellement associées à un drainage partiel du Lac Agassiz-Ojibway aient existé dans le bassin Ojibway (Roy et al., 2015). L'étendue de ces phases et leur place dans la séquence régionale de niveaux glaciolacustres Ojibway demeurent à ce jour non définies, de même que leur possible corrélation avec le niveau Fidler dans le bassin Agassiz. De plus, le sommet de la séquence sédimentaire du même secteur exhibe couramment une épaisse couche composée de silt grossier qui marque le drainage final du lac (Daubois et al., 2014). Cependant, cette unité n'est toujours pas incorporée dans la chronologie varvaire régionale (Antevs, 1925; Breckenridge et al., 2012), limitant ainsi la portée de ces nouvelles données dans les reconstructions paléogéographiques du Lac Ojibway.

Ces nouveaux éléments témoignent de la complexité des événements survenus au cours des stades finaux de la déglaciation, lesquels culminent avec le drainage final du Lac Agassiz-Ojibway. Ainsi, les scénarios qui envisagent le drainage complet du bassin Ojibway (~114 000 km^3; Veillette, 1994; Leverington et al., 2002), suivi du drainage des 49 900 km^3 restants dans le bassin Agassiz, doivent être contraints de manière adéquate à la lumière des données récentes en provenance du bassin Ojibway. Ceci souligne également les nombreuses incertitudes qui persistent dans les reconstructions paléogéographiques (Thorleifson, 1996) et paléobathymétriques (Leverington et al., 2002a), propagées par la suite dans les simulations paléoclimatiques (e.g., Gregoire et al., 2012; Matero et al., 2017). Ainsi, les données de terrain et les enregistrements géologiques corroborant l'hypothèse d'un drainage multiple du Lac Agassiz-Ojibway sont encore relativement limités et l'histoire des stades tardifs dans les bassins Agassiz et Ojibway, incluant leur coalescence présumée, demeure peu documentée. Un des aspects essentiels dans l'amélioration des reconstructions paléogéographiques couvrant l'évolution des lacs glaciaires durant cet intervalle de la déglaciation consiste à poursuivre l'étude des enregistrements sédimentaires et géomorphologiques afin de combler le manque de connaissances entourant les stades tardifs du Lac Ojibway et de la déglaciation finale. L'évaluation de l'impact climatique précis de tels forçages en eau douce qui ont perturbé la circulation thermohaline – en altérant la salinité des eaux de surface de l'Atlantique Nord – requiert des contraintes fiables sur les volumes d'eau de fonte impliqués lors du drainage final du Lac Agassiz-Ojibway et sur les taux de transfert de cette eau douce vers l'océan. Ce type de données s'avère critique dans le contexte actuel d'un réchauffement climatique rapide et de fonte accélérée des glaces du Groenland.

0.1 Objectifs et approches méthodologiques

Les enregistrements géomorphologiques et sédimentaires du NE de l'Ontario et du NO du Québec présentent une occasion unique de documenter les mécanismes qui ont contrôlé l'évolution du Lac Ojibway. En effet, leur étude a le potentiel d'améliorer notre compréhension des événements entourant la disparition du lac et ainsi préciser l'impact de son drainage sur le climat du début de l'Holocène. L'objectif principal des recherches de cette thèse est de déterminer le nombre et la chronologie des phases glaciolacustres du Lac Ojibway, ainsi que de documenter les événements tardifs comme les drainages et les réavancées glaciaires survenus dans le bassin afin de raffiner les reconstructions paléogéographiques couvrant l'évolution de ce lac de barrage glaciaire. Spécifiquement, cet objectif est divisé en trois sous objectifs :

1) Fournir des données chronologiques permettant de contraindre la séquence des niveaux glaciolacustres Ojibway afin de cadrer l'évolution du lac dans le contexte global de la dernière déglaciation;

2) Documenter la composition de séquences de varves Ojibway pour raffiner la chronologie des événements tardifs (réavancées glaciaires, drainages) dans le bassin;

3) Présenter un inventaire exhaustif des rivages glaciolacustres dans le bassin Ojibway dans le but de reconstruire les variations de niveaux et les étendues des différentes phases du lac.

Pour répondre à ces sous-objectifs, cette recherche a été menée en trois étapes qui correspondent à autant de chapitres de cette thèse. Le premier chapitre présente la datation ^{10}Be qui a été appliquée à des surfaces d'érosion littorales marquant la limite maximale atteinte durant la phase initiale du lac afin d'obtenir les premières

contraintes chronologiques directes sur l'inondation Ojibway. Dans le second chapitre, l'étude à haute résolution de la composition et de l'épaisseur des varves de deux séquences distinctes ainsi que leur corrélation avec d'autres séquences régionales sont présentées. Cette étude permet de raffiner la chronologie des réavancées glaciaires et des événements de drainage s'étant produits à l'échelle du bassin durant les stades tardifs du Lac Ojibway. Finalement, le troisième chapitre présente une reconstruction de l'évolution des niveaux du Lac Ojibway par l'entremise d'un système d'information géographique (SIG) intégrant un inventaire exhaustif de rivages Ojibway cartographiés à partir d'un modèle numérique de terrain LiDAR. Les mesures d'altitude obtenues ont été traitées pour inclure les effets du gauchissement tels que prédits par un modèle de relèvement isostatique, ce qui permet d'identifier des phases distinctes durant les stades finaux du lac.

Chacun des trois chapitres est présenté sous forme d'article. Le premier article (Chapitre 1) s'intitule "*Cosmogenic ^{10}Be dating of raised shorelines constrains the timing of lake levels in the eastern Lake Agassiz-Ojibway basin*" et a été publié en juillet 2017 dans la revue *Quaternary Research*. Le second article (Chapitre 2), "*High-resolution varve sequences document the timing of late-glacial ice readvance and drainage events in the eastern Lake Agassiz-Ojibway basin*", a été soumis en décembre 2018 à la revue *Quaternary Science Reviews*. Finalement, le troisième article (Chapitre 3) "*Reconstructing the lake-level history of the eastern Lake Agassiz-Ojibway basin using a LiDAR-based inventory of shorelines*" sera soumis à la revue *Geological Society of America Bulletin*.

0.2 Contexte physiographique et géologique

Durant la majeure partie de l'existence du Lac Ojibway, les surplus d'eau de fonte ont été évacués vers le sud, via la rivière des Outaouais vers le fleuve Saint-Laurent, par un exutoire situé le long de la ligne de partage des eaux continentales qui

a progressé vers le nord au fil du temps en raison du rebond postglaciaire (Fig. 0.1) (e.g., Vincent and Hardy, 1979). La physiographie du bassin Ojibway est caractérisée par une plaine argileuse légèrement vallonnée, dont l'altitude varie entre 290 et 320 m *asl* (above sea level), et qui est transpercée par endroits par des collines rocheuses et des crêtes d'eskers. Le principal élément géomorphologique relié à la dernière déglaciation consiste en un complexe fluvio-glaciaire interprété comme une moraine interlobaire – la moraine d'Harricana – orientée dans un axe nord-sud (Fig. 0.1) (Hardy, 1976; Veillette, 1986). La partie nord du bassin Ojibway a été submergée par les eaux postglaciaires de la Mer de Tyrrell qui a atteint l'altitude de 180 m *asl* à l'ouest et 270 m *asl* à l'est de la Baie-James. L'incursion marine a considérablement érodé, remanié et recouvert les sédiments Ojibway, de même que les accumulations marginales et autres formes de relief de la déglaciation.

La géologie du substrat rocheux du bassin Ojibway est dominée pas les roches métavolcaniques et métasédimentaires de la ceinture de roches vertes de l'Abitibi, ainsi que par les lithologies plutoniques et gneissiques felsiques qui composent le cœur de la sous-province de l'Abitibi, elle-même incluse dans la province archéenne du Supérieur (MERQ-OGS, 1984; Ayer and Chartrand, 2011). La partie nord du bassin repose sur des roches calcaires et dolomitiques paléozoïques de la plateforme sédimentaire de la baie d'Hudson (Fig. 0.1) (Telford and Long, 1986). Finalement, des dépôts de lignite mal consolidés et des sables siliceux blancs du Crétacé inférieur sont également présents dans le bassin de la rivière Moose (Fig. 0.1) (Try, 1984; Telford and Long, 1991; Long, 2000).

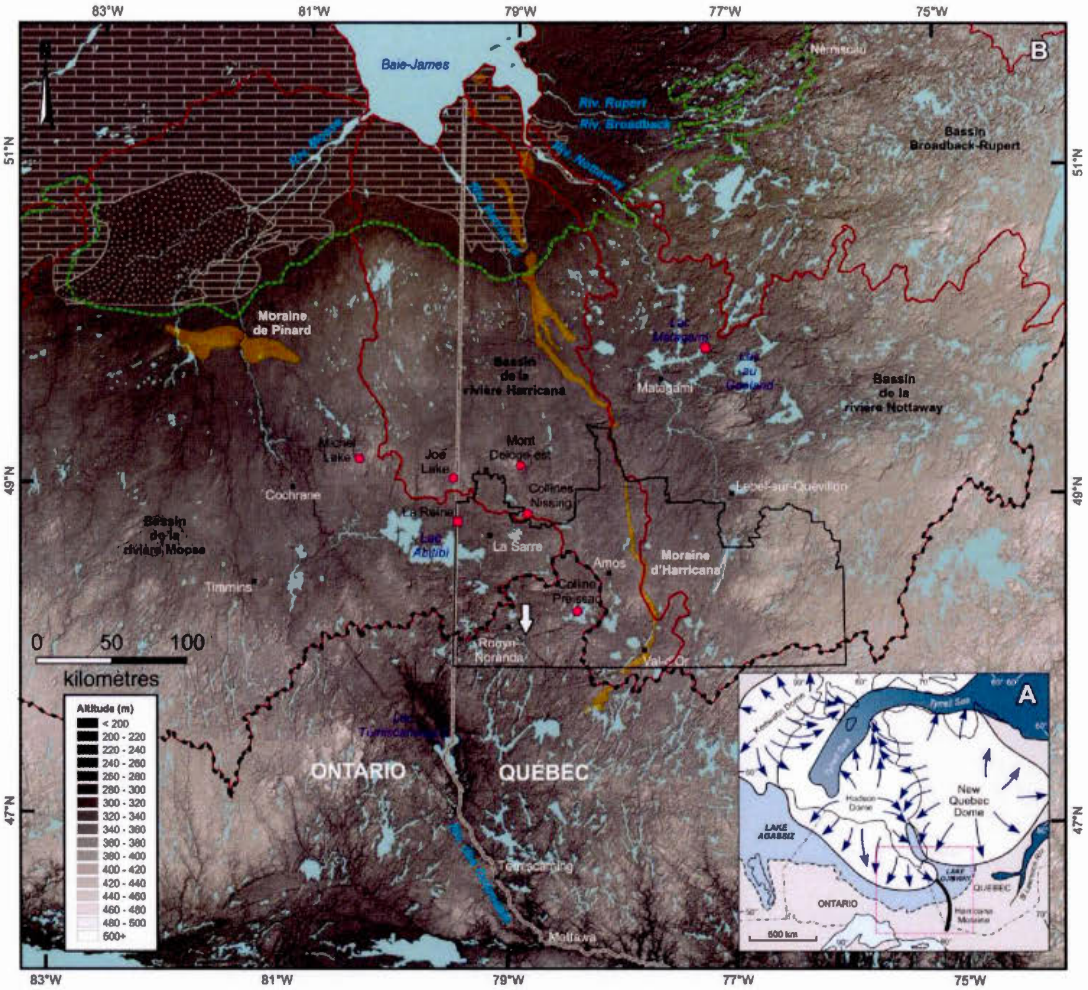

Figure 0.1 A) Carte schématique montrant l'étendue du Lac Agassiz-Ojibway et de l'inlandsis laurentidien dans le contexte de la déglaciation il y a ~8.6 cal ka BP (Dyke, 2004). L'encadré montre la localisation générale de la région à l'étude. **B)** Carte de la région à l'étude montrant la topographie du territoire dans les tons de gris (d'après le Modèle numérique de surface du Canada). Les éléments géomorphologiques principaux (moraines) dans le bassin sont représentés en orange d'après Veillette et al. (2003), Veillette et al. (2017b) et Fulton (1995). La limite atteinte par la Mer de Tyrrell est délimitée en vert (Dredge and Cowan, 1989; Vincent, 1989). Les lignes rouges délimitent les sous-bassins de drainage modernes situés au nord de la ligne de partage des eaux continentale entre les bassins du fleuve Saint-Laurent et de la Baie d'Hudson (surimpression pointillée noire). La flèche située le long de cette ligne de partage des eaux montre l'exutoire principal du Lac Ojibway vers le sud (Vincent and Hardy, 1979). **(page suivante)**

Figure 0.1 (suite) Le soubassement rocheux de la région est majoritairement composé des roches ignées et métamorphiques du Bouclier canadien, à l'exception d'une zone au nord-ouest où des roches sédimentaires paléozoïques (trame de brique) et mésozoïques (trame pointillée) sont présentes (Wheeler et al., 1997). Les cercles montrent les cinq sites échantillonnés pour la datation par isotopes cosmogéniques des rivages érosifs glaciolacustres (Chapitre 1) et les carrés correspondent aux deux endroits où ont été prélevées des séquences de varves qui documentent les événements survenus durant les stades tardifs du Lac Ojibway (Chapitre 2). L'encadré noir montre la couverture LiDAR qui a été utilisée pour inventorier les rivages glaciolacustres Ojibway et mesurer précisément leur altitude afin d'identifier et reconstruire les niveaux et les différentes phases du lac (Chapitre 3).

0.3 Méthodologie

0.3.1 Géochronologie de l'inondation glaciolacustre Ojibway

En milieu terrestre, les principales contraintes chronologiques de l'inondation Ojibway et des positions attenantes de la marge glaciaire lors de son retrait reposent principalement sur des âges minimaux ^{14}C fournis par la datation des macrorestes terricoles présents à la base des sédiments lacustres postglaciaires accumulés au fond de petits lacs situés au-delà de la limite de submersion glaciolacustre. Cependant, de tels sites sont relativement dispersés et peu abondants, en plus d'être pour la plupart situés à la périphérie sud du bassin Ojibway (Veillette, 1988; Richard et al., 1989). Ces chronologies ^{14}C seraient également sujettes à des décalages de l'ordre de quelques centaines d'années concernant la disparition de la glace (Ullman et al., 2016). À cela s'ajoute que les archives sédimentaires (varves et dépôts littoraux) qui se rapportent directement à l'épisode glaciolacustre Ojibway sont en grande partie dépourvues de matériel organique datable, qui est de surcroit sujet à une contamination par des sources de carbone inorganique ancien lorsque présent dans le sédiment (Veillette, 1988; Stroup et al., 2013; Daubois et al., 2014).

De plus, les sédiments formant les dépôts littoraux s'avèrent souvent être trop grossiers pour l'utilisation de la luminescence optique (OSL; *optically stimulated luminescence*). Conséquemment, aucune chronologie directe n'existe sur des rivages Ojibway, ce qui ne permet pas de replacer de manière ferme la succession des niveaux glaciolacustres dans le cadre chronologique de la déglaciation. La durée d'existence du Lac Ojibway est donc actuellement contrainte par une chronologie varvaire (Antevs, 1925; Hughes, 1965; Hardy, 1976; Breckenridge et al., 2012), puis replacée dans le cadre de la déglaciation par des âges ^{14}C issus de séquences sédimentaires continentales, marines et lacustres qui indiquent ensemble que l'épisode glaciolacustre a duré environ 2100 ans au cours de la période se situant entre 10 570 et 8 200-8 150 cal BP (Veillette, 1988; Lewis and Anderson, 1989; Richard et al., 1989; Barber et al., 1999; Ellison et al., 2006; Hillaire-Marcel et al., 2007; Kleiven et al., 2008).

Afin de surmonter les limitations liées aux autres méthodes géochronologiques (e.g., ^{14}C et OSL), la datation d'exposition de surface par isotopes cosmogéniques semble tout à fait adéquate pour répondre à l'objectif d'obtenir des contraintes chronologiques directes sur des rivages Ojibway. En effet, cette méthode permet de déterminer le temps d'exposition d'un bloc ou d'une surface rocheuse à la surface de la Terre en mesurant la quantité de nucléides cosmogéniques produits *in situ* dans le matériel géologique au fil du temps, lesquels dérivent d'interactions entre des particules issues du flux cosmique secondaire avec des atomes constitutifs des minéraux des roches exposées en surface (Lal, 1991). Le nucléide cosmogénique utilisé dans cette thèse est le béryllium-10 (^{10}Be), principalement produit par spallation des atomes de ^{16}O présents au sein de la structure cristalline de minéraux tels que le quartz (SiO_2). De par sa grande demie-vie (1,52 million d'années; Gosse and Phillips, 2001), l'utilisation du ^{10}Be est éprouvée pour la datation de surfaces rocheuses ou de blocs afin de contraindre l'évolution des paysages des terrains englacés en lien avec les fluctuations glaciaires au cours du Quaternaire

(e.g., Schaefer et al., 2009; Briner et al., 2013; Corbett et al., 2013), ce qui constitue l'application la plus commune des nucléides cosmogéniques (Granger et al., 2013).

Cependant, des facteurs limitants sont à considérer avec l'utilisation de la datation par isotopes cosmogéniques. La possibilité que du ^{10}Be ait été produit dans la roche lors d'une exposition antérieure combinée à une érosion glaciaire limitée crée de « l'héritage » qui conduit à une surestimation de l'âge d'exposition. De plus, la possibilité que des processus plus récents à l'exposition de la surface rocheuse (e.g., voir Veillette, 1994) mènent à une sous-estimation de l'âge d'exposition doit être considérée dans les interprétations découlant de l'application de cette méthode.

L'approche novatrive proposée dans cette thèse vise à documenter la première application de la datation de durée d'exposition de surface par isotopes cosmogéniques sur des surfaces rocheuses formant des rivages érosifs glaciolacustres; i.e. des limites de délavages (*washing limits*), qui marquent la limite de submersion associée à la première phase (Angliers) du lac. Les surfaces d'érosion que constituent les *washing limits* du Lac Ojibway possèdent les caractéristiques recherchées afin d'appliquer cette méthode. Lors de leur formation, l'action des vagues a complètement lessivé la couverture sédimentaire glaciaire (till) sur les flancs de collines rocheuses qui formaient des îles dans le Lac Ojibway, permettant ainsi d'exposer aux rayons cosmiques les surfaces de roc fraîchement délavées. Les limites de délavage les mieux développées constituent des endroits perchés, peu végétalisés, ouverts et bien exposés aux éléments, ce qui permet de limiter au minimum les corrections dues aux effets du *shielding* (e.g., végétation, couvert nival). De par leur nature granitique, les roches qui forment la plupart des collines où se sont développées des limites de délavages sont idéales pour l'application de la datation d'exposition de surfaces par isotopes cosmogéniques. En effet, le quartz qui constitue le minéral cible pour ce type d'analyse y est relativement abondant. La présence de polis glaciaires sur les surfaces ciblées laisse supposer peu d'héritage dû à un minimum d'érosion glaciaire, en plus du

très faible niveau d'érosion postglaciaire, deux éléments essentiels pour l'application de cette méthode.

0.3.2 Analyses compositionnelles et chronologie de séquences de varves Ojibway

Afin d'améliorer la compréhension des événements liés aux réavancées de la marge glaciaire (e.g., Hardy, 1976) et aux événements de drainage survenus dans le bassin Ojibway durant les stades tardifs du lac (e.g., Roy et al., 2011), des séquences de varves ont été échantillonnées et leur composition documentée. Pour ce faire, ces séquences ont été prélevées en surface (sous le solum) à l'aide de gouttières métalliques insérées directement dans des sections fraîchement excavées et/ou nettoyées où sont exposées des séquences de varves non dérangées. Plusieurs gouttières ont été utilisées afin d'échantillonner suffisamment de sédiments pour les analyses sédimentologiques et géochimiques en s'assurant d'un chevauchement suffisant entre les différentes sections de varves comprises par chacune des gouttières.

Cette méthode d'échantillonnage a l'avantage de prévenir la compaction et la déformation du sédiment puisque les séquences prélevées ont été radiographiées à haute résolution (1 pixel = 600 μm) à l'aide d'un tomodensitomètre (CT-scan) afin de documenter les variations de densité et caractériser la structure du sédiment en 3D. Les images en tons de gris qui en résultent montrent normalement des alternances de couches, où celles de plus faible densité apparaissent dans les teintes pâles et celles de densité plus élevée dans les teintes foncées; ces dernières étant respectivement associées aux lits d'été et lits d'hiver des varves. Ces images mettent en lumière les variations subtiles entre les couches argileuses et silteuses (e.g., Boespflug et al., 1995), ce qui facilite l'identification des couplets de varves puisque ces dernières ont été comptées et mesurées afin d'être corrélées dans la principale chronologie varvaire Ojibway (Antevs, 1925; 1928) qui a récemment été mise à jour (Breckenridge et al., 2012).

Afin de documenter de manière adéquate les événements enregistrés dans les séquences de varves échantillonnées, des analyses granulométriques et de perte au feu ont été effectuées à une résolution saisonnière (lit d'été/lit d'hiver). Les variations de la taille granulométrique des grains composant les varves renseignent notamment sur les fluctuations de la marge glaciaire, tandis que la perte au feu a été utilisée afin de déterminer les variations du contenu en matière organique du sédiment (e.g., Ball, 1964; Dean, 1974; Luke et al., 2009) qui peuvent également refléter l'activité glaciaire dans les lacs proglaciaires (Nesje and Dahl, 2001). Aussi, la susceptibilité magnétique – qui reflète principalement la composition, la concentration et la forme/taille des minéraux magnétiques présents dans le sédiment (St-Onge et al., 2007) – a été mesurée afin de fournir de l'information supplémentaire sur la dynamique glaciaire, où des contrastes marqués indiquent des variations dans les sources sédimentaires et les mécanismes de dépôt (Stoner et al., 1996).

Les propriétés géochimiques du sédiment ont été également mesurées avec un scanneur ITRAX afin de documenter l'influx détritique et la provenance du sédiment. Ce dispositif permet d'obtenir de manière rapide, automatique et non destructive des enregistrements à haute résolution (submillimétrique) des variations relatives dans la composition du sédiment directement à partir des sédiments laminés (varves) non traités (Guyard et al., 2007). Plus spécifiquement, les éléments majeurs et traces détectés sont utilisés afin de documenter des contrastes compositionnels (subannuels) marqués associés à la dynamique glaciaire durant la déglaciation et/ou à des événements de drainage dans le bassin Ojibway. De par leur nature semi-quantitative, les données XRF (*X-Ray Fluorescence*) générées ont été normalisées en utilisant des ratios afin de minimiser les variations d'intensité détectées causées par les propriétés physiques des échantillons, telles la géométrie et la taille granulométrique des particules (Cuven et al., 2010), le contenu en matière organique (Löwemark et al., 2011) et la porosité/contenu en eau du sédiment (Tjallingii et al., 2007), qui

s'additionnent à l'effet de fermeture (*closed-sum*) généralement rencontré dans les analyses compositionnelles (Aitchison, 1986; Rollinson, 1993).

0.3.3 Reconstruction des niveaux glaciolacustres et identification des phases Ojibway

Peu d'études documentent l'évolution du Lac Ojibway durant la déglaciation. Cette situation est principalement due à la distribution éparse des rivages et des éléments géomorphologiques associés à travers le bassin, dont l'identification et les mesures directes d'altitude sont compliquées par un couvert forestier dense qui limite l'accès au territoire. Une étude régionale a présenté une synthèse des données de rivages qui ont été groupées en trois niveaux liés à autant de phases qui marquent possiblement des surfaces glaciolacustres stables: la phase Angliers, ainsi que celles du *early* et *late* Kinojévis (Vincent and Hardy, 1979). Chacune d'entre elles est associée à un niveau de submersion stable atteint par le Lac Ojibway, où la phase *late* Kinojévis marque la dernière surface de stabilité du Lac Ojibway avant son drainage final dans la Mer de Tyrrell il y a 8,205 (8,128-8,282; 1σ) cal ka BP (Roy et al., 2011). Des travaux ultérieurs ont fourni des mesures additionnelles sur le niveau maximal atteint par les eaux du lac, majoritairement obtenues par photogrammétrie sur des limites de délavage (*washing limits*) identifiées à partir de photos aériennes (Veillette, 1994). Ces données, conjuguées à des mesures d'altitude obtenues sur des erratiques paléozoïques délestés durant les stades tardifs du lac à l'intérieur de séquences littorales Ojibway, ont permis de raffiner le niveau *late* Kinojévis qui a par la suite été utilisé afin de fournir une première estimation du volume d'eau douce transféré dans la Mer de Tyrrell lors du drainage final du Lac Ojibway (Veillette, 1994).

Plus récemment, des mesures d'altitude réalisées à l'aide d'une utilisation combinée d'altimètres électroniques et d'un DGPS sur des rivages glaciolacustres situés à l'est du Lac Abitibi ont permis de documenter avec une précision verticale de

l'ordre du mètre une séquence de 2 niveaux glaciolacustres marqués par une série d'escarpements (terrasses) d'érosion glaciolacustre (*wave-cut scarps*) sculptés dans la plaine argileuse Ojibway. Le fait que ces niveaux se projettent sous l'exutoire *late* Kinojévis, qui évacuait vers le sud les surplus en eau de fonte avant le drainage final du Lac Ojibway dans la Mer de Tyrrell, témoigne d'un probable drainage séquentiel du lac, possiblement via des tunnels sous-glaciaires (Josenhans and Zevenhuizen, 1990; Lajeunesse and St-Onge, 2008; Roy et al., 2011). Toutefois, le territoire où ces 2 niveaux ont été documentés est retreint et leur extension à l'échelle du bassin Ojibway reste à confirmer.

La récente disponibilité de modèles numériques de terrain (MNT) LiDAR de très haute résolution (1 m/pixel) générés par le Ministère des Forêts, de la Faune et des Parcs (MFFP) à l'échelle 1:20 000 a permis de couvrir de manière continue un territoire de 28 741 km^2 en Abitibi (feuillets NTS 1:250 000 32C et D, avec des parties de 32E et F). Ce type de produit permet de s'affranchir de la principale limitation liée à la reconnaissance de plages soulevées Ojibway en représentant la surface terrestre au niveau du sol; i.e. sans le couvert forestier, qui en plus complique l'accès au territoire pour la prise de mesures directes d'altitude. Ainsi, avec une très grande résolution verticale (~0,3 m ou mieux dans les contextes physiographiques caractérisés par des terrains de faible pente avec couvert forestier dense) (Hodgson and Bresnahan, 2004; Iordan and Popescu, 2015), les MNT LiDAR ont permis à l'aide d'outils GIS l'extraction d'altitudes avec une plus grande précision que les mesures directes sur le terrain qui sont de l'ordre d'environ 1 m à >10 m; un avantage certain dans le cadre de reconstructions de niveaux glaciolacustres à l'échelle régionale.

Afin de supporter les reconstructions de niveaux, la paléotopographie du bassin Ojibway a été reconstruite en utilisant le Modèle numérique de surface du Canada (MNSC) assemblé pour les régions couvrant le bassin Ojbway entre les latitudes

46°N–56°N et les longitudes 72°W–90°W. La déformation du bassin liée au rebond postglaciaire différentiel a pour sa part été évaluée à partir des valeurs d'ajustements glacio-isostatiques proposées par le modèle ICE-6G (Peltier et al., 2015).

CHAPITRE I

COSMOGENIC ^{10}BE DATING OF RAISED SHORELINES CONSTRAINS THE TIMING OF LAKE LEVELS IN THE EASTERN LAKE AGASSIZ-OJIBWAY BASIN

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Contribution des auteurs:

P.M.G., M.R., J.V. et J.M.S. ont développé cette étude et prelevé les échantillons. J.M.S. a préparé les échantillons et procédé aux datations. P.M.G. a écrit l'article et préparé les figures. M.R., J.V. et J.M.S. ont participé à l'interprétation des données et contribué à la rédaction de la version finale de l'article.

Abstract

Surface exposure dating was applied to erosional shorelines associated with the Angliers lake level that marks an important stage of Lake Ojibway. The distribution of 15 ^{10}Be ages from five sites shows a main group (10 samples) of coherent ^{10}Be ages yielding a mean age of 9.9 ± 0.7 ka that assigns the development of this lake level to the early part of the Lake Ojibway history. A smaller group (3 samples) is part of a more scattered distribution of older ^{10}Be ages (with 2 outliers) that points to an inheritance of cosmogenic isotopes from a previous exposure, revealing an apparent mean age of 15.8 ± 0.9 ka that is incompatible with the Ojibway inundation and the regional deglaciation.

Our results provide the first direct ^{10}Be chronology on the sequence of lake levels in the Ojibway basin, which includes the lake stage presumably associated with the confluence and subsequent drainage of Lakes Agassiz and Ojibway. This study demonstrates the potential of this approach to date glacial lake shorelines and underlies the importance of obtaining additional chronological constraints on the Agassiz-Ojibway shoreline sequence to confidently assign a particular lake stage and/or lake level drawdown to a specific time interval of the deglaciation.

Keywords: Glacial Lake Ojibway, Lake Agassiz-Ojibway, meltwater volume, Last deglaciation, Laurentide Ice Sheet, geochronology, surface exposure dating.

1.1 Introduction

The decay of the Laurentide Ice Sheet (LIS) during the end of the last deglaciation led to large-scale releases of meltwater that accumulated over the isostatically-depressed terrain of the Canadian prairie in the west and the James Bay basin in the east, resulting in the formation of Lake Agassiz and Lake Ojibway, respectively (Fig. 1.1A) (Teller, 1987). These ice-dammed lakes evolved independently until the final stages of deglaciation when continued ice retreat presumably allowed their coalescence, giving rise to the so-called Lake Agassiz-Ojibway (Elson, 1967; Dyke and Prest, 1987; Leverington et al., 2002a; Teller et al., 2002; Dyke, 2004). Interest in the final stages of Lake Agassiz-Ojibway comes from its abrupt drainage into a climatic key region of the North Atlantic Ocean where the sudden and massive injection of meltwater likely slowed the meridional overturning circulation and triggered a major short-lived cold pulse around 8.2 ka (Alley et al., 1997; von Grafenstein et al., 1998; Barber et al., 1999; Kleiven et al., 2008). Assessing the impact of this freshwater forcing and the resulting feedbacks in the Earth's climate system requires reliable estimates of the meltwater volumes involved in the drainage, as well as geochronological constraints on this lake discharge. However, geomorphological (shoreline) records constraining the changes in areal extent and depth of Lake Agassiz and Lake Ojibway during their late-stages – including their northward expansion and subsequent confluence – are relatively rare and remain inadequately documented. The timing (and number) of the inferred lake stages is also still largely unconstrained due to the physiographic setting of these basins that does not favour the use of radiocarbon (^{14}C) dating or other geochronological methods (e.g., Thorleifson, 1996; Dyke, 2004).

The history of these glacial lakes is documented from complex sequences of raised shorelines and associated geomorphic features that record fluctuations in lake levels, which occurred in association with changes in basin configuration that were

largely controlled by the position and dynamic of the retreating ice margin (Upham, 1895; Johnston, 1946; Elson, 1967; Vincent and Hardy, 1979; Teller and Thorleifson, 1983; Smith and Fisher, 1993; Lewis et al., 1994; Veillette, 1994; Thorleifson, 1996; Teller and Leverington, 2004; Lewis et al., 2005; Fisher et al., 2009). Reconstructions of Lake Agassiz regroup the different lake levels reported into five main phases, the last of which comprising the coalescence and drainage of Lake Agassiz and Lake Ojibway (e.g., Thorleifson, 1996; Teller and Leverington, 2004). This last phase (named Ojibway), however, involves correlation of lake levels that are separated by several hundred of kms and that are based on shoreline records that are for the most part still inadequately constrained due to their sporadic occurrence and scattered distribution across remote and forested northern regions.

Our current comprehension of the final stages of Lakes Agassiz and Ojibway comes from the eastern (Ojibway) basin (Fig. 1.1B) where raised shorelines were used to define three lake stages (Fig. 1.2) (Hughes, 1959; Vincent and Hardy, 1979; Veillette, 1983; 1988; 1994). The Angliers lake stage represents the highest and best-defined lake level documented (Veillette, 1994), while the lower elevation early and late Kinojévis lake stages were defined by a lesser number of shorelines (Vincent and Hardy, 1979), which introduces substantial uncertainties on the configuration (elevation, extent) of the associated water planes and regional isobases. Nevertheless, in the absence of a better-defined lake level record, reconstructions have associated the lowest lake level – the late Kinojévis lake stage – with the time interval preceding the final drainage of the coalesced Lake Agassiz-Ojibway (c.f., at ~8.2 ka) (e.g., Leverington et al., 2002a; Teller et al., 2002; Teller and Leverington, 2004). However, the recent recognition of well-defined shorelines standing below the late Kinojévis lake level raises new questions on the timing of lake level changes in the Ojibway basin (Roy et al., 2015). The newly documented lake levels indicate the occurrence of additional (late) stages that point to a lake configuration characterized by a lower surface-elevation and restricted areal extent, which in turn has important implications

for the reconstructions of the volumes of meltwater discharges of the late deglacial interval. Overall, these different lake level reconstructions underlie the importance of having reliable geochronological constraints on the sequence of shorelines in order to properly place the associated lake levels and their attendant meltwater volumes into the chronological framework of the last deglaciation.

Here we apply ^{10}Be surface exposure dating to erosional shorelines associated with the Angliers lake stage in the Ojibway basin in order to evaluate whether this method can be used to date former lake levels and gain insights on the timing of the main stages of Lake Ojibway during the late deglaciation. The novel approach developed here has the potential to bring new (and direct) geochronological constraints on the complex sequences of raised shorelines forming glacial lake reconstructions and their attendant estimates of meltwater volumes, a set of constraints that is critically needed to assess the role of meltwater discharges in the late deglacial climate interval.

1.2 History of Lake Ojibway stages

Lake Ojibway developed due to the accumulation of meltwater between the height of land formed by the Hudson Bay–St. Lawrence River drainage divide to the south and the ice margin to the north (Coleman, 1909), which progressive retreat caused the lake to expand and form a large meltwater reservoir (Fig. 1.1A) (Leverington et al., 2002a; Dyke, 2004). Lake Ojibway was initially connected for a brief interval with glacial Lake Barlow, which had previously invaded the upper Ottawa River valley to the south of the divide (Vincent and Hardy, 1979; Veillette, 1994). Temporal reconstructions of the Ojibway submergence, and the attendant positions of the retreating ice-margin, are mainly based on minimum-limiting ^{14}C ages obtained from the first organic matter accumulated in small lakes present on high grounds that rose above the former lake limit. Such sites are relatively scattered

and not abundant, in addition to be located for the most part at the periphery (south) of the basin (Veillette, 1988; Richard et al., 1989). Sedimentary archives relating directly to Lake Ojibway are largely deprived of organic matter suitable for ^{14}C dating, and if present, the material is often prone to contamination by old carbon sources (Veillette, 1988; Stroup et al., 2013; Daubois et al., 2014). The time span of Lake Ojibway is currently constrained by a varve chronology (Antevs, 1925; Hughes, 1965; Hardy, 1976; Breckenridge et al., 2012) and ^{14}C ages from continental sediment sequences and marine and lake sediment cores (Veillette, 1988; Lewis and Anderson, 1989; Richard et al., 1989; Barber et al., 1999; Ellison et al., 2006; Hillaire-Marcel et al., 2007; Kleiven et al., 2008). Together, these studies indicate that the glaciolacustrine episode lasted for about 2100 years (varve record), being bracketed between 10,570 and 8,200-8,150 cal yr BP, where the timing of the lake termination may vary depending on the chronology used for the meltwater outburst(s) associated with the final drainage of Lake Agassiz-Ojibway into Hudson Bay (Fig. 1.2) (e.g., Jennings et al., 2015).

For most of the lake's existence, including its confluence with Lake Agassiz, meltwater overflow was controlled by a single outlet system located in the southern Ojibway basin (Fig. 1.1B). The elevation and position of a rocky sill forming this outlet varied through time due to the on-going glacial isostatic adjustment of the land, and the complex changes in outlet configuration apparently played a strong role on the development of lake levels in the Ojibway basin (Vincent and Hardy, 1979). The Ojibway lake level history has long been articulated around three lake stages that are attributed to periods of maximum submergence (Fig. 1.2) (Vincent and Hardy, 1979; Veillette, 1994). The Angliers stage, presumably the oldest, was controlled by an outlet standing at 260 m near the Des Quinze River, while the early and late Kinojévis stages are associated with the Kinojévis River outlet standing at 275 m and 300 m, respectively (Fig. 1.1B). The Kinojévis stages, however, are based on the correlation of relatively few shorelines that spread across a large area and were

primarily defined to outline the trend of shoreline development within the basin (Vincent and Hardy, 1979, p.14).

In spite of these uncertainties, regional isobases originally defined in the southern Lake Agassiz basin were subsequently modified and tentatively expanded at the scale of the entire Agassiz-Ojibway basin in paleogeographic reconstructions (Thorleifson, 1996). This approach led to the correlation of the Ponton lake level in the west with the late Kinojévis lake level in the east (Vincent and Hardy, 1979), thereby giving rise to the confluence of Lake Agassiz and Lake Ojibway (Thorleifson, 1996). This connection, although probable, is not supported by firm geomorphological data, but rather inferred by paleoecological data (Stewart and Lindsey, 1983), an early varve chronology (Satterly, 1937; Elson, 1967) and by ice margin histories that are broadly constrained for the time interval involved (c.f., Dyke, 2004). Nevertheless, extensive mapping in the Ojibway basin outlined several geological considerations and predictable relationships arguing for the existence of a stable water plane before the demise of the ice dam in Hudson Bay, which implied a pre-drainage lake surface controlled by an outlet standing at an elevation of ~300 m (i.e., Veillette, 1994), thus comparable to the one ascribed to the late Kinojévis stage in an earlier lake level reconstruction (Vincent and Hardy, 1979).

However, the recent documentation in the lowest parts of the Ojibway basin of post-late Kinojévis shorelines (Roy et al., 2015) provides evidence for significant changes in the configuration of the lake before its final drainage. These late-stage shorelines form two closely related lake levels projecting below the elevation of the main (Kinojévis) outlet (Fig. 1.2). These lake levels may be equivalent to similar low-elevation shorelines in the Agassiz basin (the Fidler beaches) that also lie below the Kinojévis outlet (Dredge, 1983; Klassen, 1983). The Fidler lake level is poorly understood and has been interpreted as evidence for a two-step drainage of Lake Agassiz-Ojibway involving separate (but closely spaced) discharges from the eastern

(Ojibway) and western (Agassiz) basins (Thorleifson, 1996; Leverington et al., 2002a; Teller et al., 2002). An alternative interpretation associates the low-elevation strandlines with subglacial drainage(s) across the ice dam in Hudson Bay (Klassen, 1983; Shoemaker, 1992), a mechanism that is now supported by glaciological modeling (Clarke et al., 2004) and geological data (Roy et al., 2011). Regardless of their origin, the presence of the newly defined (low-elevation) shorelines in the Ojibway basin implies substantial changes in the areal extent and depth of the lake across the entire Agassiz-Ojibway basin near the end of the deglaciation, with water planes potentially lying up to 10 to 17 m below the late Kinojévis lake level. Unlike previous models articulated around a single drawdown from a fairly elevated lake surface, these results argue for multi-step lake drainage involving lower lake levels (and thus smaller meltwater volumes). Although these results point to a complex history that is more compatible with marine records showing several outbursts of meltwater during the late deglacial interval (e.g., Jennings et al., 2015), the lack of geochronological constraints on the shoreline sequence defining these lake levels prevent the assignment of the associated lake stages with specific intervals of the late deglaciation.

1.3 Geomorphic setting of Ojibway shorelines

Reconstruction of Ojibway lake stages is complicated by the physiography of this basin, which forms a large clay plain averaging 310-320 m in elevation (e.g., Roy et al., 2015). This terrain is broken in places by topographic rises that lie for the most part below the maximum lake level reported (i.e., 460 m near Goéland Lake, ~250 km northeast from the study area; Fig. 1.1B; Veillette, 1994), thus leaving very few bedrock-core hills to record the development of high- and intermediate-elevation lake levels. For this reason, Ojibway lake stages were identified using the elevation of dispersed shorelines throughout the basin, in addition to ice-front reconstructions providing insights on the northern limit of the lake (e.g., Veillette, 1994).

All shorelines targeted in this study come from the Angliers lake level (Figs. 1.2; 1.3A), which was primarily documented from distinct erosional shorelines that are commonly present on bedrock knobs (hills) standing above the clay plain (Fig. 1.3B) (Veillette, 1994). During the lake inundation, these hills stood out as isolated islands where the littoral (wave) erosion caused the removal of the glacial sediment cover from the hill flanks, leaving narrow and sub-horizontal rims of bare bedrock that mark the former stable lake surface (Figs. 1.4; Supplementary Figure 1.7). Extensive photogrammetric measurements of these so-called washing limits yielded a statically significant large set of elevation data points that outlined a slightly tilted water plane, thereby constraining broad regional isobases (Veillette, 1994). This setting allows the sampling of this lake level with a high degree of confidence, while the bedrock forming these erosional shorelines is ideally suited for the application of ^{10}Be surface exposure dating.

1.4 Methods

We apply cosmogenic ^{10}Be dating to raised erosional shorelines belonging to the Angliers lake stage. The premise behind our approach is that once the sediment has been removed by lakeshore erosion and the lake surface has dropped – in response to a partial or complete drawdown – the newly uncovered (wave-washed) bedrock surface becomes exposed to cosmic rays, starting the cosmogenic ^{10}Be accumulation clock. As shown in Figure 1.4A, boulder beaches may be present in places in the basin, but these are primarily composed of small rounded boulders (25-40 cm in diameter) forming unstable surfaces, thereby precluding their use for ^{10}Be surface exposure dating. The erosional shorelines were sampled at 5 sites along the 405 m isobase to ensure the dating of the same (Angliers) lake surface. This particular isobase has the advantage to intersect several prominent hills within a reasonably restricted area (Fig. 1.3B). The sites were chosen by means of aerial photographs and satellite imagery (Google Earth and ArcGIS 10.3) to favor settings characterized by

sparse vegetation and a good exposition to the elements (wind). These sites were underlain by granitic or tonalitic lithologies rich in quartz, with slightly inclined and largely unweathered bedrock surfaces (Supplementary Figures 1.8-1.12). Most rock surfaces exhibited a well-preserved glacial polish, with striations and grooves still present, thereby indicating negligible erosion of the bedrock surfaces by the lakeshore processes. Lakeshore erosion was apparently limited to the removal of the sediment cover and did not affect the underlying bedrock.

Specifically, three samples of surface rock averaging 500g were collected at each site; the samples being separated by 10 to 15 m from each other along a given contour line (i.e., within the same elevation range). The samples were processed following standard procedures developed at the Lamont-Doherty Earth Observatory Cosmogenic Dating Laboratory (c.f., Schaefer et al., 2009) and $^{10}Be/^{9}Be$ ratios were determined at Lawrence Livermore National Laboratory (California, USA). Ages were calculated with version 2.2 of the CRONUS Earth online calculator, using the Baffin Bay/Arctic ^{10}Be production rate given in Young et al. (2013), which is similar in value to the North America production rate of Balco et al. (2009), and altitude and latitude scaling according to Lal (1991) and Stone (2000), referred to as 'Lm' scaling (Balco et al., 2008). ^{10}Be ages for individual sample are given within 1σ analytical errors (Supplementary Table 1.2). The exposure ages for the raised shorelines were calculated using the arithmetic mean of the individual samples from this landform. The error of the exposure age for this landform includes the standard deviation of this arithmetic mean and the error of the production rate given by Young et al. (2013).

1.5 Results

The ^{10}Be ages show analytical uncertainties of typically 2-3% (only two samples yielded a >4% 1σ error; Table 1.1). Total ^{10}Be blank corrections were below 5,000 atoms, boron corrections were below 0.5%, thus the total background

corrections for the samples (300,000 – 1,500,000 atoms ^{10}Be total) were smaller than 2%. With the exception of one site (Preissac Hill), the ^{10}Be concentrations of the samples dated within each washing limit (i.e., at each site) show a remarkable internal consistency (Supplementary Table 1.2). When plotted together, the 15 samples dated show a distribution of ^{10}Be ages falling into two groups (Fig. 1.5A). The first group is formed by samples from three sites (Joe Lake, Nissing Hills and East Deloge Hill; n=9) showing ages ranging from ~9000 to 10,300 yr, with one sample being slightly older (11,100 ± 500 yr) (Fig. 1.5B). At each of these three sites, the scatter of ages varies between ~1,000 and 1,500 yr (Table 1.1). The second group is represented by one site (Michel Lake; n=3) where ages range from ~15,200 to 16,800 yr (Fig. 1.5C), for an age spread of ~1,600 yr (Table 1.1). Finally, one last site (Preissac Hill; n=3) shows a distinctively larger age scatter (4,300 yr), with ages of 10,600 ± 500 yr, 13,600 ± 300 yr, and 15,000 ± 500 yr (Fig. 1.5A; Table 1.1).

The main group of ages ranging from ~ 9,000 to 11,100 yr is consistent with previous time span estimates presented for Lake Ojibway, which range from ~10,600 and 8,200 cal yr BP according to varve and marine sediment records (e.g., Breckenridge et al., 2012; Jennings et al., 2015). Conversely, the older ages forming the second group, which range between ~15,200 to 16,800 yr, are incompatible with the history of Lake Ojibway and are difficult to reconcile with our current understanding of the regional deglaciation.

The large scatter of ^{10}Be ages documented at Preissac Hill seems to underlie a complication with the application of surface exposure dating at this site. This age scatter may be explained by a slight but measureable inheritance of cosmogenic isotopes from previous exposure, which has not been entirely removed by the subsequent glacial erosion of the bedrock surfaces dated. Within this context, the youngest ^{10}Be age at Preissac Hill could possibly provide a minimum-limiting age constraint on the timing of the rock surface exposure at this site during the

deglaciation, and in turn on the formation of the Angliers shoreline. The youngest age of 10,600 ± 500 yr at Preissac Hill is indeed consistent with the 9 other ^{10}Be ages obtained for Group 1 (Fig. 1.5A). Therefore, we include this sample into the calculation of the mean age for the younger group of ages (9,900 ± 700 yr; Fig. 1.5D). The remaining two ^{10}Be ages at Preissac Hill are considered too old to relate to the regional deglaciation. Accordingly, these two samples are excluded from the data set and considered as outliers.

The old ^{10}Be ages obtained at Michel Lake are also likely related to an inherited ^{10}Be signal (and insufficient glacial erosion). However, because these three ^{10}Be ages show a relatively good internal consistency, we cannot exclude that the apparent mean age of ~15,800 yr ± 900 yr may record another geomorphological feature reflecting a slightly earlier deglaciation process in the region. An alternative interpretation for this second group is discussed below within the framework of the last deglaciation.

1.6 Discussion

1.6.1 The 9.9 ka ages and the chronology of lake levels

The well-defined group of ages centered at 9.9 ± 0.7 ka (Fig. 1.5D) is consistent with the fact that the shorelines sampled belong to the same lake level, as showed by their elevation range (393-412m) that roughly falls onto the 405 m isobase of this former water plane (Fig. 1.3B). Previous studies broadly assigned the Angliers lake stage to the onset of the regional deglaciation based on paleogeographic considerations articulated around ^{14}C ages coming from outside the Ojibway basin (Vincent and Hardy, 1979; Veillette, 1994). Current reconstructions place the beginning of ice retreat and the concomitant glaciolacustrine inundation in the study area at ~10.2 cal ka BP (i.e., 9.0 ^{14}C ka in Dyke et al., 2003; Dyke, 2004). The ^{10}Be

age thus indicates that the high-elevation Angliers lake level developed during the early stages of the Ojibway invasion, which appear to have occurred rapidly after the withdrawal of the ice margin in the region. Considering the difficulties in identifying the position of the ice margin within the Ojibway basin during the deglaciation and the concomitant lack of chronological constraints on the continent-scale ice-margin histories, these results also yield important data for the deglacial chronology (Dyke, 2004). These ^{10}Be ages provide a minimum-age constraint on ice withdrawal within the basin, which until now relied on minimum-limiting ^{14}C ages from lake sediment cores that typically document the disappearance of the lake and/or onset of post-glacial sedimentation. These ^{14}C chronologies are also prone to centuries-scale lags with respect to the disappearance of ice (e.g., Ullman et al., 2016).

These ^{10}Be ages bring the first direct constraints on the timing of lake surface elevation changes in the Ojibway basin. Prior to this study, the overall lack of geochronological data on the three high-elevation lake levels had so far forced glacial lake reconstructions to rely on a chronology based on the above paleogeographic reconstructions, as well as on the assumption that the last (and lowest) lake level that was then defined in the Ojibway basin – the late Kinojévis lake stage – formed the lake surface that preceded the drainage of the coalesced Lake Agassiz-Ojibway, which took place ~8.2 ka (Barber et al., 1999; Roy et al., 2011; Jennings et al., 2015). The mean ^{10}Be age of 9.9 ± 0.7 ka obtained on the Angliers lake level now places an upper age limit on these three closely-related Ojibway lake stages. Accordingly, if the assignment of the late Kinojévis lake level to the 8.2 ka time-interval of the deglaciation is correct, this would indicate that Lake Ojibway experienced only two lake level drops over a period of about 1700 years, which represents about three quarters of the lake's existence. This apparent stable lake configuration seems rather improbable given the overall rapid ice retreat of the LIS margin in the region (450 m/yr; Veillette, 1994) that likely caused the opening of lower outlets, as well as the occurrence of late-glacial readvances of the ice margin into the lake (Vincent and

Hardy, 1977) that may have produced additional lake-level changes during that time interval. More importantly, the recent documentation of well-defined low-elevation shorelines forming water planes projecting below the Kinojévis outlet in the Ojibway basin (Roy et al., 2015) adds to similar findings in the Agassiz basin (Dredge, 1983; Klassen, 1983), which together argue for the existence of significant lake level(s) post-dating the late Kinojévis lake stage. Altogether, this situation could be improved by applying ^{10}Be surface exposure dating to key shoreline sequences, which could potentially refine correlations of lake levels and the chronology of the attendant glacial lake reconstructions.

1.6.2 The 16 ka ages and the regional deglaciation

Current understanding of the deglaciation suggests that the mean age of 15.8 ± 0.9 ka obtained at Michel Lake (Fig. 1.5C) is too old to be related to Lake Ojibway, whose initial formation is ascribed to ~10,600 cal yr BP by a varve chronology (Antevs, 1925; Breckenridge et al., 2012). Furthermore, paleogeographic reconstructions indicate that the area was still covered by ice at that time, with the southern LIS margin located into the Great Lakes basin (~700 km from the study area) at ~16 cal ka BP (c.f., the 13 ^{14}C ka time slice in Dyke, 2004). These data are consistent with the interpretation attributing these older ^{10}Be ages to the inheritance of cosmogenic isotopes from previous exposure due to limited glacial erosion of the bedrock surfaces (washing limits) dated, a phenomenon commonly encountered in glaciated terrains (e.g., Stroeven et al., 2002; Harbor et al., 2006), and as evidenced here by the large scatter of ^{10}Be ages at Preissac Hill. As for the intensity of glacial erosion with respect to former ice-flow movements (Veillette et al., 1999a; Veillette et al., 2017a), our results do not show a clear trend between the occurrence of old ages and the position of a sample site on the bedrock high versus the orientation of the main ice flows. Although Preissac Hill is located in a down-ice (sheltered) position from the dominant ice flows, the sites of Joe Lake and Nissing Hills were

sampled in a similar setting and yielded a tight cluster of young ages. Furthermore, the washing limits of Michel Lake and East Deloge sites were both sampled on the up-ice (stoss) side of topographic highs and should thus have been subjected to severe glacial erosion; yet, they revealed contrasting results (Table 1.1). Consequently, the intensity of glacial erosion seems to be site-specific and is likely dependent on a combination of local macro- and micro-topographical features influencing the degree of abrasion and plucking by subglacial processes.

An alternative explanation could be related to the fact that the sites sampled are located on the highest topographic rises in the region (Fig. 1.3B). At about 16 ka (~13 ^{14}C ka), the deglaciation was well underway and the latitudinal retreat of the LIS southern ice margin was apparently accompanied by a significant increase in surface melting (Carlson et al., 2009; Ullman et al., 2015), consistent with marked changes in global ice volumes and sea level across this interval (e.g., Tarasov and Peltier, 2004; Lambeck et al., 2014). If so, significant thinning of this sector of the ice sheet could have caused these hills to emerge (break) at the ice surface as "nunataks", and then be exposed to cosmic rays early in the deglaciation (see model in Fig. 1.6). Comparable deglaciation process has been documented in Fennoscandia, Greenland and Antarctica (Brook et al., 1996; Stone et al., 2003; Rinterknecht et al., 2004; Goehring et al., 2008). Yet, topographic rises in the study area show a relatively small elevation difference (~80-120 m) with respect to the lower clay plain, indicating that the ice cover had to be very thin to allow these moderate hills to break through the ice surface. Such an ice margin configuration appears incompatible with an active ice retreat and the damming of a large lake, and remains largely unsupported by available field evidence, geomorphological data, and existing ice retreat patterns. Furthermore, this thinning mechanism would also require the absence of a sediment cover on the hills dated (or a very thin one) in order to have a significant exposition of the bedrock surface and allow the onset of the ^{10}Be clock. However, the geomorphological setting

at the site of Michel Lake shows about the same sediment cover as the other sites dated.

Consequently, based on these arguments, we believe that the ~16 ka ages obtained at Michel Lake are best explained by a slight inherited ^{10}Be signal related to insufficient glacial erosion of the bedrock surfaces dated. This small cluster of older ^{10}Be ages thus calls for further investigations involving additional surface exposure dating of important topographic hills in the region, as the existing set of ^{10}Be ages cannot entirely resolve this issue.

1.7 Conclusion

The application of ^{10}Be surface exposure dating to raised shorelines marking a major stage of Lake Ojibway provides the first direct geochronological constraints on the glaciolacustrine episode and the associated history of lake level changes in the north-central region of the LIS during the last deglaciation. The ^{10}Be ages indicate that the Angliers lake level formed at around 9.9 ± 0.7 ka, thus assigning the development of this high-elevation lake stage to the early part of the history of Lake Ojibway. This study also adds new data to deglacial chronologies documenting the recession of the ice margin across the Ojibway basin (c.f., Dyke, 2004), whereby the results provide minimum-limiting ages on the onset of ice withdrawal in this large region, which otherwise is difficult to constrain due to the overall lack of ice-margin features and the scarcity of material for ^{14}C dating.

These results bring important constraints on the timing of lake surface elevation changes associated with the three high-elevation lake levels in the Ojibway basin, in which the lowest lake level has long been associated with the drainage of Lake Agassiz-Ojibway. The ^{10}Be ages obtained for the uppermost (Angliers) lake level tend to place this sequence to the early segments of the lake history and,

combined with evidence for low-elevation lake levels in both Agassiz and Ojibway basins (Klassen, 1983; Roy et al., 2015), argue for a lake configuration involving a substantially less extensive and lower lake surface than the one presented in previous reconstructions for the late-stages of the deglaciation. Accordingly, these results motivate further investigations focussing on the ^{10}Be dating of key shoreline sequences that will facilitate correlations of lake levels and improve the overall chronology of the final stages of these glacial lakes.

This study demonstrates that ^{10}Be surface exposure dating of raised shorelines represents an important step towards improving temporal reconstructions of glacial lakes. The approach outlined here could be applied to other important ice-dammed lakes that formed and drained during the LIS deglaciation. Obtaining new chronological constraints on shorelines associated with particular lake stages and/or lake level drawdowns could lead to more robust estimates of meltwater volumes for specific time intervals of the last deglaciation, thereby refining fundamental input data for ocean models that assess the impact of freshwater discharges on the North Atlantic thermohaline circulation and Earth's climate (e.g., Bauer et al., 2004; Renssen et al., 2007; Böning et al., 2016).

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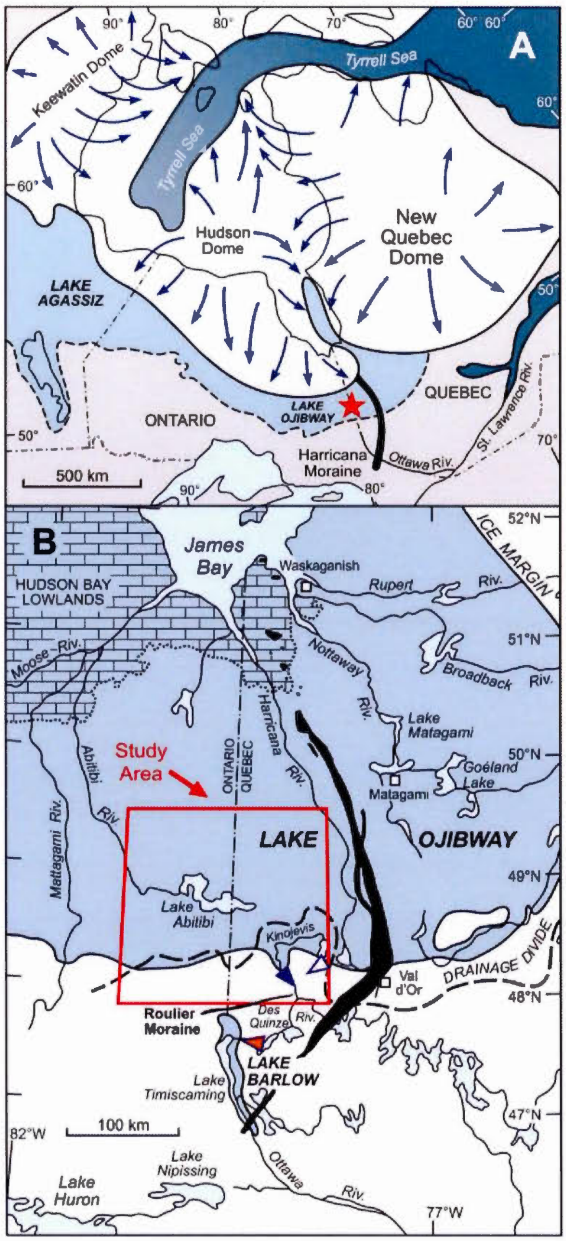

Figure 1.1 A) Schematic extent of Lake Agassiz and Lake Ojibway in the context of the Laurentide Ice Sheet at ~8.5 cal yr BP (Dyke, 2004); location of the study area (red star). **B)** Study area and main physiographic features of the Ojibway basin in Ontario and Québec. Note that the red box covers the area shown in Fig. 1.3. Triangles show the location of the outlet system related to the main stages of Lake Ojibway (orange: Angliers; blue: early Kinojévis; white: late Kinojévis; after Vincent and Hardy, 1979).

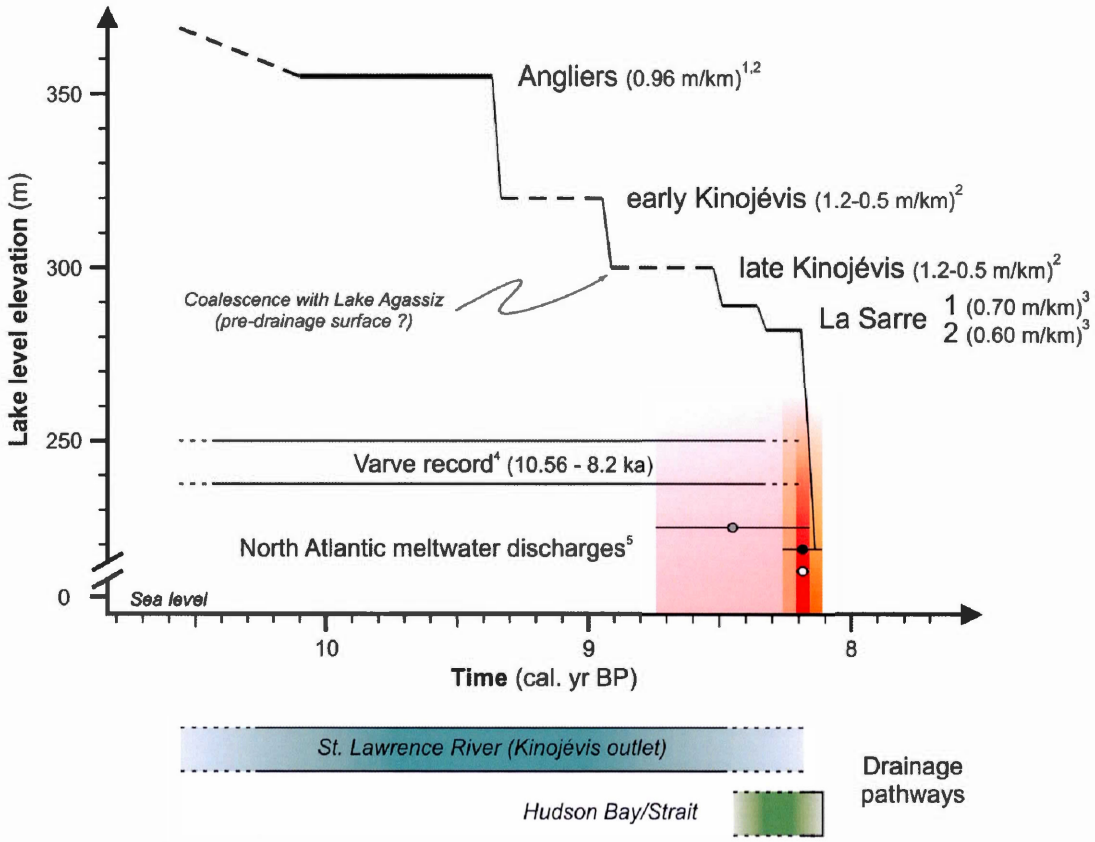

Figure 1.2 Schematic representation of the main lake levels reported in the Lake Ojibway basin, with the corresponding uplift gradients (1: Veillette, 1994; 2: Vincent and Hardy, 1979; 3: Roy et al., 2011). Full and dotted horizontal lines represent well- and poorly-defined lake levels, respectively. The timing and duration of each lake level is unknown; elevations are approximate and based on a crude projection of these lake levels in the southern Lake Abitibi region. Time span for the lake comes from a varve chronology (4: Antevs, 1925; Breckenridge et al., 2012), while its termination is given by the chronology of meltwater discharges associated with the final lake drainage (5: Jennings et al., 2015). Shaded areas correspond to calibrated ages reported for the lake drainage (with 1σ error bars): pink is from marine sediment cores (Barber et al., 1999); orange is from continental sediment sequences (Roy et al., 2011). Red bar corresponds to the 8.2 ka event documented in the Greenland ice-core records (Rasmussen et al., 2006). The lower rectangles show proposed drainage pathways for meltwater overflow/discharges for the lake.

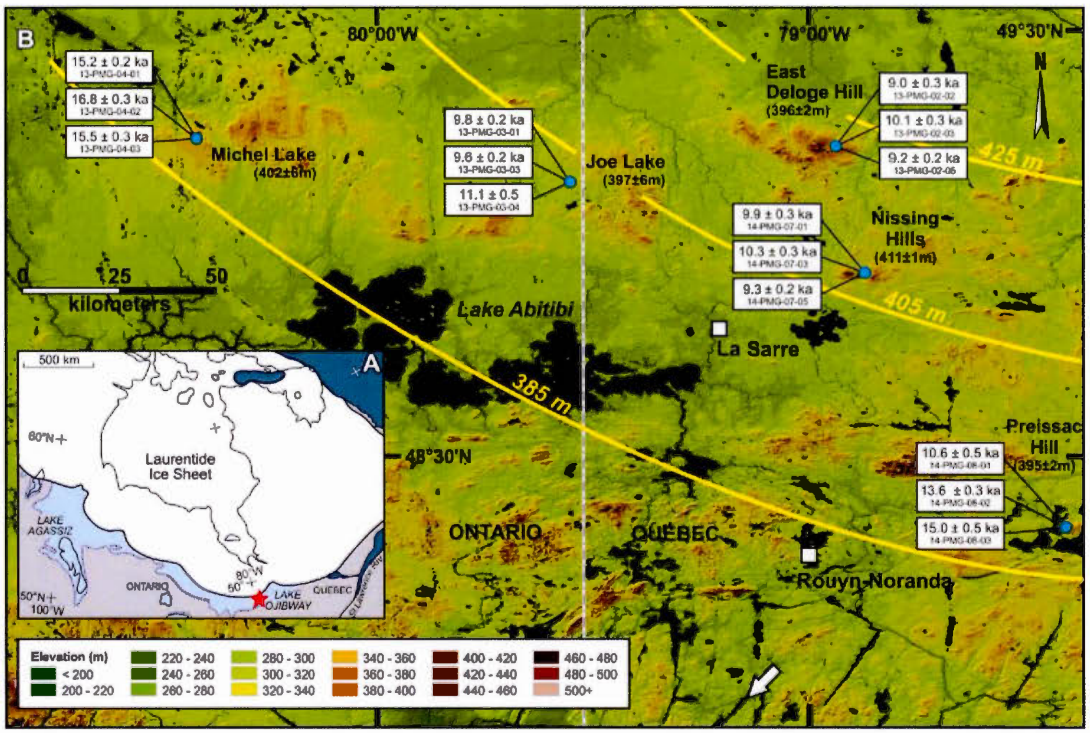

Figure 1.3 A) Location of the study area (red star) with respect to Lakes Agassiz and Ojibway and the Laurentide Ice Sheet margin at ~9.5 cal ka BP (Dyke, 2004). **B)** Digital elevation model showing the physiography of the study area. The low-lying areas (green colors) correspond to the flat-lying Ojibway clay plain, which is broken in places by hills (brown colors) where raised erosional shorelines of the Angliers lake level developed. Yellow lines show the isobases associated with the inclined water plane formed by the Angliers lake level (Veillette, 1994). White boxes show ^{10}Be ages and sample numbers (see Fig. 1.5; Table 1.1 and Supplementary Table 1.2 for details). The high-rise terrains to the south of Lake Abitibi mark the continental drainage divide that encompasses the Kinojévis River outlet system. The outlet at the time of the Angliers lake stage was located ~40 km to the south of the river identified by the white arrow (see Fig. 1.1 for location).

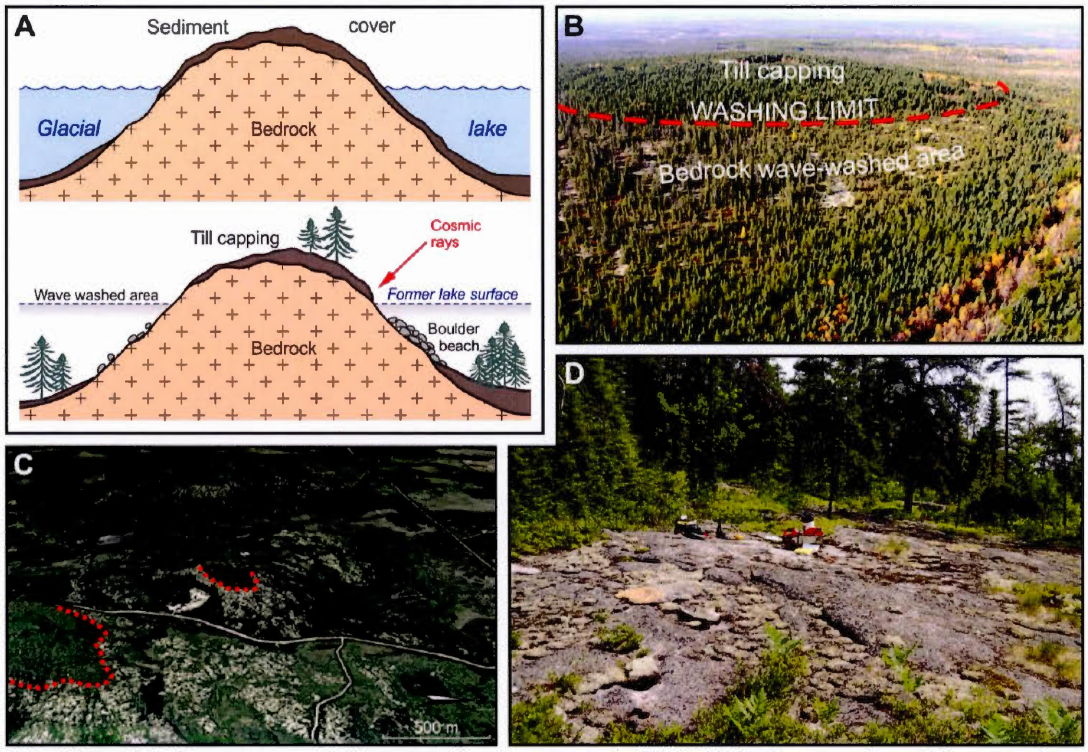

Figure 1.4 A) Schematic model showing the development of lakeshore erosional shorelines known as washing limits (see text for details). **B)** Photograph of Michel Lake site showing an oblique aerial view of wave-washed bedrock rim (tree-less areas with whitish colors) formed by the lakeshore erosion. Note the presence of a capping of untouched sediments that marks the upper limit reached by the wave erosion. **C)** Google Earth satellite image of the washing limit exposed at the Nissing Hills site. **D)** Example of a bedrock surface sampled for ^{10}Be surface exposure dating (Nissing Hills; rock saw width is 75 cm). Pictures of the three other sites sampled are showed in Supplementary Figure 1.7.

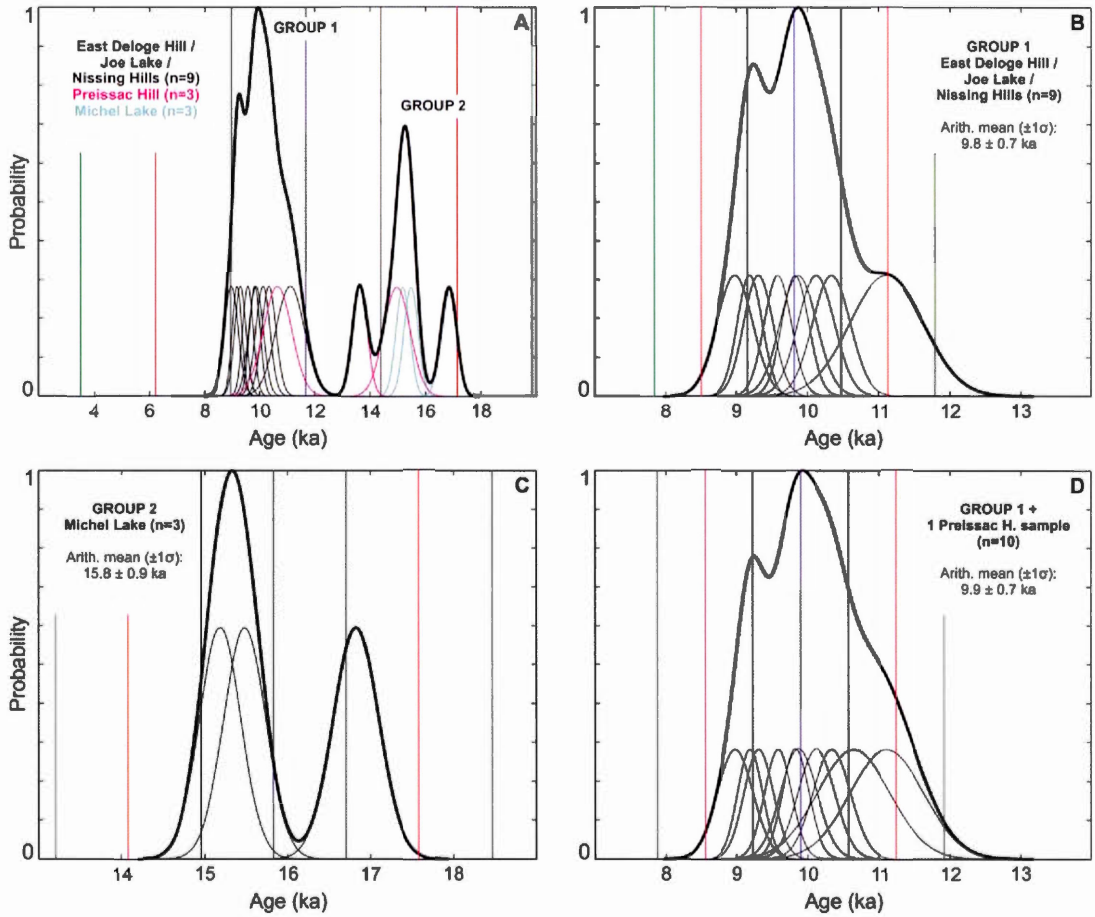

Figure 1.5 Probability density functions (PDF) plots for ^{10}Be surface exposure ages and associated uncertainties (68% (1σ) confidence interval in black; 2σ given in red and 3σ in green). The blue vertical line denotes the arithmetic mean value of the age population; thin curves represent individual ages within 1-σ uncertainties (see Table 1.1 and Supplementary Table 1.2 for data). **A)** Distributions of all 15 ages obtained from 5 sites in this study. Note that the two oldest ages from Preissac Hill are considered as outliers (see text for details). **B)** PDF for the ages forming Group 1 seen in A. **C)** PDF for the older ages forming Group 2. **D)** PDF for the population of younger ages composed by the samples forming Group 1 and the younger age obtained at Preissac Hill. We used the arithmetic mean ages (blue line) of this PDFs as formation age of the Angliers lake level. Reported errors for these ages are calculated by quadratic propagation of the standard deviation of the respective arithmetic mean and the production rate error given by Young et al. (2013).

Table 1.1 Samples information and surface exposure ages.

Site name	Sample no.	Rock type	Latitude (DD)	Longitude (DD)	GPS altitude (m)	Lm ± 1σ (yr)	1σ
East Deloge Hill	13-PMG-02-02	Granite	49.22640	-78.93556	399	8978 ± 254	2.8%
East Deloge Hill	13-PMG-02-03	Granite	49.22666	-78.93529	396	10121 ± 256	2.5%
East Deloge Hill	13-PMG-02-05	Granite	49.22658	-78.93519	395	9189 ± 177	1.9%
Joe Lake	13-PMG-03-01	Tonalite	49.14309	-79.55013	404	9829 ± 188	1.9%
Joe Lake	13-PMG-03-03	Tonalite	49.14247	-79.55063	394	9584 ± 191	2.0%
Joe Lake	13-PMG-03-04	Tonalite	49.14232	-79.55115	393	11110 ± 516	4.6%
Nissing Hills	14-PMG-07-01	Monzonite	48.92992	-78.86851	411	9872 ± 256	2.6%
Nissing Hills	14-PMG-07-03	Monzonite	48.93010	-78.86778	412	10335 ± 264	2.6%
Nissing Hills	14-PMG-07-05	Monzonite	48.93062	-78.86706	411	9310 ± 206	2.2%
Michel Lake	13-PMG-04-01	Tonalite	49.24764	-80.41727	406	15184 ± 249	1.6%
Michel Lake	13-PMG-04-02	Tonalite	49.24775	-80.41731	406	16831 ± 276	1.6%
Michel Lake	13-PMG-04-03	Tonalite	49.24748	-80.41560	395	15480 ± 254	1.6%
Preissac Hill	14-PMG-08-01	Monzogranite	48.33950	-78.40414	393	10645 ± 511	4.8%
Preissac Hill	14-PMG-08-02	Monzogranite	48.33940	-78.40424	396	13644 ± 265	1.9%
Preissac Hill	14-PMG-08-03	Monzogranite	48.33941	-78.40442	397	14973 ± 478	3.2%

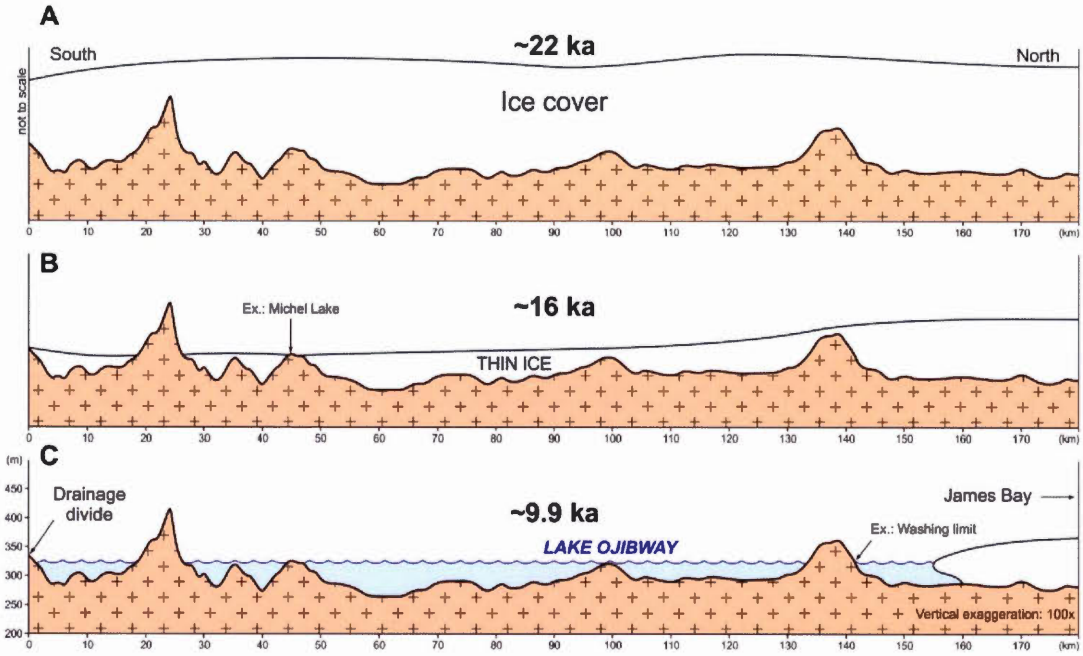

Figure 1.6 Schematic model showing the deglacial thinning mechanism proposed as an explanation for the small group of ^{10}Be ages centered at ~16 ka. **A)** Cross section depicting the ice cover during the full glacial conditions (ice thickness not to scale, unlike the underlying topography). **B)** As the deglaciation proceeds, significant ice-mass loss is thought to occur through surface melting, causing the high-elevation terrains to be exposed to subareal conditions and cosmic rays. **C)** Submersion by meltwater as the ice margin retreats north of the continental drainage divide. Several geological considerations indicate that this model cannot be retained (see discussion for details).

1.8 Supplementary material

Table 1.2 Analytical and procedural data.

Sample no.	CAMS #	Quartz (g)	$^{10}Be/^{9}Be$ (10^{-14})	1σ (10^{-15})	Thickness (cm)	Density (g cm^{-3})	Shielding correction	Erosion (cm yr^{-1})	[^{10}Be] ± 1σ (10^{4} atoms g^{-1})
13-PMG-02-02	BE36887	15.1606	6.44	1.82	2.33	2.7	1.00	0	5.27 ± 0.16
13-PMG-02-03	BE37487	10.0568	4.79	1.21	2.16	2.7	1.00	0	5.93 ± 0.15
13-PMG-02-05	BE36888	16.5009	7.04	1.35	2.02	2.7	1.00	0	5.32 ± 0.16
13-PMG-03-01	BE36889	17.4724	8.09	1.54	3.01	2.7	1.00	0	5.75 ± 0.17
13-PMG-03-03	BE36890	15.0750	6.71	1.34	3.22	2.7	1.00	0	5.54 ± 0.17
13-PMG-03-04	BE37488	4.7753	2.47	1.15	2.82	2.7	1.00	0	6.45 ± 0.30
14-PMG-07-01	BE38799	7.9263	3.70	0.96	2.74	2.7	1.00	0	5.69 ± 0.14
14-PMG-07-03	BE38800	6.6795	3.24	0.83	2.84	2.7	1.00	0	5.96 ± 0.15
14-PMG-07-05	BE39847	14.9817	6.53	1.44	2.63	2.7	1.00	0	5.46 ± 0.12
13-PMG-04-01	BE36891	15.2103	10.99	1.80	1.96	2.7	1.00	0	9.00 ± 0.27
13-PMG-04-02	BE36892	15.2727	12.15	1.99	2.45	2.7	1.00	0	9.89 ± 0.30
13-PMG-04-03	BE36893	15.4313	11.17	1.83	2.41	2.7	1.00	0	9.07 ± 0.27
14-PMG-08-01	BE39845	15.0036	7.32	3.50	2.83	2.7	1.00	0	6.11 ± 0.29
14-PMG-08-02	BE39846	15.0023	9.37	1.82	3.01	2.7	1.00	0	7.84 ± 0.15
14-PMG-08-03	BE38801	10.0748	6.98	2.22	2.90	2.7	1.00	0	8.55 ± 0.21

We spiked all Quartz samples with LDEO ^{9}Be Carrier-5, with an initial concentration of 1024 ppm, that was continuously weight-corrected for evaporation (maximum correction 1.2%). All beryllium isotope ratios were measured relative to the AMS standard 07KNSTD (Nishiizumi et al., 2007).

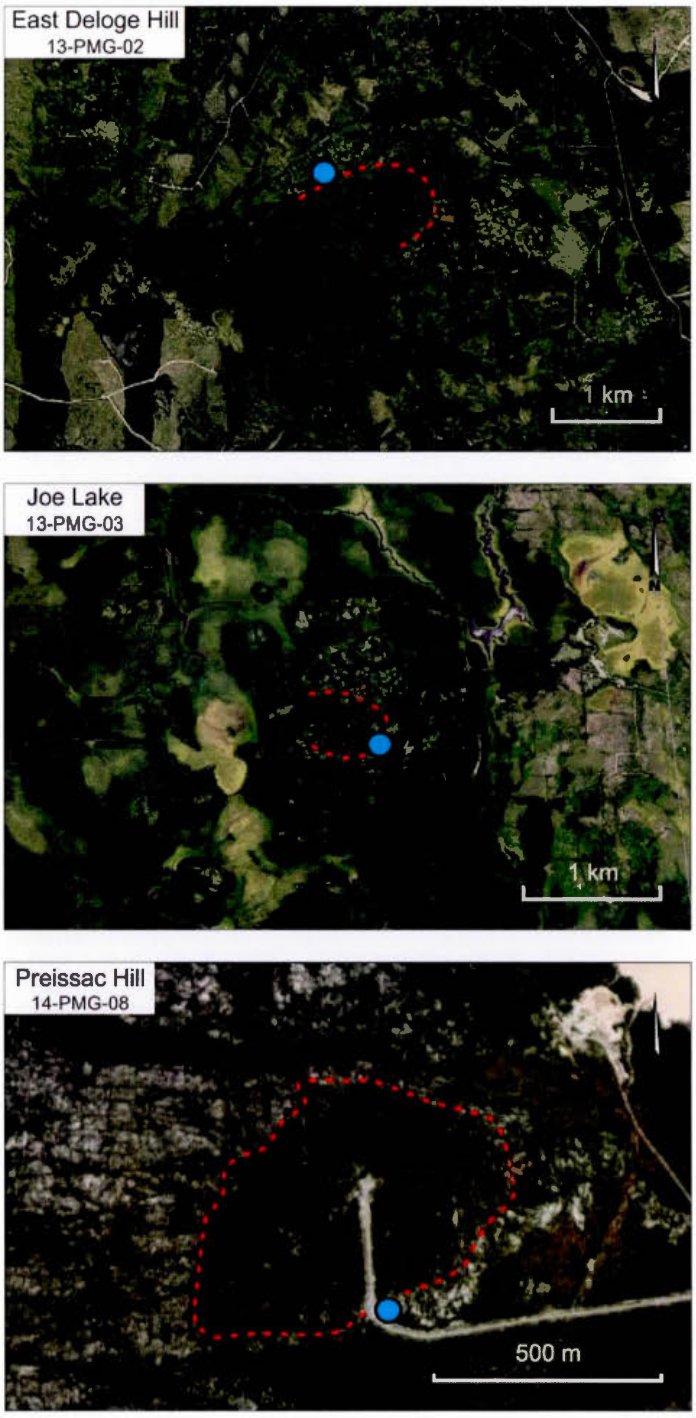

Figure 1.7 Google Earth images showing the erosional shorelines sampled at the East Deloge Hill, Joe Lake and Preissac Hill (see Fig. 1.2 for the two other sites).

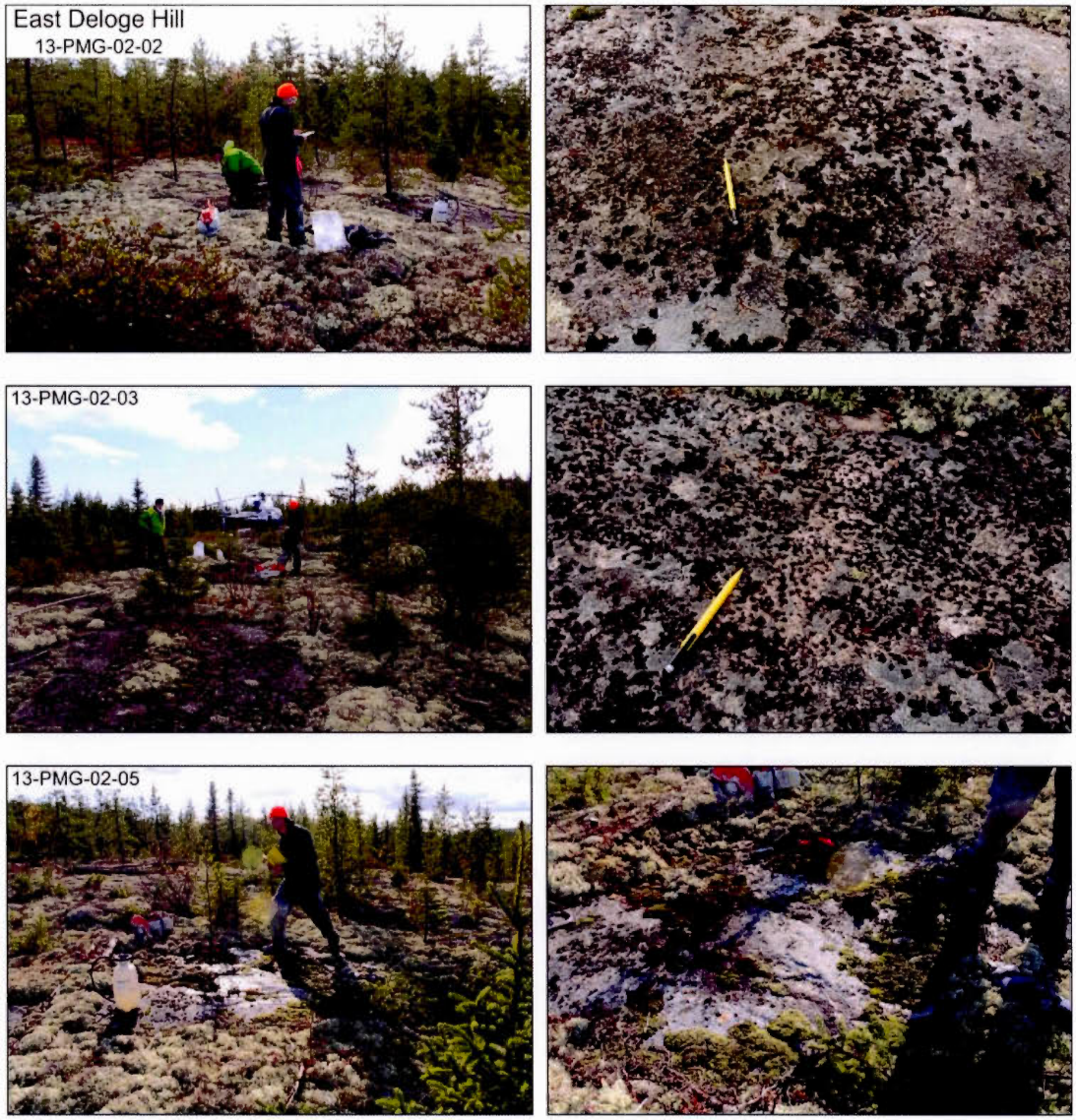

Figure 1.8 Photographs showing general and detailed views of the erosional shorelines sampled at the East Deloge Hill site.

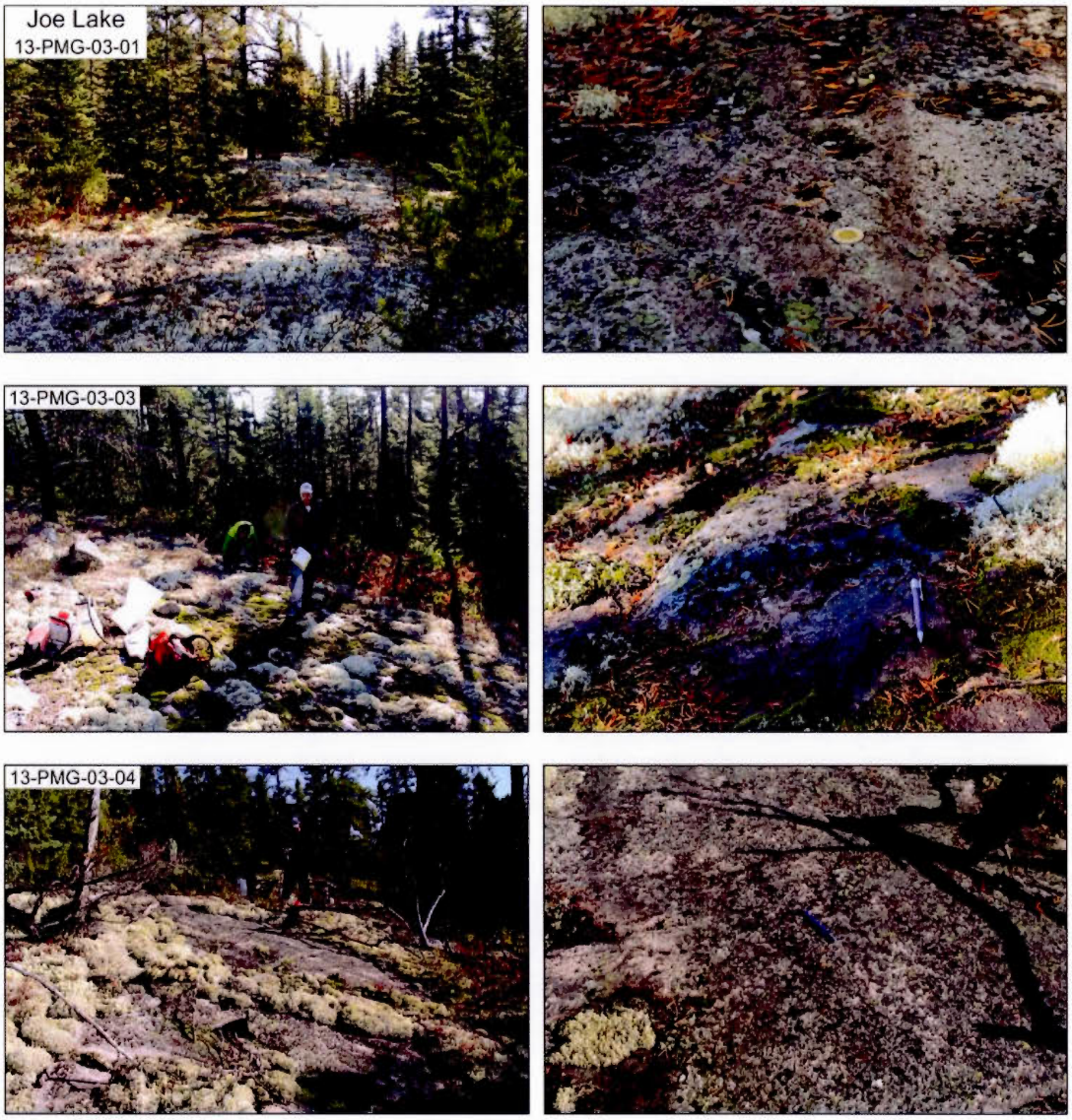

Figure 1.9 Photographs showing general and detailed views of the erosional shorelines sampled at the Joe Lake site.

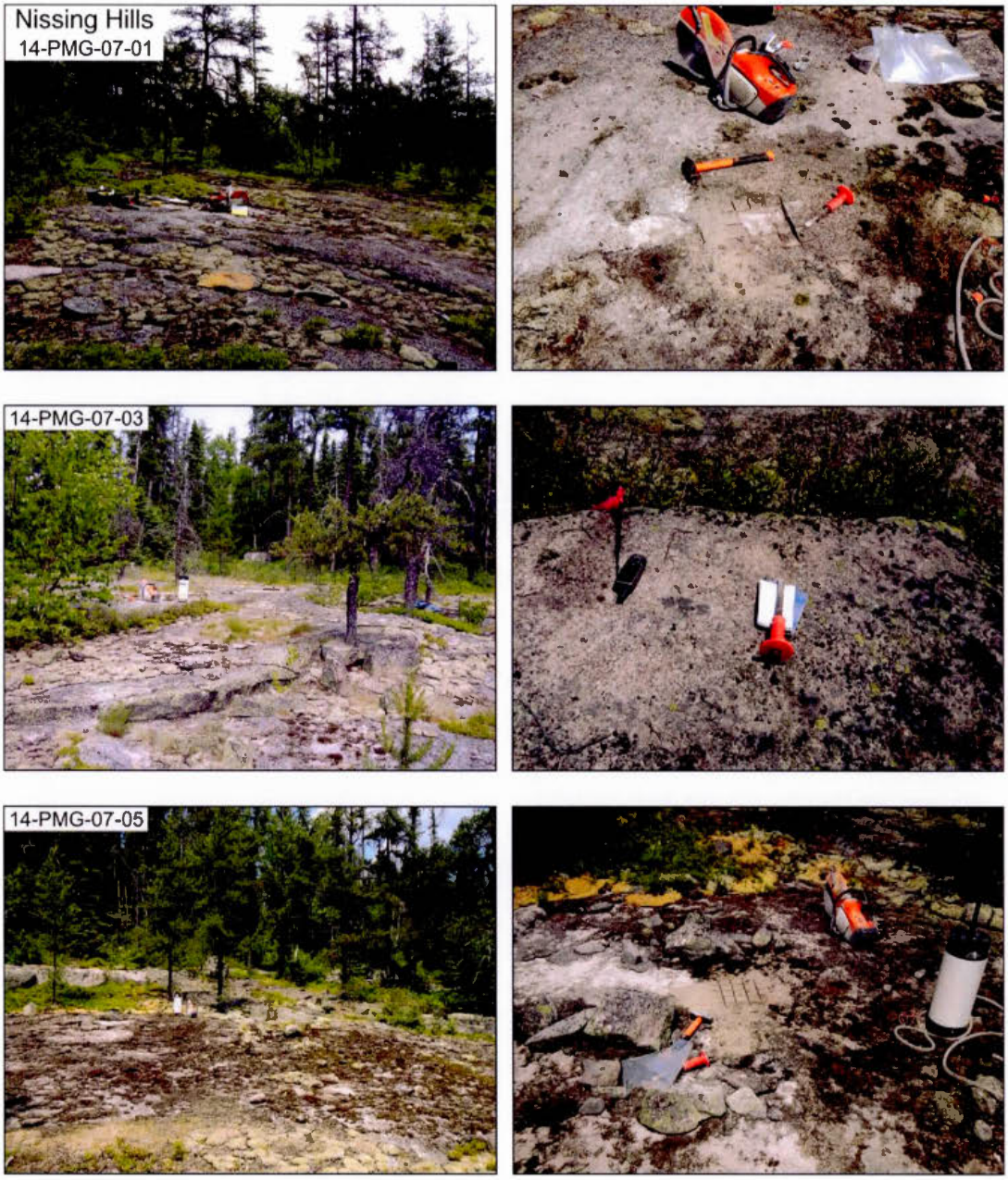

Figure 1.10 Photographs showing general and detailed views of the erosional shorelines sampled at the Nissing Hills site.

Figure 1.11 Photographs showing general and detailed views of the erosional shorelines sampled at the Michel Lake site.

Figure 1.12 Photographs showing general and detailed views of the erosional shorelines sampled at the Preissac Hill site.

CHAPITRE II

HIGH-RESOLUTION VARVE SEQUENCES DOCUMENT THE TIMING OF LATE-GLACIAL ICE READVANCE AND DRAINAGE EVENTS IN THE EASTERN LAKE AGASSIZ-OJIBWAY BASIN

Pierre-Marc Godbout, Martin Roy & Jean Veillette

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Contribution des auteurs:

P.M.G., M.R. et J.V. ont développé cette étude. P.M.G. a prelevé les échantillons, procédé aux analyses, interprété les données sédimentologiques et géochimiques, écrit l'article et préparé les figures. M.R. et J.V. ont participé à l'interprétation des données et contribué à la rédaction de la version finale de l'article.

Abstract

Lake Ojibway developed at the southern Laurentide ice sheet margin during the last deglaciation and covered vast expanses of northeastern Ontario and northwestern Québec (Canada). The late-stage history of the lake is complex, presumably marked by a coalescence with Lake Agassiz and by late-glacial ice readvance(s) into the basin shortly before its final drainage ~8,200 years ago. However, these events remain poorly defined in the Ojibway varve record. Here we address these issues using high-resolution compositional analyses of two varve sequences located near Matagami and La Reine in northwestern Québec. The Matagami section contains 231 varves and comprises an interval recording a late-glacial (Cochrane) ice readvance. The La Reine section spans 100 varves and the base of the sequence is characterized by a set of chaotic rhythmites that marks a sharp interruption in the otherwise distal sedimentation documented in this interval. These rhythmites are overlain by a set of 65 thick varves, which are in turn capped by a thick silt bed associated with the final drainage of Lake Ojibway. Varve thickness measurements allow the correlation of these sections with the main Ojibway varve record that spans ~2129 years in the region. The Matagami sequence covers varve years 1644-1874 and assign the onset of the Cochrane readvance to varve year 1817. The lower part of the La Reine sequence below the bottom rhythmites was deposited between varve years 1843-1877, while the overlying set of thick varves is correlated to the varve years 2065-2124, thus indicating the occurrence of a hiatus of 188 varves. The distinct thick varves show strong compositional and stratigraphic similarities with the Connaught sequence reported elsewhere in the basin and point to a connection with the late-glacial (Cochrane) ice dynamics, which appear to have played an important role on the lake evolution. The bottom rhythmites and the upper silt bed show sedimentological characteristics that are interpreted as evidence for major lake drawdowns. Consequently, the results indicate that the late-stage history of Lake Ojibway was marked by the Cochrane major ice readvance which was

followed by two drainage events separated by at least 65 years, consistent with North Atlantic sediment records that document a two-step drainage of Lake Agassiz-Ojibway.

Keywords: Glacial Lake Agassiz-Ojibway; varves; last deglaciation; ice readvances, drainage events; 8.2 ka cooling event.

2.1 Introduction

Meltwater produced by the retreat of the southern Laurentide Ice Sheet (LIS) during the 10,570 to 8,200-8,150 cal yr BP interval of the last deglaciation (Dyke, 2004) led to the development of a succession of large ice-marginal lakes that occupied the newly deglaciated and isostatically depressed terrains (Fig. 2.1A) (e.g., Elson, 1983; Teller, 1987). Lake Agassiz submerged the central Canadian prairies (Elson, 1983) and Lake Barlow-Ojibway inundated northeastern Ontario and northwestern Québec (Coleman, 1909). Lake Barlow refers to the meltwater body that accumulated south of the continental drainage divide between the Hudson Bay and the St. Lawrence River watersheds, while Lake Ojibway formed north of this divide (Coleman, 1909). Lake Agassiz and Lake Ojibway evolved independently throughout most of the deglaciation, with their areal extent being controlled by glacial isostatic adjustment of the land surface and the dynamics of the retreating ice margin that caused shifts in the location of outlets that regulated excess runoff from the decaying LIS margin (e.g., Thorleifson, 1996). Continued ice retreat presumably allowed their coalescence during the late stages of the deglaciation, which were marked by readvances of the ice margin into the lake (Antevs, 1925; Hughes, 1959; Prest, 1970). Rapid disintegration and the concomitant collapse of the LIS remnant over Hudson Bay allowed the drainage of Lake Agassiz-Ojibway into the Tyrrell Sea first and then into the Labrador Sea (Dyke and Prest, 1987; Veillette, 1994; Barber et al., 1999; Teller et al., 2002; Hillaire-Marcel et al., 2007; Kleiven et al., 2008; Jennings et al., 2015). Glaciological (hydraulic) modelling indicate that this outburst flood was likely initiated though a subglacial drainage (Clarke et al., 2004), a mechanism supported by geomorphic and sedimentary records in the southern Hudson/James Bay region (Josenhans and Zevenhuizen, 1990; Lajeunesse and St-Onge, 2008; Roy et al., 2011). The abrupt release of a massive volume of meltwater caused the freshening of the North Atlantic surface waters that disturbed the Atlantic

Meridional Ocean Circulation (Barber et al., 1999; Ellison et al., 2006; Kleiven et al., 2008) and triggered a 160-year long climate anomaly centered *ca.* 8200 yr BP according to Greenland ice cores (Alley et al., 1997; Kobashi et al., 2007; Thomas et al., 2007).

Our current understanding of the late-stage evolution of Lake Agassiz and Lake Ojibway – including their coalescence and subsequent drainage – comes from raised shoreline sequences that provide insights on changes in areal extent and depth of the lakes and from varve records that provide a floating annual chronology for the ice-margin dynamics and the LIS paleohydrology. Pioneer work on varve sections from several localities across the greater Ojibway basin allowed correlations based on varve thickness measurements that resulted in the establishment of a main varve template comprising a total of 2027 varves (Antevs, 1925; 1928). Subsequent investigations in Ontario confirmed the work of Antevs and provided evidence for an additional set of ~60 anomalously thick varves containing inclusions of ice-rafted material (Fig. 2.1B) (Hughes, 1959; 1965). This set of younger varves – named the Connaught sequence – is separated from the underlying Timiskaming series by an unconformity and was attributed to renewed deposition in a shallow remnant of Lake Ojibway resulting from ice margin fluctuations (Hughes, 1959; 1965). The exact position of the Connaught sequence within the overall Ojibway varve chronology remains, however, unspecified as thickness measurements for the whole Connaught sequence were never available, thereby preventing correlations with nearby records and precluding firm interpretation on the significance of the sequence. Similar variations in both varve thickness and ice-rafted material content of late-stage Ojibway varves were later reported from clay bluffs exposed along the shorelines of Lake Matagami (Québec) where two intervals of coarse, thick and carbonate-rich varves were identified in the otherwise thin and carbonate-free distal Ojibway varves forming the sequences (Hardy, 1976; 1982). These two sets of anomalous varves were associated with late glacial ice (Cochrane) readvances of the Hudson Lobe into

Lake Ojibway, of which the youngest set was considered correlative to the Connaught sequence based on a broad varve count and similar stratigraphic position (Hardy, 1976; 1982; Vincent, 1989). Again, the lack of detailed sedimentological descriptions of the sequences, including thickness measurements, prevented this interpretation to be confirmed.

The recent study of Ojibway sediment cores from the southern Ojibway basin (Fig. 2.1B) shed new light on previously published varve records and increased the understanding of the late-stage evolution of Lake Ojibway (Breckenridge et al., 2012). The review and analyses of several varve thickness records contributed to an updated Antevs' main varve chronology and refined the timing of sedimentological changes that occurred in the Ojibway basin, notably in the upper Ojibway sequence, for which some issues were solved regarding the position (timing) of the Connaught varves in the main Ojibway template. The presence of a widespread unconformity that formed near the end of a Cochrane readvance raised questions about the chronology of the late-stages of the lake, underlying the need to improve our current understanding of the complex sequence of events that ultimately led to the final drainage of Lake Ojibway.

Information on the final lake stages also came from thick (up to 15 cm) whitish silt bands present in the uppermost metre of some varved clay sections along the shorelines of Lake Abitibi, in Québec and Ontario, that were first reported from a sub-bottom coring and acoustic profiling program of the lake (Prévost et al., 1995; Veillette et al., 1999b). A subsequent investigation within the upper Moose River watershed in Québec showed that the marker silt bands occur sporadically inland in freshly dug ditches along roads over an area of ~3600 km^2 of the clay plain, mostly below 290 m *asl* (above sea level), in the same stratigraphic position as those found along Lake Abitibi (Ménard, 2012).

Recent stratigraphic investigations of one of these anomalously thick silt bands in the eastern Lake Abitibi region provided fresh insight into late deglacial events of the region (Daubois et al., 2014). Although this marker bed was not correlated with the main varve template, oxygen isotopes ($\delta^{18}O$) measured on ostracods across the sediment sequence showed a marked change in $\delta^{18}O$ values indicating that the thick silt bed coincides with the end of glaciolacustrine sedimentation in the region (Daubois et al., 2014). It was interpreted as a drainage varve, which may be correlative to a similar drainage unit present in stratigraphic sections in the James Bay region radiocarbon dated at 8.205 (8.128-8.282) cal ka (Roy et al., 2011). There, the presence of marine microfossils in varves directly underlying the drainage unit provided evidence for subglacial exchanges between Lake Ojibway and the marine waters in Hudson Bay (Roy et al., 2011), suggesting that the drainage of Lake Agassiz-Ojibway likely occurred through a multi-step drawdown, consistent with marine records that show multiple meltwater discharges across this interval of the deglaciation (Ellison et al., 2006; Jennings et al., 2015). Although these studies improved our understanding of this drainage, many issues remain, notably regarding the number (and chronology), duration and magnitude of the outburst floods, while the expression and timing of these drawdown events in the Ojibway varve sequences also need to be identified. These uncertainties reflect the complexity of the late stages of the deglaciation and their relation with the development and evolution of these glacial lakes.

We present high-resolution analyses of two Ojibway varve sequences from northwestern Québec that bring new insights on late-glacial ice dynamics and its influence on the late-stage evolution of Lake Ojibway (Fig. 2.1B). Sedimentological and geochemical data provide evidence for two distinct drainage events, which are inserted into the main Ojibway varve chronology using varve thickness measurements. The results also document the occurrence of a late-glacial (Cochrane) readvance, which had a strong impact on the sedimentation of the last 300 years of

the lake. Overall, this study refines the sequence of events that led to the final drainage of the lake and provides new data that should help resolving the discrepancies between continental and marine records pertaining to the timing of early Holocene freshwater forcing events.

2.2 Physiographic setting and deglacial history of the Ojibway basin

During most of its existence, meltwater overflow from Lake Ojibway drained southward via the Ottawa River and into the St. Lawrence River, through an outlet located along the continental drainage divide, which changed position through time due to glacial isostatic adjustment (Fig. 2.1B) (e.g., Vincent and Hardy, 1979). The physiography of the Ojibway basin is characterized by a gently-rolling clay plain with an elevation ranging from 290 to 320 m, which is broken in places by bedrock-core hills and the crests of eskers. The main geomorphic feature in the basin relates to the last deglaciation and consists in a major glacio-fluvial complex interpreted as an interlobate deposit – the Harricana Moraine, which is oriented roughly north-south (Fig. 2.1B) (Hardy, 1976; Veillette, 1986). The northern part of the basin was submerged by the postglacial Tyrrell Sea, which reached up to 180 m to the west and 270 m to the east of James Bay (Fig. 2.1B). The incursion of marine waters substantially eroded, reworked or covered the Ojibway sediments as well as ice-marginal deposits and other deglacial landforms. The bedrock geology of the Ojibway basin is dominated by metavolcanic and metasedimentary rocks of the Abitibi Greenstone Belt and felsic plutonic and gneissic lithologies that form the core of the Abitibi Subprovince, which is part of the Archean Superior Province (MERQ-OGS, 1984; Ayer and Chartrand, 2011). The northern part of the basin is underlain by Paleozoic limestone and dolomite rocks of the Hudson Bay sedimentary platform (Fig. 2.1B) (Telford and Long, 1986). Poorly consolidated lignite and abundant white silica sands of lower Cretaceous age are also present in the Moose River Basin (Try, 1984; Telford and Long, 1991; Long, 2000).

The deglaciation of the greater James Bay region was highly dynamic, with ice streaming (Hicock, 1988; Veillette et al., 2017a), glacial readvances (Hughes, 1959; 1965; Hardy, 1977; 1982; Dredge and Cowan, 1989; Roy et al., 2011) and iceberg discharges into Lake Ojibway (Veillette et al., 1991; Veillette and Paradis, 1996; Paulen, 2001). The late-glacial ice readvances, also known as the Cochrane surges, were documented from criss-crossing fields of glacial flutings showing a general radial pattern originating from southeastern Hudson Bay and covering extensive areas of northern Ontario and northwestern Québec (Fig. 2.1) (Prest, 1970). The Cochrane ice predominantly overrode fine-grained glaciolacustrine sediments that were mixed with bedrock fragments of the underlying Archean crystalline terrains and Paleozoic carbonates of the Hudson Platform (Fig. 2.1B). The partially grounded (or semi-buoyant) Cochrane ice left a distinctive pebbly, silty-clay and carbonate-rich diamicton (till) that overlies or truncates Ojibway varves (Smith, 1992). The occurrence of Cochrane Till and the presence of late-glacial flutings are commonly used to delineate the maximum extent reached by the Cochrane ice (Fig. 2.1B). In spite of the distinct imprint on the regional stratigraphy and geomorphology left by the late-glacial surging, there is no consensus on the number and the timing of Cochrane readvances, underlying a certain misunderstanding in the chronological order of these important ice margin fluctuations (e.g., Breckenridge et al., 2012; Veillette et al., 2017a).

2.3 Methods

2.3.1 Sites and sediment sampling

A ~3.6 m-long varve sequence was sampled from a natural bluff exposed along the eastern shore of Lake Matagami (Fig. 2.2A-B-C), in the same general area where compositional changes in varves were used to identify late-glacial readvances (Hardy, 1976). Another ~2.2 m-long varve sequence was collected from a roadside excavation near La Reine (Fig. 2.2D-E-F), at the same locality where a thick silt bed resting on Ojibway varves was documented (Daubois et al., 2014). The sequences were sampled using oriented U-shape galvanized-steel trays (61 cm long, 10 cm wide and 5 cm deep) that were inserted into freshly cleaned sections exposing undisturbed varves. Both sections were samples below the solum. Several trays were used to recover the sequences, ensuring an overlap of ~1-10 cm between the upper and lower parts of the sediment-sections, following procedures outlined in previous studies (Antevs, 1925; Hughes, 1965; Agterberg and Banerjee, 1969). This sampling technique has the advantage to prevent sediment compaction/deformation. Excess sediment was cut using a thin steel wire and the sediment sections were immediately wrapped with a thin plastic film and placed in insulated boxes for transport. The sections were subsequently stored in a cold dark room to minimize surface oxidation and desiccation.

2.3.2 Varve counting and thickness measurements

Following visual inspection, the two varve sequences were analyzed through CT-scanning using a Siemens SOMATOM Definition AS+ 128 at the INRS-ETE laboratory facilities in Québec City (Canada) to document density variations and to characterize sediment structure in 3D (e.g., Crémer et al., 2002). The high-resolution gray-scale tomograms (CT; 1 pixel = 600 μm) typically show alternating layers of lighter (lower density) and darker (higher density) gray tones that can be associated

with summer and winter layers of varves. Tomograms also highlight subtle changes between silty and clayey laminations (e.g., Boespflug et al., 1995), thereby facilitating the identification of varve couplets. Varves were counted and their thickness measured on high-resolution composite red, green and blue (RGB) images using the Image-J software in order to obtain temporal records. The varve thickness measurements of the two sediment sequences were then correlated with the main Ojibway varve chronology (Antevs, 1925; 1928), which was recently updated from 2027 varves to a total number of 2124 varves (Breckenridge et al., 2012).

2.3.3 Loss on ignition and grain-size analyses

Loss on ignition (LOI) and grain-size analyses were ran at the UQAM-GEOTOP laboratory facilities and carried out at a seasonal resolution (i.e., on individual summer and winter layers), with the exception of the upper part of La Reine sequence (0.135-0.37 m) where sampling was carried at a 0.5 cm resolution due to the occurrence of very thin varves and a thick massive bed.

LOI analysis was used to determine changes in organic matter content (OC) of sediments (e.g., Ball, 1964; Dean, 1974; Luke et al., 2009), which can reflect glacial activity in proglacial lakes (Nesje and Dahl, 2001). We used a low ignition temperature (400°C) and exposure time of 4 hours in order to avoid evaporation of the water lattice in the clay- and carbonate-rich sediments (Mook and Hoskin, 1982; Heiri et al., 2001; Boyle, 2004). The drying temperature was set to 60°C for ~48hrs to avoid organic matter degradation and the loss of structural water from clay minerals (Leong and Tanner, 1999; Barillé-Boyer et al., 2003). Specifically, wet bulk sediment samples averaging ~3g were evenly spread on the surface of pre-weighted ceramic crucibles to avoid the formation of an insulating surface crust and to prevent incomplete and irregular drying/ignition (Smith, 2003).

Grain-size analyses were carried out with a Microtrac Bluewave S3500 laser diffraction analyzer and the particle size distribution (PSD) of samples was calculated using the Microtrac FLEX software. For each sample, 0.5g of dry sediment was deflocculated in a solution of sodium hexametaphosphate and samples were stirred in a tumbler for a week to break down clay nuggets and ensure optimal sediment dispersion. Prior to measurements, 2.5 mL of solution was agitated through ultrasonication for 30 seconds. The PSD value for each sample corresponds to the average value of the measurements obtained from 6 different runs.

2.3.4 Compositional analyses

Compositional analyses were conducted on the fresh sediment sections to gain insights into detrital influx and sediment provenance. The surface Magnetic Susceptibility (MS; reported in 10^{-5} SI) was measured at a 0.5 cm interval using a Bartington MS2E sensor. MS values reflect mainly the composition, concentration and grain size/shape of magnetic minerals in sediments (St-Onge et al., 2007) and can be used to reconstruct ice sheet dynamics, as marked contrasts indicate variations in sediment sources and depositional mechanisms (Stoner et al., 1996).

The geochemical properties of the sediment sequences were documented with an ITRAX core scanner as this device represents a rapid, automatic and non-destructive method to obtain down-core high-resolution (sub-millimeter resolution) records of relative variations in the bulk major and trace elements directly from untreated laminated (varve) sediments (Guyard et al., 2007). Specifically, we use major and minor elements to document and track sharp (sub-annual) compositional contrasts that may record changes in provenance associated with the deglacial ice dynamics and/or paleohydraulic events in the basin. Geochemical analyses were carried out at a 500 μm resolution with an X-Ray Fluorescence (XRF) ITRAX™ Core Scanner equipped with a molybdenum (Mo) tube set to 30 kV and 40 mA using

a 10s exposure time. This setup is adequate to detect the concentration of light elements such Al and Si and yields a detection limit as low as 20 ppm for medium-heavy elements (e.g., Croudace et al., 2006; Cuven et al., 2007). Prior to the measurements, sections surfaces were lightly scraped along (parallel) the varve laminations to obtain a clean and flat surface, which was subsequently covered with a thin Ultralene® film to ensure a uniform X-ray transmission and to avoid sediment desiccation/contamination during the analyses. Surface topography of the sections was initially mapped using a laser distance finder to ensure a constant working distance for the X-ray detector, and a high-resolution RGB optical imaging at 50 μm/pixel was captured by the digital line camera.

2.4 Results

2.4.1 General physical and geochemical characteristics of varves

The two Ojibway varve sequences are characterized by couplets of alternating light-coloured (bottom) and dark-coloured (top) layers typical of detrital fine-grained sediment deposited in proglacial lakes where sedimentation is controlled by seasonal variations in the sediment inputs (Sturm, 1979). These color changes are accompanied by systematic textural (grain-size) changes that reflect differential settling of the detrital particles in the basin (Smith and Ashley, 1985), whereby the light-coloured layers are generally coarser (sand/silt) and were deposited during the summer, while the dark-coloured layers are finer (clay) and were deposited through flocculation under ice-covered conditions in winter time. The basal contact of the summer layers is typically sharp and the transition between the summer and winter layers ranges from sharp to gradational. The presence of intercalated whitish, mm-scale and coarser-grained laminations in some of the summer layers are interpreted to reflect episodic fluctuations in sediment dispersal (Smith and Ashley, 1985).

ITRAX analyses (n=13280) of the two varve sequences yielded a total of 22 geochemical elements with statistically significant intensities throughout the whole profiles; some elements showed insufficient signal (>25% of "0" cps values) and were discarded. Due to their semiquantitative nature, the XRF core scanning data were normalized by plotting elemental ratios (Rothwell and Croudace, 2015) in order to minimize variations in the detected intensities caused by the physical characteristics of samples, such as geometry, grain-size (Cuven et al., 2010), organic matter content (Löwemark et al., 2011) and porosity/water-content (Tjallingii et al., 2007), in addition to closed-sum effect that may be encountered along the measurement track of the moist sediments (Aitchison, 1986; Rollinson, 1993).

We used the best-detected elements to document the composition of the varves and to refine our interpretations of the sequences. The normalized Si/Sr and Ca/Sr ratios were used to track detrital influx variations between silicate-dominated and carbonate-dominated sediments (Hodell et al., 2008; Channell et al., 2012; Nicholl et al., 2012) and document late-stage events in the basin. In the Matagami area, increases in the carbonate content of the varves are indicative of direct inputs from the Cochrane ice that flowed towards the southeast, as the underlying (older) till was deposited by southwestward flowing ice and does not contain any Paleozoic erratics (Hardy, 1976; Veillette et al., 1991). West of the Harricana moraine (Fig. 2.1), the presence of carbonates in glacial sediments and varves is attributed to a direct deposition by ice that flowed across the Hudson Platform located to the north during the last glacial cycle (c.f., Matheson Till or Cochrane Till) or to indirect (ice-marginal) processes such as ice-rafting or gravity flows during the deglaciation. However, the La Reine site is ~20-30 km distant from these sources and indicates that the detrital carbonates were brought further south in the basin by the reworking of carbonate-rich sediments by underflow meltwater currents (Veillette et al., 2005) or by a drawdown of the lake (Daubois et al., 2014).

Additionally, the Ti/Rb ratio is used as another monitor of glacial activity (e.g., Bakke et al., 2009; van der Bilt et al., 2017), as Ti is usually tied with the silty facies in clastic varves (e.g., Cuven et al., 2010), while Rb is associated with detrital clay minerals (Croudace et al., 2006). The Ti/Rb ratio can thus track the deposition of distal, thin and very fine-grained turbiditic layers (Rothwell et al., 2006) and also detect variations in sources (Guyard et al., 2007). Changes in detrital sediment input is further documented by the relative abundance of the individual elements K, Fe and Zr (normalized by the total count rate of each spectrum or kcps) (Bouchard et al., 2011; Cuven et al., 2011), which are linked to distinct grain-size categories; K and Fe are respectively associated with a fine-grained and clay influx, while the heavy resistate mineral Zr is related with the coarser silt fraction (e.g., Cuven et al., 2010).

Overall, the distinction of varve boundaries in both sections is enhanced by the geochemical proxies Ca/Sr and K that show higher values in the coarser-grained summer layers, while Fe is enriched in the clayey winter layers. The other proxies Si/Sr, Ti/Rb and Zr display a noisy signal at a seasonal resolution, but like the MS and LOI values, they show significant variations throughout the sections that follow the broad changes documented in grain-size.

2.4.2 Matagami varve sequence

The ~3.6 m-long Lake Matagami section shows varve boundaries that are clearly discernible on the RGB and CT-scan images through contrasting variations between the lighter silty summer and the darker clayey winter layers (Fig. 2.3). The sequence contains a total of 231 ± 7 varves; the reported error corresponds to the number of uncertain varves. Detailed analyses were focussed on the upper 85 ± 2 varves because this 1.26 m-long interval shows significant variations in varve thickness and grain-size composition, in addition to the occurrence of a series of varves containing abundant ice-rafted material and numerous silt inclusions in

summer layers that together suggest deposition in an ice-proximal environment (Fig. 2.3). These compositional characteristics and the stratigraphic context present several similarities with the varve sequence used to document the late-deglacial (Cochrane) events in the region (Hardy, 1976).

All geochemical proxies, with the exception of Zr, reveal significant changes throughout the sequence. The MS values show some variations which appear to follow changes in grain-size in some parts of the section. Together, the varve thickness measurements and the physical and compositional properties indicate that the Matagami varve sequence can be divided in three segments (facies) that exhibit distinctive sedimentological characteristics (Fig. 2.3).

Matagami segment I [2.70-2.51 m]

The bottom segment comprises 27 ± 1 sub-cm varves (0.7 ± 0.2 cm) characterized by gray (5Y 6/1) to grayish brown (2.5Y 5/2) summer layers and brown (10YR 5/3) winter layers. Varves remain relatively thin throughout the segment, with the exception of the upper part where a slight increase occurs above 2.6 m. The texture and composition of the varves remains relatively constant, with a uniform grain-size in the clay fraction as shown by the average D50 value of 1.0 ± 0.2 calculated for the whole segment. A sudden and marked lowering is present in the MS while LOI values remain constant for the whole interval, although isolated (anomalous) peaks (increases) that may be related to the presence of undetected small roots fragments or old organics remains from the Hudson/James Bay Lowlands are present in the profile. Geochemical proxies do not show any significant variations. Only a slight decline is noticeable in Si/Sr, Ca/Sr, Ti/Rb and K before the signal stabilizes near the top of the segment. Altogether, these elements point to a low detrital influx in the basin during the deposition of these varves.

Matagami segment II [2.51-1.65 m]

The mid-sequence segment consists of a set of 44 (± 1) varves that show a great inter-annual variability in thicknesses, which range from 0.55 to 3.82 cm, with a mean value of 2.0 ± 1.0 cm. Noticeable changes in varve thickness are present in the lower part of this segment, notably at the very bottom (2.51 m depth) where the sub-cm varves suddenly increase from 0.74 to 1.57 cm in 2 varve years (2.2 cm). This is followed by another marked increase in varve thickness between the depths of 2.33 to 2.28 m, going from 0.55 to 3.81 cm in a 3-year span (5 cm).

Segment II is characterized by an overall coarsening of the varves in a step-wise manner that also marks the onset of enhanced contrast between the winter and the summer layers. A first significant increase occurs at the depth of 2.17 m, where the average D50 value rapidly passes from 1.0 ± 0.3 μm for the bottom 24 varves to an average value of 1.4 ± 0.5 μm for the top 20 varves above 2.17 m. The summer layers between 2.35 m and 1.89 m also contain numerous mm- to cm-scale silt pellets that vary from angular to sub-rounded in shape. The larger pellets occur only between ~2.3 m and 2.07 m, and the presence of a ~3 cm ice-rafted clast at 1.87 m is coincident with the sudden disappearance of the silt pellets in the varves.

Another distinctive feature of this segment consists in the abrupt change in color of the summer layers, which suddenly passes to a light yellowish brown (10YR 6/4) at depth of 2.51 m, while the colour of the winter layers (brown, 10YR 5/3) remains unchanged. At the depth of 2.33 m, the color of the summer layers rapidly returns to a more grayish brown (2.5Y 5/2) color with the arrival of the silt pellets in the sediment, which remains this way up to the top of the segment.

This sharp color change is accompanied by the onset of significant increases in most geochemical proxies that indicate significant variations in the detrital influx

in the basin. For instance, the Ca/Sr profile displays a marked increase between the depths of 2.51 and 2.25 m that points to the sudden arrival of detrital carbonates in the basin. The concomitant increases in Si/Sr and Ti/Rb at the base of this interval also suggest a turbiditic deposition, which is consistent with the changes documented in the varve thickness and grain-size records. A significant rise from background level is present in the LOI profile at depths between 2.51 and 1.5 m and it appears to coincide with the sudden arrival of detrital carbonates in the basin and the general upward increase documented in the grain-size from the depth of 2.17 m. The association carbonates/LOI may be related to long-distance provenance of organic detritus from the James Bay lowlands.

Matagami segment III [1.65-1.44 m]

The upper segment regroups a set of 14 thin varves with grayish brown (2.5Y 5/2) summer layers and brown (10YR 5/3) winter layers that form couplets with a mean thickness of 1.3 ± 0.2 cm. This part of the sequence is characterized by slightly coarser varves compared to the segment II, with an average D50 value of 1.5 ± 0.5 μm. These changes are accompanied by a slight increase in the MS and a reduction of the LOI values and in the Si/Sr, Ca/Sr and K content of the varves, while the overall Ti/Rb, Fe/kcps and Zr/kcps content remains fairly stable. Altogether, this suggests a gradual return to reduced detrital influx in the basin, resembling those documented in the lower segment I. Lower LOI values near the surface also reinforces the interpretation that the higher LOI values at depth could be related to far-travelled organics.

2.4.3 La Reine varve sequence

The ~2.2 m-long sequence at La Reine reveals clear and well-defined varves on the RGB and CT-scan images, from which a total of 100 ± 1 varves were counted (Fig. 2.4). The varve sequence shows significant changes in thickness and grain-size throughout the section, which is characterized by the occurrence of two distinct intervals composed of coarse sediments. The lower interval consists of a 5.5 cm-thick set of silty rhythmites containing abundant sub-mm to mm scale rip-up clay/silt clasts that lies on thin varves forming the bottom part of the section. The CT-scan shows that these rhythmites are bounded by sharp contacts consistent with abrupt variations documented in the compositional data and the geochemical proxies (Figs. 2.4, 2.5). This chaotic interval is overlain by a series of varves that show a gradual upward increase in thickness up to the middle part of the section, from where varves show an overall decrease in thickness that extends to the top of the sequence. The second break is formed by a 10 cm-thick bed of faintly laminated silts that occurs near the top of the sequence. The silt unit is in turn overlain by faintly bedded to massive clayey sediments that complete the sequence.

The variations in varve thickness and grain-size are accompanied by significant compositional changes, notably in the MS, LOI values and some geochemical proxies (Si/Sr, Ti/Rb, Zr) that show marked changes associated with the coarse-grained rhythmites at the bottom and the silt bed at the top (Fig. 2.4). Accordingly, the La Reine varve sequence can be subdivided in five segments (facies).

La Reine segment I [2.15-1.93 m]

The bottom segment of the La Reine sequence contains 35 ± 1 varves characterized by a dark gray to gray (5Y 4/1-5Y 5/1) summer layers and dark grayish brown (10YR 4/2) winter layers. These varves thin upward throughout the segment,

with a mean thickness of 1.0 ± 0.3 cm for the bottom varves and 0.4 ± 0.1 cm for the upper varves. Grain-size remains stable throughout the segment with an average D50 value of 1.0 ± 0.5 μm, with the exception of the bottom part that shows a greater interannual variability. The MS profile shows a decrease followed by an upward increase in the signal. LOI values gradually diminish upward and reach a minimum at the top of the segment. The Ca/Sr is the only geochemical proxy showing significant fluctuations in the bottom part, while the top part of the segment is characterized by a marked reduction in the carbonate content of the varves. All other proxies show a slight upward increase indicative of a greater turbidity at the bottom of the lake.

La Reine segment II [1.93-1.87 m]

The segment II is bounded by sharp upper and lower contacts and exhibits distinct color variations within the sequence. This 5.5 cm-thick set of anomalous rhythmites is formed by silty couplets ranging from 0.2 to 1.4 cm in thickness, which consist in thick layers of coarser and lighter-coloured sediment exhibiting irregular basal contacts that are sharply overlain by thin layers of finer and darker sediment. While the dark grayish brown (10YR 4/2) color of the finer layers remains unchanged throughout the segment, a marked shift from dark grayish brown (2.5Y 4/2) to grayish brown (2.5Y 4/2) is seen for the lighter/coarser layers, pointing to textural and compositional changes in this sediment interval (Fig. 2.5).

The bottom part of the segment contains less carbonates and is composed of three thin and generally finer couplets with a peak value of 5.0 μm reached in the coarse layer of the second couplet. These rhythmites contain numerous sub-mm to mm clay/silt rip-up clasts that suggest a bedload transport. The top part of the segment is richer in detrital carbonates and exhibits two thinner/finer couplets bounded by two distinctive thicker/coarser layers containing abundant rip-up material (L1 and L2; Fig. 2.5). These two thick layers record an abrupt coarsening of the

sediment that departs from an overall stable background value of 3.0 μm for the thinner couplets. The peak values of 7.3 μm and 10.8 μm for the coarser layers (L1 and L2 in Fig. 2.5) are coincident with positive spikes in the MS and Zr, as well as with sharp negative fluctuations in Fe that together indicate an overall decrease in the clay content of the sediment.

Despite the noise in their profiles, the Ti/Rb and K content of the sediment vary with the grain-size. The sharp increase in the Ca/Sr content is accompanied by the peak values in Si/Sr, underlying the presence of the detrital carbonates. For the whole segment, LOI values remained very low and unchanged, thus suggesting that the detrital carbonates are in this case not tied with far-traveling organic detritus, thereby implying a different mechanism.

La Reine segment III [1.87-0.28 m]

The mid-section segment overlying the coarse-grained rhythmites consists in a set of 65 distinct varves characterized by a significant upward thickening of the couplets. The color of the summer layers is a mix of gray (5Y 5/1) to olive gray (5Y 5/2) grading upwards into grayish brown (2.5Y 5/2), while winter layers remain dark gray (5Y 4/1). Multiple graded laminae (mm-scale) are common in the summer layers, suggesting variations in sediment influx. The lower part of these 65 varves is formed by 20 couplets thickening upward from 0.55 cm at the base to 8.50 cm at a depth of 1.15 m, for a mean value of 4 ± 2 cm per couplet. Above 1.15 m, the remaining 45 varves thin upward from 8.50 cm to 0.15 cm at a depth of 0.28 m, for a mean thickness of 2 ± 2 cm.

Grain-size data shows a gradual coarsening-upward trend, going from ~1.1 μm at the base up to the depth of 0.53 m where a peak value of 6.0 μm is reached, before declining in the upper 0.25 m to reach a value of ~2.4 μm near the top of the

segment. The bottom interval of 1.34 m contains 35 varves with an average D50 of 1.8 ± 0.9 μm, where the thickest varve of 8.50 cm at 1.15 m marks the transition from clayey to silty sediments. The upper 0.25 m of the segment contains 30 thinning varves with an average D50 value of 3.2 ± 0.9 μm.

The general trend documented in grain-size is followed by the LOI values, while the MS values remain somewhat low, although the overall segment display a slight upward increase in the signal. For the set of 65 varves, geochemical proxies document an important detrital influx as shown by increases in the Si/Sr, Ca/Sr, K and Fe content of the varves. The higher carbonate content of the varves combined with the numerous peaks in the LOI record point to a marked influence of the Cochrane ice dynamics in the deposition of this varve segment.

La Reine segment IV [0.28-0.18 m]

The fourth segment of the La Reine section is a 10 cm interval of faintly-bedded grayish brown (2.5Y 5/2) silt present in the upper varve sequence. This sediment interval is characterized by a marked increase in grain-size reaching an average D50 value of 9.4 ± 3.2 μm, where the peak value of 19 μm is coeval a sharp positive change in the MS profile. This coarse silt segment also forms another significant change in color in the La Reine sequence. The upper and lower contacts of this silt unit are irregular (Fig. 2.5). The LOI values are very low throughout the whole segment, similar to the coarse-grained rhythmites of segment II, indicating that the sediment is devoid of organic detritus. Lower values of Si/Sr, Ca/Sr, K and a sharp reduction in Fe are coincident with marked increases in the Ti/Rb and Zr content of the sediment. Altogether, these sedimentological characteristics, notably the absence of fine-grained detrital particles, suggest a deposition through sorting of lake-bottom sediments by a highly dynamic flow, thus in agreement with an earlier interpretation that associates this silt unit with the final drainage of Lake Ojibway,

based on marked change in $\delta^{18}O$ values measured on ostracods recovered across a 1 m-interval encompassing the silt unit, which goes from very negative values typical of glacial meltwater for the underlying varves and silt bed, to more positive values with near present-day (nonglacial) values in the overlying sediments (Daubois et al., 2014).

La Reine segment V [0.18-0.14 m]

The uppermost segment of the La Reine sequence is composed mostly of a mix of massive silt and clay with an average D50 of 2.9 ± 1.3 μm that marks the end of varve sedimentation in the sequence. This segment lies immediately below the surface and could not be entirely sampled since it was highly disturbed by roots and agricultural activities. The color of the segment varies between gray (2.5 Y 5/1) and grayish brown (2.5 Y 5/2). While the LOI values remain low, the MS and all the geochemical proxies, with the exception of Zr, show a rapid increase. This massive silt and clay is present at other locations in the same general area and is likely related to the occurrence of a large post-glacial lake that once covered the region, which was initially identified by Antevs (1925) based on micro-fauna analysis from clays of the La Sarre area and later documented through $\delta^{18}O$ analyses of the sediment (Daubois et al., 2014).

2.4.4 Varve thickness correlations

Varve thickness measurements of the Matagami and La Reine sections were compared to the varve thickness record of Antevs (1925; 1928), which was recently revised by Breckenridge et al. (2012) and updated for varve 2065 to varve 2124. In the absence of distinct marker varves in our sequences (e.g. varve 1528; Antevs, 1925; 1928; Breckenridge et al., 2012; Brooks, 2016), correlations of our two thickness records with the main Ojibway varve template were based on visual inspection of the overall thickness patterns and by matching distinctive peaks/troughs with other late-

stage varve thickness records (Fig. 2.6). The best-fitting segments were then analyzed using the Pearson's coefficient (R values) in order to quantify the reliability (robustness) of the varve numbering assigned to our sequences, following procedures comparable to those carried out in similar studies (Breckenridge et al., 2012; Brooks, 2016).

Specifically, the 231 ± 7 varves of the Lake Matagami sequence were treated as a single (continuous) set of varves. In the La Reine sequence, the occurrence of two breaks in the section (segments II and IV) required the subdivision of the varve sequence into two main segments: a lower set of 35 ± 1 varves and an upper one of 65 young varves. The thickness measurements of the three sets of varves were then compared with the revised main varve template in order to isolate the interval presenting the highest Pearson's R values.

The Matagami set was moved down the sequence one varve at the time from the youngest continuous varve in the sequence (varve 2027) down to varve ~1400, and R values were calculated at each step for the corresponding interval of 231 varves. The same procedures was applied to the La Reine sequence; the upper set of 65 varves were also compared against the interval 2065-2124 using the thickness data from the Lac de Courval record of Breckenridge et al. (2012). The La Reine and Lac de Courval sites are close to each other (~35 km) and they lie in a similar geomorphological setting, being located in the upper Moose River–Lake Abitibi clay plain (elevation of ~275-295 m *asl*) and in the same distance range from the maximum limit reached by the Cochrane ice (~20-30 km). The upper part of the Lac de Courval sequence also contains a ~12 cm-thick silt layer (above varve 2124; Breckenridge, *pers comm.*), which further highlights the close sedimentological similarities between these two sites.

We based our final varve numbering on the best R values calculated for each set of varve and on the optimisation of the correlation coefficient for the common 32 varve-year interval shared by the upper Matagami and lower La Reine sequences by moving ±1 varve in each sequence with respect to the other. The best match obtained indicates that the 231 ± 7 varves at Matagami were deposited between varve years 1644 and 1874 ($R = 0.72$; $p << 0.001$). This correlation assigns the sharp increase in varve thickness and the marked color change in summer layers (and the concomitant sedimentological changes) at varve number 1817. For the La Reine record, the lower 35 ± 1 varves is correlated with varve numbers 1843 to 1877 ($R=0.84$; $p << 0.001$). The upper set of 65 varves forming the middle segment of the sequence covers the varve years 2065-2129, and is best correlated for the interval 2065-2124 ($R=0.88$; $p << 0.001$) with the Lac de Courval record (Fig. 2.1B). The upper part of the Matagami varve sequence overlaps the lower part of the La Reine sequence; this common varve interval spans the varve year 1843-1874, with an optimized correlation coefficient of $R=0.84$ ($p << 0.001$).

These correlations and associated varve numbering imply a gap of 188 varves between the lower and the upper sets of varves at La Reine, which suggests that the intervening coarse rhythmites (segment II) in the lower part of the sequence may represent an unconformity. According to the thickness trend documented in the varves segment underlying the lower rhythmites, as well as the overall stability present in the varve thicknesses of the main Ojibway template for the 1877-2027 varve interval (Fig. 2.6), the 188 missing varves would correspond to the erosion of ~40 cm of sediment.

2.5 Discussion

2.5.1 The Matagami varve sequence

The Lake Matagami sequence begins with a series of thin distal varves that shows a sudden and marked color change suggesting a shift in sediment provenance. This is supported by the onset of compositional variations at the same depth, notably a significant increase in Ca/Sr. Because the Ojibway basin is predominantly underlain by crystalline lithologies, the presence of detrital carbonate in Ojibway sediments reflects sedimentary inputs deriving from the glacial erosion of Paleozoic carbonate rocks of the Hudson Bay platform by the retreating ice margin. Indeed, carbonate rock fragments and calcareous rock flour can be found enclosed in the late-glacial till (Matheson Till) that crop out in northwestern Québec and northeastern Ontario (Veillette and McClenaghan, 1996). This first input of far-travelled Paleozoic carbonate rocks was followed by a second one from the late-glacial Cochrane surge that originated deep within the James Bay basin and deposited calcareous materials well beyond the extent of Matheson Till in Québec (Veillette et al., 1991). Within this context, we associate the sudden color change and the increase of detrital carbonates with a readvance of the ice margin into the lake basin during a Cochrane surge. This interpretation is consistent with the documented increase in the thickness of varves of segment II, which doubles within a two varve-year interval, and with the variations documented in the LOI values that can be tied with far-travelled organic detritus originating from interglacial deposits present in sedimentary sequences of the James Bay lowlands. Furthermore, the occurrence of numerous angular inclusions of mm- to cm-scale silt pellets in summer layers of the mid-segment varves likely reflect ice-rafted Ojibway sediments that rained down from the base of the Cochrane ice, consistent with a mechanism proposed in earlier studies (Hughes, 1965; Breckenridge et al., 2012; Stroup et al., 2013). The increase in the MS and in the Si/Sr, K and Fe content of the varves reflects enhanced detrital influx, while the variation in Ti/Rb

argue for a turbiditic deposition (Croudace et al., 2006); all elements that support an ice readvance.

Similar changes have also been reported earlier in a series of sections along Lake Matagami (Hardy, 1976). There, two Cochrane readvances were identified in an Ojibway varve core through marked increases in detrital carbonates and varve thickness, as well as concomitant decreases in the clay-fraction percentages of varves (Hardy, 1982). However, the timing of these changes could not be firmly assessed due to the low resolution of the record (Fig. 2.6), preventing correlations of this event with more recent varve records (Breckenridge et al., 2012).

2.5.2 La Reine varve sequence

The bottom rhythmites, thick varves and silt bed

The set of 65 thick varves forming segment III at La Reine shows grain-size, thickness pattern and geochemical characteristics, as well as a stratigraphic position (above a sedimentation break; segment II), that suggest a correlation with the Connaught series of Hughes (1965). This sequence was originally described as a series of ~60 anomalously thick varves that were younger than Antevs Timiskaming varve series, but could not be correlated on a varve to varve basis as they were locally separated from the underlying varves by a disconformity (Hughes, 1965). Based on similarities in number and stratigraphic position, a series of thick and carbonate-rich varves interpreted as evidence for a second late-glacial readvance (Cochrane II) in the James Bay basin was later correlated to the Connaught sequences (Hardy, 1976; 1982; Vincent, 1989). Those features were recently used to correlate late-stage varve sequences recovered from Lake Reid, Lac de Courval and Lac Wawagosic, from which the onset of the so-called Connaught/Cochrane II deposition was tentatively placed after varve year 2060 (Breckenridge et al., 2012). However, this chronological framework also raised questions about the origin (interpretation) of this sequence,

whereby the main template for Ojibway varve chronology indicates that these compositional changes occurred over a relatively short time span, which would be hardly sufficient to accommodate a complete (or even partial) retreat of the ice margin prior to a second ice readvance in Lake Ojibway (c.f., Breckenridge et al., 2012).

We believe that the mechanism explaining the deposition of the Connaught sequence should take into consideration the coarse-grained rhythmites present in the lower part of the La Reine that mark a sharp change in the depositional regime with respect to the underlying thin distal varves as well as with the overlying thick varves that show strong similarities with the Connaught series (Fig. 2.5). These rhythmites consist in alternating layers showing marked variations in colors and grain size, which are separated by irregular/sharp contacts. These sedimentological characteristics and the presence of numerous sub-mm to mm-scale clay/silt rip-up clasts point to a deposition in a high-energy environment. Comparable units have been reported in the Ojibway basin (Roy et al., 2011) and in other glacial lake settings where layered/coarse-grained sediment intervals including reworked sediments and rip-up clasts truncate varve sequences with sharp and erosive contacts have been linked to drainage or flood events, notably for Lake Hitchcock (Ridge et al., 1999), Lake Columbia (e.g., Atwater, 1986, Fig.13) and the Baltic Ice Lake (e.g., Hyttinen et al., 2011; Heinrich et al., 2018). Varve thickness correlations also indicate that the bottom rhythmites at La Reine mark a sediment break of 188 varves (between varves 1877 and 2065). In spite of the good R-value obtained for the lower set of 35 varves, this number remains uncertain due to the difficulty in correlating short varve sequences with the main Ojibway template. However, similar hiatuses have been reported in nearby Ojibway records, such as in the Reid Lake and Lac de Courval varve sequences (Fig. 2.6), where varve numbering indicates that ~56 and 171 varves are missing, respectively (Breckenridge et al., 2012). Altogether, these different data

argue for the presence of a widespread regional unconformity in the later part of Ojibway varve records.

The segment II at La Reine also show grain size characteristics typical of flood layers called hyperpycnites, in which the transition between the inverse to normal grading correspond to the peak discharge during the flood (Mulder et al., 2001; Mulder et al., 2009). If the grain size profile obtained is taken as a flow hydrograph, the general trend documented with the D50 (μm) values thus shows an exponential rise in flow velocity that is followed by an abrupt decrease (Fig. 2.5), which can be associated with a peak discharge and an abrupt waning of the flow velocity that is generally seen during the sudden release of meltwater (Roberts, 2005). The sharp grain-size variations and irregularities within the unit also suggest rapid changes in flow dynamics whereby non-uniform currents at the bottom of the lake and associated fluctuations in the bed shear stresses during the flood cause variations in sediment entrainment and deposition (Best et al., 2005). The sharp contacts and the presence of clay/silt rip-up clasts within the rhythmites further indicate that the discharge and velocity at flood peak were high enough to erode previously deposited sediments. Such compositional characteristics are typical of glacial lake outburst flood deposits that show highly irregular variations and pulsed changes in grain sizes reflecting the evolution of tunnels in the ice (Maizels, 1997), which is due to the runaway increase in the flow capacity of a water-filled subglacial conduit (Roberts, 2005).

Accordingly, based on these compositional characteristics and paleohydraulic considerations (Shoemaker, 1992; Clarke et al., 2004), we believe that the coarse-grained rhythmites in the lower La Reine sequence form an unconformity that is likely associated with a lake drawdown event. The fact that similar hiatuses or sedimentation gap have been reported elsewhere in Ojibway sediments (Hughes, 1959; 1965; Breckenridge et al., 2012), combined with the areal coverage of these sites (Fig. 2.1B), suggest a widespread drainage event in the Ojibway basin.

Concurrently, this rules out alternative explanations related to local or small-scale erosional/depositional process involving the reworking from wave action of nearby eskers or other coarse-grained deposits. This unconformity (and associated rhythmites) likely resulted from a sudden change in the configuration of Lake Ojibway, namely an abrupt lake level drop that was caused by the opening of a northward outlet(s) towards Hudson Bay, which would have generated strong and short-lived bottom currents responsible for this unconformity.

The geomorphological record in the Lake Abitibi area suggests the occurrence of a pre-final drainage event in the Ojibway basin. There, shoreline sequences consisting of wave-cut scarps carved into the Ojibway clay plain provide unequivocal evidence of two low level late-stage phases that likely resulted from abrupt lake level drops (Roy et al., 2015). Additional evidence for a pre-final drainage event of Lake Ojibway comes from continental and marine sedimentary records. In James Bay stratigraphic sections, Ojibway varves underlying the final drainage unit contain marine microfossils that suggest the occurrence of earlier subglacial drainage event(s) that would have allowed exchanges between the waters of Lake Ojibway and the Tyrrell Sea (Roy et al., 2011). Marine cores in the Labrador Sea show two close meltwater discharges separated by ~50 years around 8.2 ka BP (Jennings et al., 2015), while other cores in this region show two detrital layers around this interval (Ellison et al., 2006; Hillaire-Marcel et al., 2007). Other evidence for a multi-step drainage of Lake Agassiz-Ojibway comes from high-resolution relative sea level (RSL) records (Hijma and Cohen, 2010; Li et al., 2012; Törnqvist and Hijma, 2012; Lawrence et al., 2016).

Associating the lower rhythmites/unconformity at La Reine to a widespread drainage event also implies that the Connaught sequence likely represents a renewed phase of varve deposition that probably took place in either a shallow remnant of Lake Ojibway (but of sufficient depth to allow varve sedimentation) or during a

refilling phase of the lake basin that could have reached the minimum level of 381 m in the Matagami area (Veillette et al., 1991). Our sedimentological and compositional data (Fig. 2.4), such as multiple graded laminae (mm-scale) in the summer layers representing temporal pulses of detrital materials, suggest that the Connaught sequence was likely sourced by strong meltwater underflows associated with subaqueous outwash fan activity, which decreased with the subsequent retreat of the ice margin. The abrupt increase in carbonate (Ca/Sr) and organic content (LOI) of these 65 varves suggests increased sediment influx in the basin from far-travelled source over the James Bay Lowlands, thus indicating a deposition linked to the Cochrane ice. The lack of ice-rafted material in the La Reine sequence (Fig. 2.4), however, indicates that the Lake Abitibi basin was likely isolated from ice-rafts and icebergs at the time of the deposition of the Connaught varves, which is consistent with deposition in a small shallow basin that was not directly influenced by the decaying ice margin, as shown by its position outside the extent of gritty clay area (Fig. 2.1B).

Although the La Reine sequence shows marked changes in varve sedimentation that may relate to drawdown events, the lack of clear unconformities points to a need of examining alternative interpretations. For instance, the 10 cm-thick rhythmites forming segment II could be interpreted as continuous varve sedimentation recording the sudden deposition of thick/coarse summer layers and thinner/finer winter layers, in which the occurrence of the silt/clay clasts would reflect IRD deposition from sediment-rich icebergs or rainout from a floating ice margin. This would imply a sudden and rapid readvance of the Cochrane ice within the basin (the Cochrane II) or a massive and abrupt disintegration of a nearby Cochrane ice margin. This interpretation would also associate the overlying thick varves (segment III, c.f. Connaught series) with a period of deposition close to the ice margin (proximal varves).

While this scenario is coherent with the deglaciation context of the Ojibway basin, a few inconsistencies remain with the documented varve record. Varve correlations based on the available Ojibway varve series (Breckenridge et al., 2012) indicate a hiatus of 188 varves in the La Reine sequence associated with the bottom rhythmites. Therefore, assuming a continuous varve deposition for this sequence would suggests the occurrence of some discrepancies in the numbering of late Ojibway varve records, such as the varve sequences of Reid and de Courval lakes where hiatuses have also been reported (Breckenridge et al., 2012). Also, if the thick varves of La Reine segment III were related to a deposition linked to a nearby Cochrane ice margin – thus similar to segment II in the Matagami varve sequence – we would expect the occurrence of more IRD clasts/pellets and compositional changes indicative of turbiditic deposition within this interval, as well as a common occurrence of IRD in varves to the south of La Reine. This later aspect is unsupported by mapping surveys (e.g., Thibaudeau and Veillette, 2005), whereas the maximum extent of the Cochrane II readvance is confined >150 km to the north in Ontario and Québec (Fig. 2.1). The transition between segments III and IV at La Reine also lacks a clear unconformity, yet the $\delta^{18}O$ data clearly show that the thick silt bed (segment IV) records the termination of glaciolacustrine sedimentation in the region (Daubois et al., 2014). For those reasons, and given the data available at this time, we tend to favour the earlier interpretation associating the bottom rhythmites at La Reine to a lake drawdown event. We also note that the two interpretations are not entirely incompatible (discordant), whereby the second readvance may have destabilized the ice dam and allowed meltwater to escape from the basin (see below). Future work on late Ojibway varve sequences should refine the spatial variability of these distinct sediment facies and improve the main varve chronology (correlations).

Finally, the section at La Reine shows another marked compositional change that is represented by a thick silt unit present in the upper part of the varve sequence (segment IV). This interval is characterized by a sharp color change and other

compositional variations that are tied to the presence of the coarse silt layer. The unit is bounded by sharp upper and lower contacts, as well as an abrupt coarsening of the sediments that is followed by a slow winnowing for the remaining of the interval (Fig 2.5). This structure is roughly similar to the one documented in the bottom rhythmites and suggests deposition in a high-energy environment, likely corresponding to the propagation of subglacial flood waves (Roberts, 2005). The upper La Reine unit can be traced over a large area (3600 km^2) and previous work on this marker bed indicates that it was associated with the final drainage of Lake Ojibway (Daubois et al., 2014). Consequently, the varve sequence at La Reine contains evidence for two closely-spaced lake-drawdown events, including the final drainage of Lake Ojibway.

2.5.3 Timing of ice readvance, Connaught deposition and drainage events

Correlation of our varve thickness records with the main Ojibway varve thickness template of Antevs (1925; 1928) indicates that the Matagami and La Reine varve sequences overlap, providing a composite sequence that documents late-stage events in the Ojibway basin. The lower part of this sequence is marked by the sudden deposition of detrital carbonates in the Lake Matagami varves that record a Cochrane readvance starting at varve year 1817. This is consistent with other Ojibway records in northwest Ontario where comparable thickness variations are present in varve series spanning the interval v1800-v1900 (Fig. 2.6), notably at the northernmost site with pre-Cochrane sediments (Antevs site 138; Fig. 2.1B) where the oldest varve covered by the Cochrane till correspond to varve year 1816 (Breckenridge et al., 2012).

If our correlation is correct, the spatial distribution of the sites documenting this event points to a rapid and synchronous basin-wide ice readvance, with an ice front spreading at least 400 km in width (Fig. 2.1B). This implies that the ice that advanced into the lake and overrode the predominantly soft, clayey bed was likely an

ice shelf, which was probably prone to severe calving (fracturing), as indicated by the widespread occurrence of iceberg furrows and numerous ice-rafted material inclusions and rip-up sediments present at the surface and in the sediment south of the maximum limit reached by the Cochrane ice (Veillette and Pomares, 2003; Thibaudeau and Veillette, 2005; Paradis, 2007a; 2007b; Veillette, 2007a; 2007b; Veillette and Thibaudeau, 2007; Paradis et al., 2017; Veillette et al., 2017d). This is also supported by the fact that Cochrane Till does not occur above a specific elevation (~300 m), which indicates that the ice front was controlled primarily by the lake level and topography, thus in agreement with the model of a thin, distal and semi-buoyant surging ice margin (Veillette et al., 2017a). The turbiditic nature of the 21 varves immediately overlying varve 1817 suggests the calcareous material was carried in the silt fraction towards the southern basin through a sediment plume that likely originated from the ice margin that had reached the Hudson-James Bay lowlands. Despite a marked increase in varve thickness, the lack of significant variations in the Zr content in the Matagami sequence highlights the absence of coarse silts in the bulk sediments, in agreement with the plume hypothesis. This is also consistent with the delayed occurrence of ice-rafted silt-pebbles in the sequence, which appear at least 9 varve years after the onset of detrital carbonate sedimentation.

Elsewhere in the basin, thin varves sedimentation occurred between varve years ~1900 and 2010, as indicated by the Temiskaming D8-D11 and Frederick House sites (Fig. 2.6) that suggest that the progression of the surging ice in the basin was accompanied by a severe reduction of the meltwater flux. The abrupt increase in varve thickness during the following varve interval 2010 to 2027 at both sites likely reflects the proximity of the advancing ice margin (Fig. 2.1).

The coarse-grained rhythmites marking the lower unconformity (segment II) in the La Reine varve sequence represents the second significant sedimentological change in this late Ojibway varve record, which is interpreted as a major lake

drawdown. This event took place after the Cochrane readvance reached its southernmost extent after varve years 2024-2027, as indicated by the Temiskaming D8-D11 and the Frederick House sequences (Fig. 2.6), and prior to the return of varve sedimentation in the southern basin shortly after varve year 2060, which marks the onset of the rapid melting of the Cochrane ice and the deposition of the Connaught sequence (Hardy, 1976; Breckenridge et al., 2012). The thickness of the first Connaught varve at La Reine shows a good correlation with the nearby Lac de Courval varve sequence, which assigns the onset of Connaught sedimentation at varve year 2065, following an initial drainage of the lake, presumably close to a retreating Cochrane ice margin (Breckenridge et al., 2012). A rapid rise in the meltwater influx from the Cochrane ice margin could explain the sharp increase of the Connaught varves between v2065 and ~v2080, where the greatest varve thickness observed in all the Connaught sequences is reached and likely reflect a peak in the meltwater discharge. Immediately following this peak, a rapid thinning of varves is observed in all the Connaught sequences and is associated with the rapid and generalized retreat of the Cochrane ice margin in the basin. Our varve chronology also places the uppermost varve of the Connaught sequence, thus the last Ojibway varve, at varve year number 2129, which is overlain by the thick silt bed that record the final drainage of the lake (segment IV at La Reine) (Daubois et al., 2014). The two drainage events documented in the La Reine sequence are separated by 65 years, which is a minimum time span given the sharp/irregular contact with the overlying drainage unit, which suggests that some erosion may have occurred during the deposition of this silt bed.

Altogether, these results point to a single, rapid and basin-wide expansion (surging) of the Cochrane ice in Lake Ojibway. This readvance may have played a role in the first drainage event documented, mainly through a destabilization (thinning) of the ice dam formed by the LIS remnant in Hudson Bay. This initial lake drawdown through a subglacial outburst floods was likely followed by a refilling of

the lake basin, which together with sustained thinning and disintegration of the ice dam initiated a subglacial drainage and triggered the final drawdown of Lake Ojibway. This single ice-surge interpretation contrasts with earlier work that argued for the occurrence of two Cochrane events from varve sections around Lake Matagami (Hardy, 1976; 1982). If a second Cochrane readvance occurred, it was likely restricted to local events in the northern parts of the Ojibway basin (c.f., Hardy, 1976). However, our investigations indicate that the uppermost part of the section sampled at Lake Matagami comprise an additional set of thick varves (Fig. 2.2B) that could represent the second readvance implied by Hardy (1976; 1982). This part of the Matagami section could not be sampled due to the intense desiccation and important disturbance of the varves by roots and vegetation. Nonetheless, our varve chronology suggests that these thick varves lie at a stratigraphic position that corresponds to the Connaught sequence (Fig. 2.6). Our interpretation is consistent with other Ojibway records that also document a single major Cochrane readvance in the basin (Hughes, 1959; 1965; Breckenridge et al., 2012).

2.6 Conclusions

High-resolution analyses of two varve sequences in northwestern Québec document late-stage events in the Lake Ojibway basin that covers the last ~310 years of its existence.

- The base of the record shows marked sedimentological and compositional changes characterized by the sudden arrival of detrital carbonates and ice-rafted material, which are associated with the late-glacial Cochrane readvance. The late Ojibway varve record suggests a synchronous and widespread Cochrane event in the basin, which likely took place under an abrupt ice surge characterized by a shelf-like margin that was controlled by the level of the lake and constrained by topography.

- This major ice readvance appears to have played an important role on the evolution of the lake. The Cochrane varves are topped by a set of coarse-grained rhythmites that mark an important sedimentological change in the late-stage varve sedimentation, which our varve chronology associates with an important hiatus that we attribute to a major lake drawdown. An alternative interpretation associates the anomalous rhythmites with a deposition linked to a sudden and quick readvance of the ice margin in the basin (c.f., Cochrane II), but this scenario involving continuous varve deposition is difficult to accommodate with the available late-stage varve records and other geological considerations. Nonetheless, the Cochrane readvance may have destabilized the ice dam profile and allowed this drawdown event. Sedimentation resumed rapidly in a shallow Lake Ojibway, as these rhythmites are overlain by 65 thick varves that can be correlated with the varves forming the Connaught sequence recognized elsewhere in the basin (Hughes, 1959; 1965; Breckenridge et al., 2012).

- The Connaught varves are capped by a faintly laminated to massive silt unit that is associated with the final drainage of Lake Ojibway based on stratigraphic considerations and contrasting oxygen isotope compositions between the silt unit and the overlying massive clay (Daubois et al., 2014). This marker bed shows several compositional and sedimentological characteristics with the bottom coarse-grained rhythmites thus arguing for the occurrence of two unconformities within the sequence.

- The correlation of our varve sequences with the main Ojibway varve record indicates that the sedimentological/compositional changes documented have a regional significance as similar features of comparable magnitude were identified elsewhere in the Ojibway basin. The results thus indicate that late-stage history of

Lake Ojibway is marked by two distinct and widespread drainage events, which are identified for the first time in a single varve sequence.

- According to our varve chronology, the two drainage events are separated by at least 65 years. This is consistent with marine and costal records that document at least two closely-spaced meltwater discharges and sea level rises during the interval of the last deglaciation comprising the drainage of Lake Agassiz-Ojibway.

- These results provide important field-based constraints on the timing and the number of meltwater discharges from Lake Agassiz-Ojibway into the North Atlantic Ocean during the final stages of the deglaciation. Efforts should be made at identifying the geomorphic expression (shoreline sequence) of the lake levels associated with these lake drawdowns in order to quantify the meltwater volumes involved in these events, which represent critical constraints in assessing the impact of freshwater forcings on climate, an important issue in a context of rapidly warming climate.

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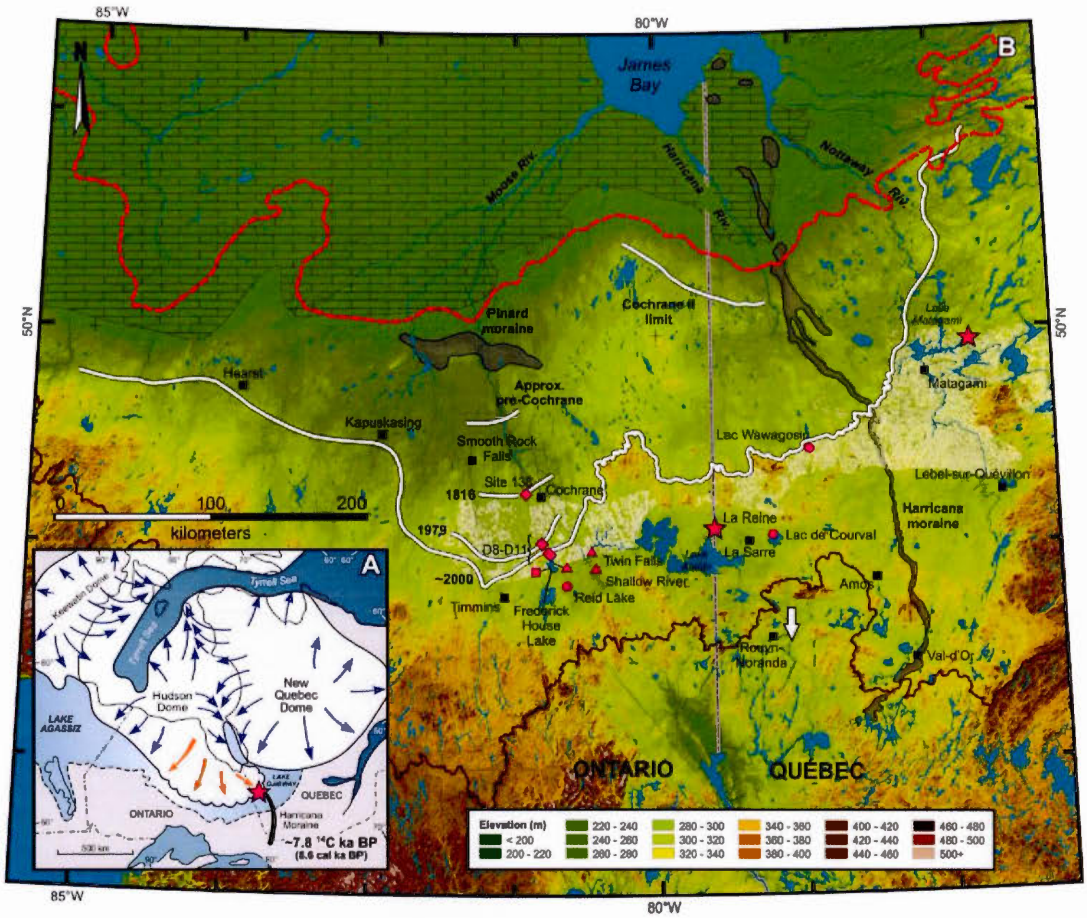

Figure 2.1 A) Schematic map showing the extent of Lake Agassiz-Ojibway and the Laurentide Ice Sheet at the time of the Cochrane readvance (orange arrows) (Dyke et al., 2003; Dyke, 2004). Pink star shows the general location of the study area. **B)** General map of the study area showing the location of the Matagami and La Reine varve sections (pink stars) and the main geomorphic (moraine) features in the basin (grey) (Fulton, 1995; Veillette et al., 2003; Veillette et al., 2017b). Other varve localities are also showed in pink, where diamonds refer to Antevs sites (Antevs, 1925; 1928); triangles correspond to localities where the Connaught sequence was originally described (Hughes, 1959; 1965); circles refer to other sites with Connaught varves were identified (Breckenridge et al., 2012); and squares correspond to the recently cored Frederick House Lake sequence (Greg Brooks, *pers. comm.*). **(continued)**

Fig. 2.1 (continued) The thick white line shows the southern limit of the Cochrane ice readvance (grounding line) and the white shaded areas correspond to the extent related surge deposits where an ice-rafted debris-rich layer (*gritty clay*) is present at the top of the Ojibway sequence (Boissonneau, 1966; Veillette and Pomares, 2003; Thibaudeau and Veillette, 2005; Paradis, 2007a; 2007b; Veillette, 2007a; 2007b; Veillette and Thibaudeau, 2007; Paradis et al., 2017; Veillette et al., 2017d). The limit of the Cochrane II ice extent is also presented (Hardy, 1976). Shorter thick white lines show the southward progression of the Cochrane ice front in Ontario (Breckenridge et al., 2012). The red line outlines the Tyrrell Sea limit (Dredge and Cowan, 1989; Vincent, 1989) The maroon line correspond to the present-day drainage divide separating the St. Lawrence River and the Hudson Bay watersheds. The white arrow along the divide corresponds to the late Kinojévis outlet with an elevation of 300 m (Vincent and Hardy, 1979). The area is underlain by igneous and metamorphic rocks of the Canadian Shield, except to the north, where Paleozoic and Mesozoic sedimentary rocks (brick pattern) are present (Wheeler et al., 1997).

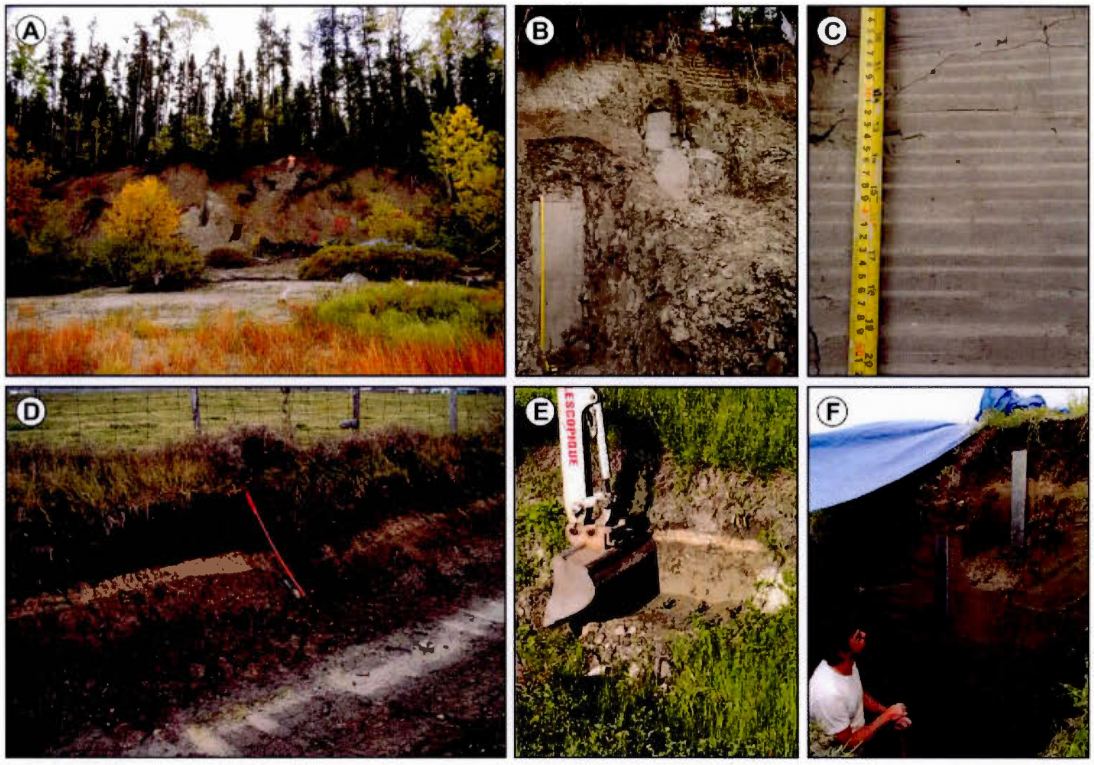

Figure 2.2 Sample sites. **A)** Lake Matagami stratigraphic section, **B)** close view of this section, and **C)** close view of the sampled varves. **D)** drainage varve in the region of La Reine (Daubois et al., 2014), **E)** close view of the drainage varve at the La Reine site, and **F)** close view of the sampled varves.

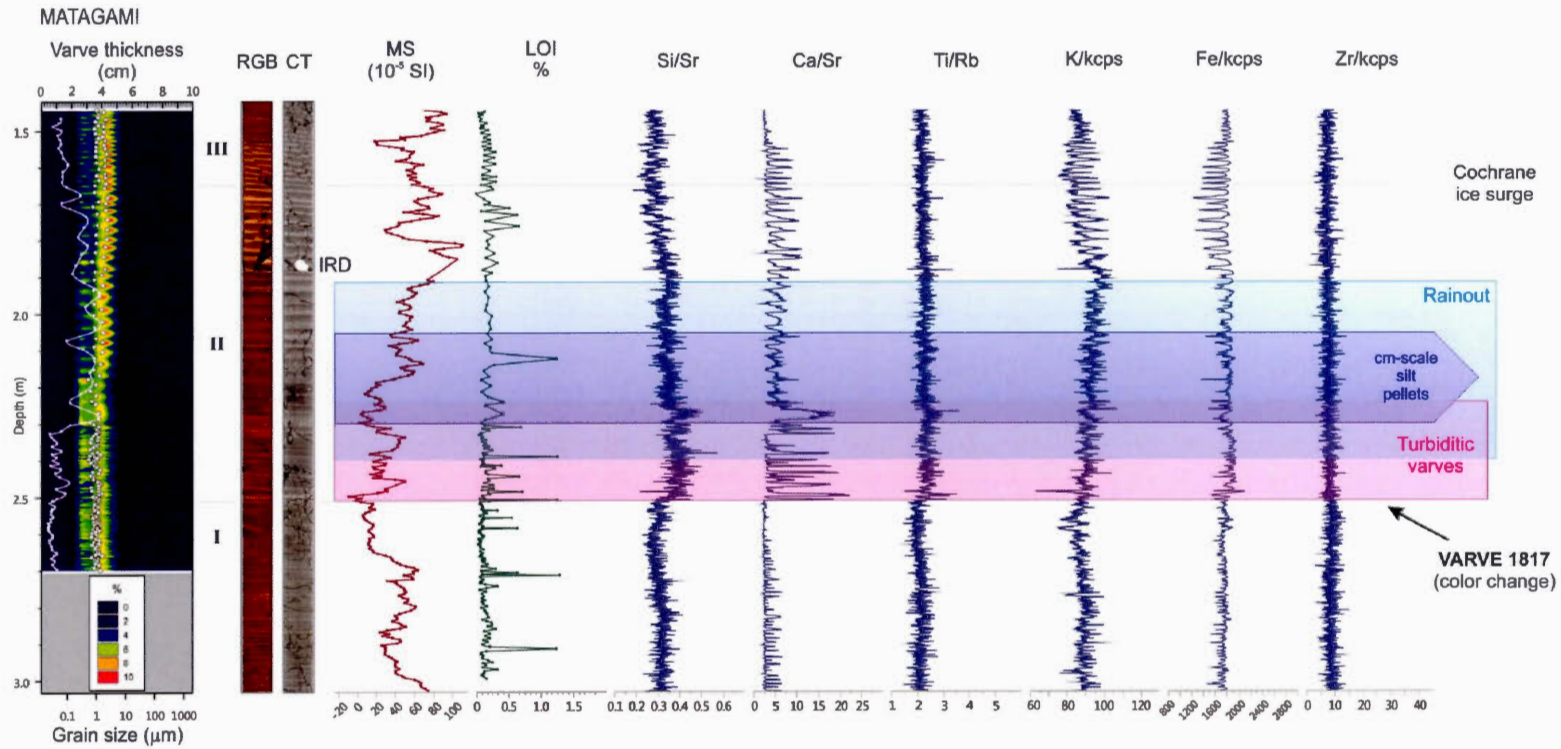

Figure 2.3 Particle size distribution for the Matagami varves are expressed as surface plots of grain-size data (Beierle et al., 2002) with the D50 or median (white dots) values. Varve thickness data (white line) are superimposed on the grain-size data. High-resolution RGB and CT-scan images are also shown along with the magnetic susceptibility (MS) and loss on ignition (LOI) data. High-resolution elemental ratios are shown by the blue lines. Note that the apparent lighter color of the summer layers upward from 1.87 cm is not linked to sedimentological changes, but to the sampling conditions of the sediments that were desiccated towards the top of the section.

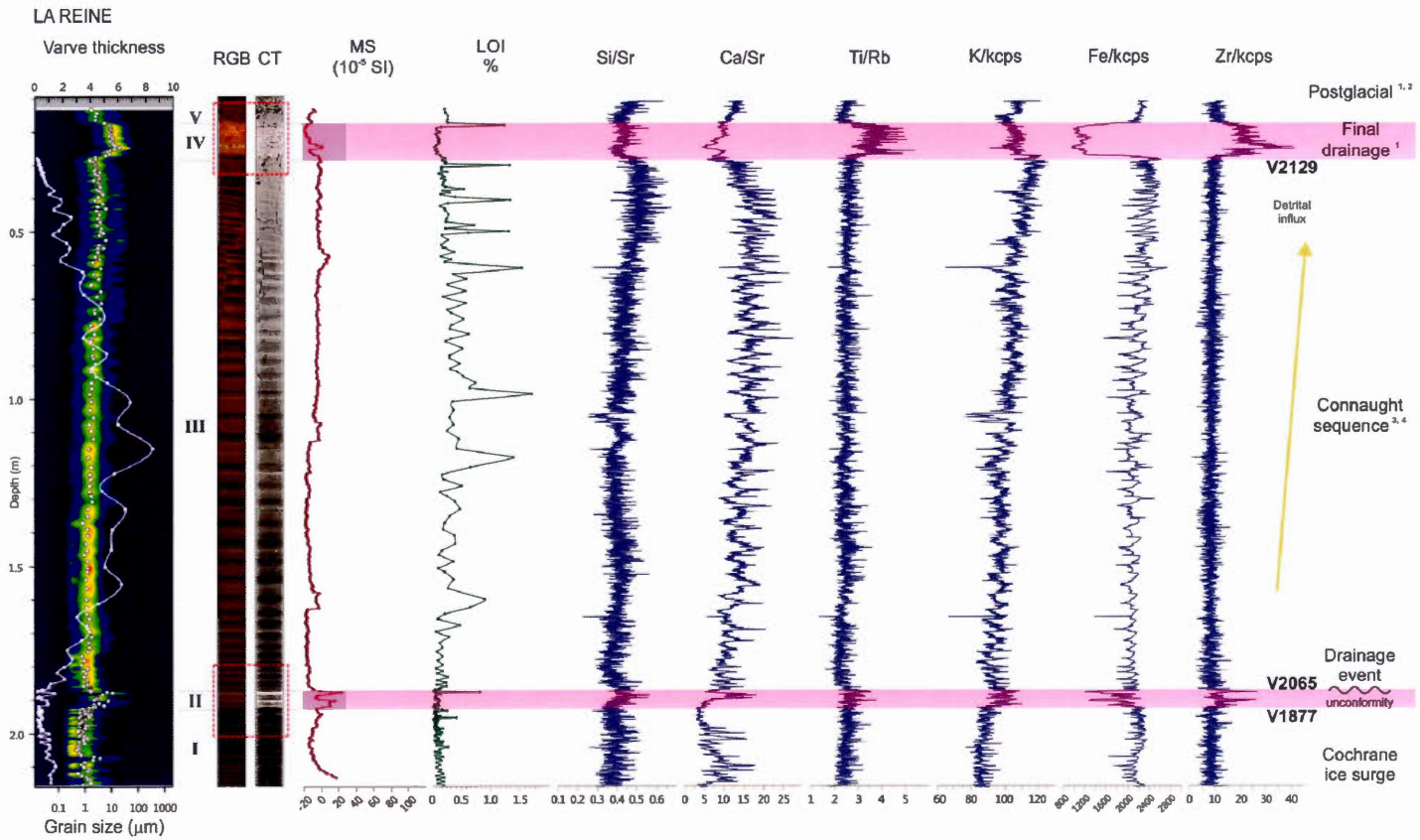

Figure 2.4 Particle size distribution for the La Reine varves are expressed as surface plots of grain-size data (Beierle et al., 2002) with the D50 or median (white dots) values. Note that the color scale is the same as the one used in Fig.2.3. Varve thickness data (white line) are superimposed on the grain-size data. High-resolution RGB and CT-scan images are also shown along with the magnetic susceptibility (MS) and loss on ignition (LOI) data. High-resolution elemental ratios are shown by the blue lines. Red dashed boxes refer to the close-up views presented in Fig. 2.5. 1: Daubois et al. (2014); 2: Antevs (1925); 3: Hughes (1959; 1965) and 4: Breckenridge et al. (2012).

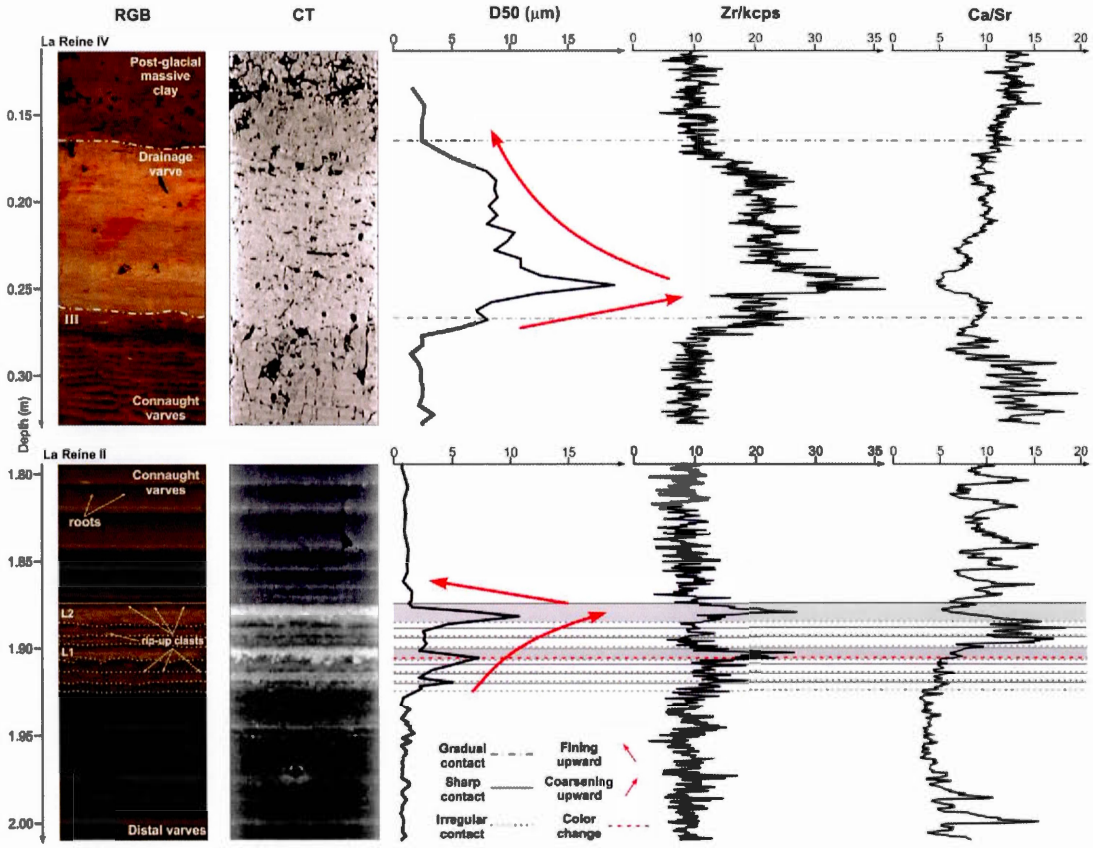

Figure 2.5 Close-up views of RGB and CT images for the two coarse sediment intervals present in the La Reine varve sequence. The coarse rhythmites forming the lower interval was interpreted as an unconformity while the silt bed at the top was documented as a drainage varve (Daubois et al., 2014). The D50 or median grain-size values are shown along the Zr/kcps and Ca/Sr high-resolution profile to document these two layers (see text for details).

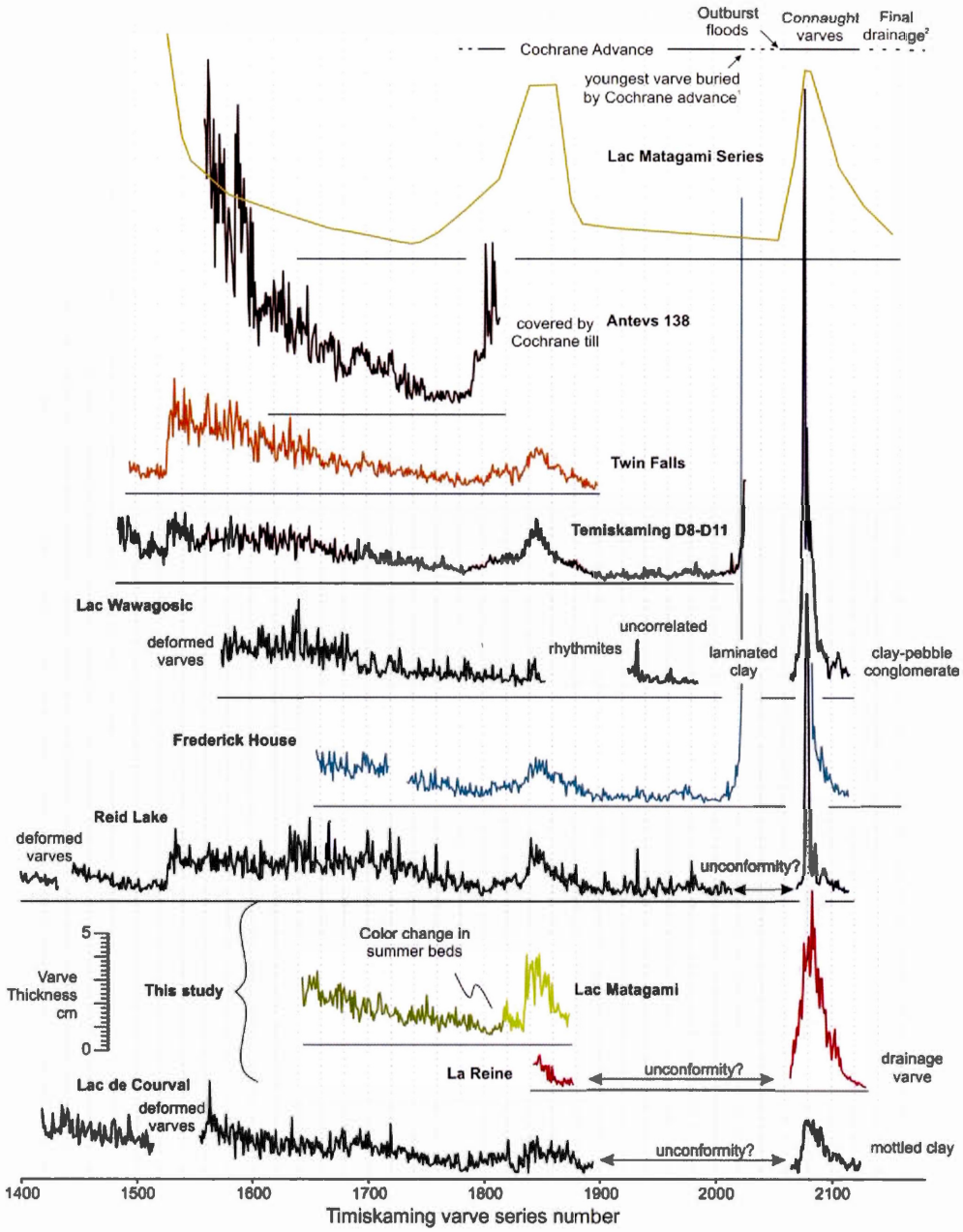

Figure 2.6 Correlated varves thicknesses records related with the Lake Ojibway late-stages according to the varve number. Present study Lake Matagami data (green) and La Reine (red) compared with the Lake Matagami Series (yellow) from Hardy (1976), Site 138 and Temiskaming D series (maroon) from Antevs (1925; 1928), Twin Falls (orange) data from Hughes (1959; 1965), and late-stage sequences from Breckenridge et al. (2012) (dark blue) and Brooks (*pers. comm.*) (light blue). Modified from Breckenridge et al. (2012). 1: Breckenridge et al. (2012); 2: Daubois et al. (2014)

CHAPITRE III

RECONSTRUCTING THE LAKE-LEVEL HISTORY OF THE EASTERN LAKE AGASSIZ-OJIBWAY BASIN USING A LIDAR-BASED INVENTORY OF SHORELINES

Pierre-Marc Godbout, Martin Roy & Jean Veillette

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Godbout, P.-M., Roy, M. & Veillette, J.J. (2018). *Reconstructing the lake-level history of the eastern Lake Agassiz-Ojibway basin using a LiDAR-based inventory of shorelines.*

Contribution des auteurs:

P.M.G., M.R. et J.V. ont développé cette étude. P.M.G. a interprété les données, écrit l'article et préparé les figures. M.R. et J.V. ont participé à l'interprétation des données et contribué à la rédaction de la version finale de l'article.

Abstract

Lake Ojibway occupied NE Ontario and NW Québec between 10.6 and 8.2 ka cal BP. Paleogeographic reconstructions depict Lake Ojibway and Lake Agassiz sharing a common water plane late in the last deglaciation, shortly before their final drainage ~8,200 years ago. This pre-drainage lake surface is defined from shorelines present in the Ojibway basin and is associated with an outlet standing at 300 m. However, the associated lake stage is constrained by scattered and inadequately defined geomorphologic evidence, which convey large uncertainties in the meltwater volume calculations used to assess the impact of the freshwater forcing associated with the final drainage of the lake. Here, we address this issue by mapping and measuring the elevation of 3098 shorelines from a LiDAR digital terrain model (DTM). Our GIS-based reconstruction integrates the paleotopography of the Ojibway basin at 8.5 ka using the ICE-6G model. Our results identify 3 widespread stable lake-levels separated by two major lake drawdowns. The documented lake level sequence indicates that the outlet formerly associated with the lake surface of the coalesced Lake Agassiz-Ojibway does not correspond to a stable water plane. Our reconstruction provides firm evidences for a two-step drainage of Lake Agassiz-Ojibway, and indicates that the pre-drainage surface(s) and even the connection between the two lakes should be reevaluated. Overall, the results refine considerably the Ojibway shoreline sequence and the documented changes in lake levels are consistent with continental, marine and relative sea-level records showing evidence for at least two significant meltwater outbursts during the late deglacial interval.

Keywords: Lake Agassiz-Ojibway; Reconstructions of lake levels; 8.2 ka cooling event; drainage events; LiDAR DTM.

3.1 Introduction

The retreat of the south-central sector of the Laurentide Ice Sheet (LIS) during last deglaciation was accompanied by the development of large ice-contact lakes such as Lake Agassiz and Lake Ojibway that inundated vast expanses of the newly deglaciated terrains (Fig. 3.1A) (e.g., Elson, 1983; Teller, 1987). The areal extent and depth of these glacial lakes were largely controlled by the configuration and dynamics of the retreating ice margin, which was marked in places by minor oscillations. The basin geometry of the lakes was therefore intimately linked with the pattern of ice retreat, while lake levels fluctuated with the opening of outlets and/or with spillway erosion, as well as with changes in glacial isostatic adjustment of the land surface. Lake Barlow-Ojibway (Coleman, 1909) occupied northwestern Québec and northeastern Ontario between 10 570 and 8 200- 8 150 cal yr BP (Dyke, 2004), while Lake Agassiz of longer duration already occupied the central Canadian Prairies (Fig. 3.1A). Both lakes evolved independently throughout most of deglaciation, until the late deglacial stages when ice retreat presumably allowed both lakes to coalesce and inundate the low-lying terrains from Manitoba to Québec (e.g., Thorleifson, 1996). The rapid disintegration of the LIS remnant over Hudson Bay and the subsequent collapse of the ice dam allowed the drainage of this then presumably single water body into postglacial Tyrrell Sea (Dyke and Prest, 1987; Josenhans and Zevenhuizen, 1990; Veillette, 1994; Teller et al., 2002; Lajeunesse and St-Onge, 2008). The sudden and massive discharge of meltwater into the Labrador Sea – a climatically sensitive region of the North Atlantic – impeded the Atlantic meridional overturning circulation (Barber et al., 1999; Ellison et al., 2006; Hillaire-Marcel et al., 2007; Kleiven et al., 2008) and triggered a widespread 160 years cold anomaly centered *ca.* 8200 yr BP, as documented in Greenland ice cores (Alley et al., 1997; von Grafenstein et al., 1998; Kobashi et al., 2007; Thomas et al., 2007).

Assessing the impact of freshwater forcings from glacial lakes requires reliable estimates of meltwater volumes involved in drainage events (e.g., Clarke et al., 2004), which in turn rely on accurate paleogeographic reconstructions depicting the evolution of these glacial lakes (e.g. Leverington et al., 2002a). The history (evolution) of glacial lakes is generally reconstructed from complex sequences of raised shorelines that record changes in lake levels, while the areal extent (and depth) of specific lake stages rely on correlations of shoreline sequences from different regions that are often separated by several hundred of kms (e.g., Thorleifson, 1996). The mapping and correlations of shorelines form a critical step in evaluating the impact of glacial lake drainage, as most of the uncertainties in meltwater volume calculations arise from the lack of knowledge on the geometry of the lake basins, which varied markedly during deglaciation in response to shifts in outlet locations, position of the ice margin, and constantly changing topography (elevation) due to the differential post-glacial uplift. In the case of Lake Agassiz and Lake Ojibway, the understanding of their evolution during the late-stages of deglaciation hinges primarily on rare and scattered shorelines and associated geomorphological features present in the eastern (Ojibway) basin (Thorleifson, 1996), which form the lowest terrain south of latitude 49°N. These shorelines were used to identify three lake levels and associated outlets that controlled the elevation of the lake surface throughout its existence (Vincent and Hardy, 1979).

The lowest (and presumably the youngest) of these lake levels – the late Kinojévis lake stage – has been commonly associated with the lake surface that preceded the final drainage of the Lake Agassiz-Ojibway in several reconstructions (Thorleifson, 1996; Leverington et al., 2002a; Teller et al., 2002). However, the record of shorelines defining the late Kinojévis lake stage is scarce, with only fewshorelines providing firm constraints on this lake level (Fig. 2; Vincent and Hardy, 1979). Although other geomorphological considerations argue for a stable lake surface resembling the late Kinojévis lake level (Veillette, 1994), this lake stage

remains nonetheless only broadly defined in the Ojibway basin, a situation that introduces significant uncertainties in paleogeographic reconstructions. In the absence of a better-constrained lake level sequence, reconstructions have tentatively correlated shorelines of the late Kinojévis lake stage to those of the Ponton lake stage in the Agassiz basin, thereby giving rise to a widespread lake surface spanning several hundred of kms of across the Agassiz-Ojibway (e.g., Thorleifson, 1996; Leverington et al., 2002a). However, recent investigations of low-elevation shorelines in the core-basin of Lake Ojibway provide unequivocal evidence for the occurrence of additional lake levels (Roy et al., 2015), which form water planes projecting below the elevation of the Kinojévis outlet system that controlled the lake surface elevation. These lake levels argue for abrupt lowering of the lake surface during the late-stages of deglaciation and provide support for a sequential drainage, as suggested by sedimentary records in the basin (Roy et al., 2011; Godbout et al., submitted) and in the marine environment (Lajeunesse and St-Onge, 2008; Jennings et al., 2015). Although these lake levels may be correlative to similar low-lying "Fidler" shorelines in the western Agassiz basin (Klassen, 1983), this link remains to be proven. Furthermore, because detailed study of shorelines mainly focussed on the maximal level of submergence in the Ojibway basin (Fig. 2; Veillette, 1994), documenting the occurrence and extent of shorelines of intermediate and low elevation could help resolving discrepancies on the late-stage evolution of the lake. Altogether, these new elements call for a revaluation of the Lake Agassiz-Ojibway lake-level evolution to ultimately refine our understanding of the events surrounding the final drainage of the lake.

Here, we present a synthesis of lake levels in the Ojibway basin based on 3098 elevation measurements of shorelines mapped using a high-resolution LiDAR digital terrain model (DTM) covering ~29,000 km^2 in northwestern Québec (Canada), which was supplemented by field-based measurements of shoreline sequences. Our reconstruction of the lake-level history is centered on a Geographic Information

System (GIS) methodology that projects the new shoreline data set on a land surface represented by the Canadian Digital Surface Model (CDSM) and that takes into account the paleotopography at 8.5 ka, i.e., the isostatically deformed land surface predicted by the ICE-6G model (Peltier et al., 2015). This approach allows the identification of distinct shoreline populations that record the development of stable lake levels and intervening lake surface drawdowns. Our results considerably refine the lake-level history of the Ojibway basin and provide a better understanding of the sequence of late-stage events that led to the final drainage of the Lake Agassiz-Ojibway.

3.2 Lake Ojibway background

During deglaciation, the northward retreat of the LIS margin caused a succession of two main glacial lakes to develop and progressively expand during a period of ~2100 years in NE Ontario and NW Québec, where emergence of the land surface caused by progressive glacial isostatic adjustment resulted in the separation of these meltwater bodies. They later presumably shared a common water plane for a brief interval of time – the Lake Barlow-Ojibway (Antevs, 1925). Lake Barlow initially occupied a basin comprising the upper Ottawa River valley while Lake Ojibway refers to the vast meltwater accumulation confined to the north of the drainage divide between the Hudson Bay and the St. Lawrence River (Coleman, 1909). For most of its existence, including its coalescence with Lake Agassiz, excess meltwater from the Ojibway basin is presumed to have drained southward via the Ottawa River through a single outlet, which position and elevation varied through time due to the glacial isostatic emergence of the drainage divide (Vincent and Hardy, 1979; Veillette, 1994).

Few studies document the evolution of Lake Ojibway during deglaciation. This is mainly due to the discontinuous distribution of shorelines and associated

geomorphological features across the basin. Additional constraints include a dense forest cover and limited ground access, which complicate the identification and direct elevation measurements of shorelines. A regional survey presented a synthesis of shoreline data that were grouped under three lake-level phases that presumably marked stable lake surfaces: the Angliers and the early and late Kinojévis lake stages (Vincent and Hardy, 1979), which were linked to the maximum level of submergence reached by Lake Ojibway. Subsequent work provided additional measurements on the maximum level reached by the lake, mostly washing limits, and a first volumetric estimate of freshwater transferred to Tyrrell Sea at the time of the final lake drainage (Veillette, 1994).

In these reconstructions, the different lake stages were linked to a series of outlets with specific positions and elevations. The Angliers stage marks the isolation of the Lake Ojibway north of the continental drainage divide and was initiated by the glacial isostatic emergence of a rocky sill at 260 m above sea level (asl; thereafter all elevations are in asl) (Figs. 3.1B; 3.2). This high-elevation lake level represents so far the best-defined stage in the basin, with a maximum level of submergence reaching up to 424 m at Mont Plamondon in the study area (Veillette, 1994) (Figs. 3.1B; 3.2). The lake surface may have reached higher levels north of Mont Plamondon, but the lack of topographic rises in this part of the James Bay basin prevents such levels to be recorded. A straight line joining this 424 m lake-limit to the location of the 260 m outlet along the defined regional tilt axis orientated at N 17°E outlines a shoreline gradient of 0.9 m/km for this lake level (Vincent and Hardy, 1979; Veillette, 1994) (Fig. 3.2). The application of surface exposure dating on rock surfaces at the core of erosional shorelines (washing limits) constrained the Angliers stage at 9.9 ± 0.7 ka, thereby providing the first and only chronology on the Ojibway shoreline sequence, and assigning this lake stage to the early stages of regional deglaciation (Godbout et al., 2017).

The two Kinojévis lake stages mark the northward migration and progressive emergence of the drainage divide along the Kinojévis River system towards its present-day position (Fig. 3.1B). The early and late Kinojévis stages represent arbitrary lake levels that were initially defined to illustrate the trend of shoreline development and the gradual lowering of lake levels in the basin, which lead to broad estimations of lake surface gradients varying between 0.5-1.2 m/km for both stages (Vincent and Hardy, 1979). The early Kinojévis lake stage was associated with an outlet standing at 275 m and does not represent a stable water plane, while the late Kinojévis stage was linked to a 300 m-high outlet characterized by deeply incised channels cutting across the drainage divide that clearly formed the last possible routing of meltwater overflow to the south (Figs. 3.1B; 3.2) (Vincent and Hardy, 1979). For this reason, it has long been considered as the main lake stage that preceded the final drawdown of Lake Ojibway and consequently was used to reconstruct the coalesced water plane with Lake Agassiz (Thorleifson, 1996; Leverington et al., 2002a).

However, the number of geomorphological evidence (raised shorelines) marking a stable late Kinojévis lake level remains low in the Ojibway basin (c.f., Fig. 2 Vincent and Hardy, 1979). This situation reflects the lack of topographic rises high enough to record high-elevation lake levels deep within the Ojibway basin, which has always limited recognition of shorelines. According to available reconstructions (Vincent and Hardy, 1979; Thorleifson, 1996), the development of the two Kinojévis stages was coincident with readvances of the southern LIS margin into Lake Ojibway during the late stages of the deglaciation (e.g., Hardy, 1976). Although the number, extent and exact timing of these Cochrane events remain to be specified, recent studies suggest that the late-glacial ice dynamics likely played a significant role in changing the lake configuration (elevation/extent) and possibly triggered lake drawdown events in the Ojibway basin (Roy et al., 2011; Roy et al., 2015; Godbout et al., submitted).

Despite these uncertainties, the paleogeographic context during deglaciation provides vital information about the level of the lake at the time of Cochrane events. Indeed, these ice readvances brought into the basin distinct ice-rafted glacial erractics from the carbonate rocks of the Hudson Platform and from Proterozoic rocks of Churchill Province located to the north (Veillette et al., 1991; Veillette, 1994). Because these erratics were not found above a certain elevation (c.f., ~350 m at Mt. Plamondon; Figs. 3.1B; 3.2), their altitudinal (and geographic) distribution was used to reconstruct the lake surface associated with the late Kinojévis outlet (Veillette, 1994). This reconstruction of the late Kinojévis level remains the most accurate representation of what was then considered a pre-drainage surface in the Ojibway basin.

Extensive mapping of the surficial deposits carried out by the Geological Survey of Canada (GSC) (e.g., Veillette et al., 2003) resulted in the recognition of additional raised shorelines in the Ojibway basin, notably in the Lake Abitibi area along the Québec/Ontario provincial border (Thibaudeau and Veillette, 2005). High-precision elevation measurements were obtained in the field on low-level wave-cut scarps carved in the Abitibi clay plain (e.g., Fig. 3.3A-B). Taking into account crustal rebound, the 154 points measured on raised shorelines defined four distinct lake levels, among which two new low-elevation levels with uplift gradients between 0.6-0.7 m/km we identified (Roy et al., 2015). This reconstruction provides unequivocal evidence for the occurrence of lake levels projecting below the late Kinojévis outlet that drained excess meltwater south and clearly indicates that the lake experienced significant changes in depth and areal extent near the end of deglaciation, thereby outlining the need to re-visit the late-stage evolution of Lake Ojibway in current reconstructions. Although these additional levels could be the geomorphic expression of a partial drainage of Lake Ojibway, additional data are required over larger areas to fully evaluate the extent of the related water plane and to assess the potential connection with the lower levels documented in the Agassiz basin.

3.3 Methods

3.3.1 Sources of shoreline data

Our lake level reconstruction is based on a total of 299 high-precision shoreline elevation measurements that were used to define the highest and lowest Lake Ojibway stages in previous studies (Figs. 3.1B; 3.2). Additionaly, a total of 3098 elevation points were measured on other raised shorelines of the study area mapped on a shaded relief derived from a LiDAR-based digital terrain model (DTM; bare-earth; grid resolution of 1 m/pixel) which was assembled from 1:20,000 datasets generated by the Québec Ministère des Forêts, de la Faune et des Parcs (MFFP) covering an area of 28,741 km^2 in the study area (NTS map sheets 1:250,000 32C and D, with parts of 32E and F). This type of LiDAR DTM generally yields a very high vertical accuracy – quantified by the root mean square error (RMSE) – that is commonly in the order of ~0.3 m or better in physiographic context comparable to the study area, i.e. characterized by gently sloping terrains and relatively dense forest cover (e.g., Hodgson and Bresnahan, 2004; Iordan and Popescu, 2015). The elevation of shorelines was taken at the slope break of distinct features consisting mostly of raised beaches and wave-cut scarps (Fig. 3.4).

Finally, we also measured the elevation of 29 other shorelines at 7 sites (Fig. 3.3C) during a field survey using two Suunto altimeters following an established procedure (Roy et al., 2015) to document intermediate and lower lake levels in the region outside the LiDAR coverage.

3.3.2 Paleotopographic reconstruction and model vertical accuracy

The paleotopography was reconstructed using the Canadian Digital Surface Model (CDSM) assembled for the area covering the Ojibway basin between latitudes 46°N–56°N and longitudes 72°W–90°W, combined with the 8.5 ka land deformation

indicated by the ICE-6G model (Peltier et al., 2015). The 8.5 ka paleotopography was chosen because it covers a time slice of ~300 years before the final drainage of the lake. The CDSM derives from the original Shuttle Radar Topographic Mission (SRTM) digital surface model [30 m/pixel with a 3.64 m RMSE; Gesch et al. (2014)], but with a finer resolution (19.6 m/pixel), although its RMSE is unspecified. The RMSE can be determined by comparing raster elevations extracted from locations with accurate ground control points (i.e., geodesic benchmarks). There are, however, few control points in the study area and most are found in unrepresentative settings, such as cleared and levelled land near roads and railways. The use of these control points would likely introduce an underestimation of the vertical error in our model. Nonetheless, the high vertical accuracy of LiDAR DTMs can be used to evaluate the RMSE of the CDSM and in this way, to characterize the overall vertical accuracy of our reconstruction (e.g., Oksanen and Sarjakoski, 2006; Pourali et al., 2014).

The vertical accuracy of our CDSM-based reconstruction was thus assessed by comparing the elevations of 3098 ground-control points extracted from the LiDAR DTM with those extracted from the CDSM at the corresponding locations. We calculated a mean absolute vertical error of -0.63 ± 2.45 m, where the negative error correspond to a slight underestimation of the CDSM elevations compared with the LiDAR reference control points. This yielded a RMSE value of 2.53 m and an absolute vertical accuracy of 4.96 m, which correspond to the overall vertical resolution of our lake level reconstruction.

3.3.3 GIS and lake level reconstruction

All geospatial analyses were performed in ArcGIS 10.6 using a combination of tools available with the Spatial Analyst and 3D Analyst extensions. All the operations on Ojibway shorelines were made using customized projections that enabled the use of map units in meters and allowed the reduction of area, distance and

angle distortion at the regional scale (e.g., Kuniansky, 2017). This also ensures the use of a common datum and grid resolution (Leverington et al., 2002b), which is required to perform raster operations and elevation extractions from the LiDAR DTM and the CDSM (modern and 8.5 ka topography). We used the Near tool (Analyst) to project all the shoreline elevation-points perpendicularly to the transect corresponding to the regional tilt axis (N 17°E) in order to construct distance-elevation diagrams and identify lake levels.

The proper representation of the glacial isostatic deformation at the basin scale was ensured through the extraction of 1620 point-data (1 degree spacing) corresponding to the glacial isostatic deformation predicted by the ICE-6G model at 8.5 ka (Peltier et al., 2015) for the land surface between latitude 36°N and 66°N and longitude 54°W and 108°W. A continuous isobase (rebound) surface was interpolated from the sampled points at the CDSM resolution (19.6 m/pixel), then subtracted from the CDSM modern topography to adjust the topography of the Ojibway basin for the effects of the glacial isostatic rebound at 8.5 ka, where a reconstructed water plane represents a flat surface of constant elevation (Leverington et al., 2002b). Using this flat surface as a reference, distinct groupings of shorelines within the same elevation range can be used to quantitatively characterize former lake levels marking stable periods, which provide insights on the different stages that marked the evolution of Lake Ojibway.

3.4 Results

3.4.1 Shoreline data set

Our shoreline inventory in the Ojibway basin yielded at total of 3098 elevation control points measured on the LiDAR DTM. Raised shorelines located above the level of the clay plain (~320 m) consist of beaches formed in coarse

deposits (till, sand and gravel) from wave action that left a lag of coarse materials, while most wave-cut scarps (WCS) were carved in the clay plain at lower elevation, but without a residue of coarse deposits. Wave-cut notches also occur in other deposits below 320 m, but are just not as prominent as those carved in clay. Accordingly, 1798 were obtained from raised beaches mostly located along important glaciofluvial deposits such as the Harricana moraine and other large eskers protruding above the clay plain (Fig. 3.4A) and 1291 from the lower surface of wave-cut scarps carved into the Abitibi clay plain (Fig. 3.4B). Only 9 points were taken on the highest lake levels (Fig. 3.4C) since the main focus of the study is on intermediate and lower levels and because the maximum elevation of the lake has been thoroughly established from earlier work (Veillette, 1994).

3.4.2 Shoreline selection for lake level reconstructions

We use the mean absolute vertical error as a hard constraint to filter the data set and reduce the 'noise' introduced in our reconstruction by the lesser resolution of the CDSM, where all the points within one standard deviation from the mean value were selected for each type of shoreline features. The shorelines were initially separated into two types: beaches (n=1798) and WCS (n=1291). The mean vertical error was calculated using the difference between the LiDAR DTM and the CDSM modern topography, yielding a mean absolute vertical error of -0.29 ± 2.33 m for beaches and -1.10 ± 2.53 m for WCS. Accordingly, we selected all the points within one standard deviation, which led to the final collection of 1222 beaches and 917 WCS, representing 69% of the whole dataset. These point-elevation data were subsequently projected on a 600 km transect oriented parallel to the regional tilt axis of N 17°E (Fig. 3.5).

For our lake level reconstruction, we used elevation values extracted from the CDSM with the 8.5 ka land surface to characterize the distribution of the selected

beaches and WCS. The shoreline elevation data points were placed into a 5 m class-interval histogram in order to identify distinct populations of shorelines; this class-interval is consistent with the vertical accuracy of ~5 m of our reconstruction. This indicates that the elevation range of the mapped shorelines varies from a minimum value of 75.95 m to a maximum value of 231.56 m, which were respectively rounded to 75 and 235 m for the purpose of the analysis, thus giving 32 intervals of 5 m that spread over a 160 m-elevation range (Fig. 3.6).

The high-elevation bins in the histogram of Fig. 3.6 do not show marked groupings forming well-defined populations or clear breaks, suggesting the absence of a stable lake level in this elevation range. The 877 elevation data points forming the 15 bins to the right of the histogram (789 beaches and 88 WCS) correspond to high-elevation/transient levels that likely developed during the early stages of Lake Ojibway. This near-uniform shoreline-elevation spread is also seen in the latitudinal distribution of shorelines in Fig. 3.5, and together this regularly-spaced scatter suggests that these shorelines were formed during a gradual lowering of the lake level due to the combined effect of glacial isostatic adjustment (GIA), as well as the gradual northward ice retreat and outlet migration. Alternatively, the lack of clear population breaks among the high-elevation shorelines may relate to the "young" paleotopography used for this reconstruction (vs. the onset of the Ojibway inundation). However, earlier trials with "older" land surfaces – involving a more important glacial isostatic deformation than the one predicted at 8.5 ka – did not have a significant impact on the distribution of the high-elevation shorelines, at least not so pronounced as to produce the formation of distinct populations. Accordingly, the use of a 8.5 ka rebound surface remains adequate to evaluate the formation of lake levels during the late-stages of the lake, which were marked by ice readvances and drainage events during the last 300 years of its existence (e.g, Hardy, 1976; Roy et al., 2011; Daubois et al., 2014; Godbout et al. submitted).

The moderate- and low-elevation bins show three clear populations with high number of shorelines, which suggest the occurrence of well-defined lake levels that likely reflect periods of stability in the basin that favoured the formation of shorelines within a specific elevation range (Fig. 3.6). The interval 1 comprises a total number of 620 control points (397 beaches and 223 WCS), interval 2-308 control points (1 beach and 307 WCS) and interval 3-79 control points (all WCS). Another important feature of the histogram is a marked drop in the number of shorelines between these intervals, which suggests the absence of a stable lake level at these elevations. These 3 apparent stable lake levels and intervening gaps are also present in the latitudinal distribution of the shorelines (Fig. 3.5) where the control points are clearly aligned along uplift lines that are separated by intervals with few or no shorelines.

The elevation of points forming the main populations of shorelines in the histogram is used to calculate the uplift gradients associated with the lake levels identified. The gradients calculated are presented in Table 3.1 and the reconstructed shoreline and water depths associated with each lake level is based on the mean value ($\pm 1\sigma$) calculated for each 5 m interval (Supplementary Figures 3.9-3.11).

3.5 Discussion

A dense forest cover and difficult land access have always impeded the study of raised shorelines in the Ojibway basin. The availability of a LiDAR DTM that cover a large portion of the core Ojibway basin in Abitibi may now greatly reduce these limitations and allow the mapping and description of raised shorelines at an unprecedented resolution. The combination of LiDAR DTM with the former land surface elevation that takes into account the glacial isostatic depression at the time of the Lake Ojibway submergence further facilitates shoreline correlations and the reliable identification of Ojibway lake levels. A total of 3098 elevation control points were acquired on distinct shoreline features – mainly wave-cut scarps and beaches –

present on the LiDAR DTM. This data set was filtered to acknowledge the mean vertical error ($\pm 1\sigma$) associated with the use of the CDSM in our reconstruction, yielding a final data set comprising 2139 elevation control points. These points were separated between feature type (WCS and beaches) and projected along the regional tilt axis on a distance-elevation diagram using their modern LiDAR elevation (Fig. 3.5). At each point, the corresponding elevation was extracted using the paleotopography reconstructed at 8.5 ka with the ICE-6G model and the elevation distribution of these 2139 points was characterized using a histogram (Fig. 3.6). This technique allowed the selection of all the points within a 5 m interval marking a flat lake surface with respect to the 8.5 ka topography. This shows that the shorelines are concentrated around distinct elevation range and plot within three main intervals. This suggests the occurrence of three periods of relative stability during the late-stages of Lake Ojibway, which favored the development of at least three widespread lake levels across the basin.

3.5.1 High-elevation lake levels

The shoreline record shows a large number of high-elevation shorelines that spread over a wide elevation range between the maximum lake limit that was defined earlier (Veillette, 1994) and the first concentration of shorelines forming interval 1 (Fig. 3.6). This distribution pattern and the lack of clear lake levels are attributed to the combination of the gradual retreat of the ice margin across the basin and the effect of GIA on the newly deglaciated terrain.

3.5.2 Interval 1: the Kinojévis-type lake stage

Interval 1 comprises a large number of shorelines that are concentrated in a narrow elevation spread ranging from 299 to 350 m that form a clear tilted water plane in the elevation-distance diagram (Fig. 3.5). Close examination of the data indicates that this set of shorelines consists of two main populations (Fig. 3.6), which

are highlighted in the elevation-distance diagram presented on Fig. 3.7. This suggests that the gradual lowering of the lake surface from high-elevation stands eventually led to a period of stability that gave rise to a well-developed lake stage that appear to be characterized by two closely-related lake levels (1a, 1b). We here define this lake stage with the lower of the lake level since it represents the last level of stability (Fig. 3.7; Supplementary Figure 3.9).

This stable level is ~11 m higher than the 300 m outlet used to define the late Kinojévis lake stage at the same latitude in earlier studies (Vincent and Hardy, 1979). It is also ~10 m lower than the minimum elevation of ~350 m reached by eastern Hudson Bay ice-rafted indicators linked to the Cochrane readvances at the latitude of Mt. Plamondon (Veillette et al., 1991; Veillette, 1994). These differences of elevation for the outlet suggest that this lake level is likely associated with the Kinojévis stage of the lake, although our data show important differences with previous reconstructions. The uplift gradient of 0.37 m/km for this water plane contrasts with the values of 0.5-1.2 m/km previously reported for the early and late Kinojévis lake levels, which were originally defined with a low number of shorelines (Vincent and Hardy, 1979). When compared to the 0.9 m/km shoreline gradient calculated for the Angliers stage (Vincent and Hardy, 1979; Veillette, 1994), the value of 0.4 m/km indicates that this intermediate-elevation lake level and the associated Kinojévis-type lake stage likely developed near the late-stages of the lake. This last stable lake level also corresponds to the highest WCS measured in the Lake Abitibi region (Roy et al., 2015) (Fig. 3.8) and marks the onset of the erosion of the Ojibway clay plain.

3.5.3 Interval 2: the La Sarre lake stage

Interval 2 is represented by a large number of shorelines displaying two populations centered over a specific range of low elevations (Fig. 3.6) that form a

tilted sub-horizontal alignment of shorelines that outline two closely-spaced and well-defined lake levels (Fig. 3.7). These lake levels are composed almost exclusively of wave-cut scarps (176 WCS for level 2a and 131 WCS for level 2b) that are carved in the Ojibway clay plain and the water planes they define clearly lie below the 300 m outlet (Figs. 3.7; 3.8). Within the overall shoreline sequence we report, these erosional shorelines and the associated lake levels mark the development of another period of stability in the basin. The low number of shorelines between the lake levels of intervals 1 and 2 suggests the occurrence of a major lake surface drawdown (drainage event?), with the few intervening shorelines representing short-lived, transient lake levels that developed between the stable periods marked by intervals 1 and 2.

These lake levels combine the two low-elevation lake levels previously documented in the La Sarre area, i.e., Level 2 and Level 3 of Roy et al. (2015). At the latitude of La Sarre, the elevation of 285 m we report for our lake level 2a is 4 m lower than the Level 2 (289 m; 0.7 m/km) and 3 m higher than their Level 3 (282 m; 0.6 m/km), while the 283 m we report for our lake level 2b is only 1 m above the Level 3. We note, however, that the overall vertical accuracy of 5 m associated with our reconstruction indicates that the lake levels 2a and 2b are statistically indistinguishable from each other. Although field evidence indicates that there might be two closely-spaced low-elevation Ojibway lake levels present in the La Sarre area (Roy et al., 2015), our high-resolution LiDAR based inventory suggests that this set of shorelines likely form a single lake level that develop after a marked drawdown of Lake Ojibway. Consequently, we used the lower of these two lake levels (2b) to reconstruct the extent of the water plane corresponding to the La Sarre lake stage (Fig. 3.10)

Our large shoreline data set and the high accuracy of our LiDAR-based model also refine the uplift gradients for these low-elevation lake levels, which earlier

calculation had yielded values of 0.7 and 0.6 m/km (Roy et al., 2015). Our results indicate that the uplift gradients for the lake levels 2a and 2b are in the order of 0.36 m/km and 0.35 m/km, respectively. These differences may result from the lower number of shorelines and the smaller area investigated in the earlier study. Again, in the context of the uplift gradients reported for the glacial lakes that fringed the southern LIS margin, it suggests that these lake levels formed during late-stages. Indeed, shorelines gradients of 0.4 to 0.7 m/km were measured on short segments of low- and intermediate-level Ojibway shorelines in north-central Ontario (Hughes, 1965).

3.5.4 Interval 3: the Palmarolle lake stage

The last shoreline population isconcentrated in a low-elevation range that defines an unequivocal lake level composed exclusively of 79 WCS that are present in the depressions and low-lying areas around Lake Abitibi. This lake level shows a strong match with the lowest lake level documented by Roy et al. (2015) at an elevation of 272 m near La Sarre, although we reported a slightly higher gradient (0.33 vs. 0.24 m/km). Because of these characteristics and the spatially restricted distribution of these shorelines, this lake level was associated with the development of a post-glacial water body in the Lake Abitibi region (Fig. 3.11). The existence of this paleolake Abitibi that once covered the region was initially suggested by Antevs (1925) due to the presence of a massive clay containing a postglacial micro-fauna and overlying varved sediments in the La Sarre area. Additional evidence for this postglacial lake was provided by sedimentological data and $\delta^{18}O$ values measured on ostracods that indicate that this lake was not fed by glacial meltwaters (Daubois et al., 2014).

3.5.5 Paleogeographic implications

Fig. 3.8 shows our results combined with the maximum lake levels for the total area covered by Lake Ojibway. The 11 levels measured at Mt. Plamondon clearly show that shoreline formation in the basin during the early stages of Lake Ojibway was largely controlled by the glacial isostatic rebound and the northward outlet migration. This compilation also highlights that the last stable level of the Kinojévis-type stage forms a lake surface ~11 m higher than the late Kinojévis outlet (300 m) at the same latitude. Similarly, this lake level lies ~10 m below the minimum lake elevation of 350 m during the Cochrane readvance at Mt. Plamondon, although the higher level of this lake stage may be correlative to the surface defined by Veillette (1994) (Fig. 3.8). These results indicate that the lake levels of the Kinojévis-type stage cannot be linked to an outlet standing at 300 m, unlike suggested in earlier reconstructions (Vincent and Hardy, 1979). Furthermore, using the late Kinojévis lake level associated with a 300 m outlet of earlier reconstructions as a pre-drainage lake surface likely represent a significant overestimate in areal extent and volume, as clearly indicated by our reconstruction that shows that the lake level preceding the major drawdown was at least 10 m lower than previous estimate.

Extending a straight line across the shoreline defining the last (lower) lake level of Kinojévis-type stage in Fig. 3.8 provides further context. This line intersects the lowest shorelines with elevations of 298 and 308 at a distance of ~195 km that correspond to the westernmost washing limits recognized in the Ojibway basin (Fig. 1B) (Veillette, 1994). This line also seems to correlate with the lowest shorelines measured in the James Bay basin and located at 450 km and ~565 km along the transect. This indicates that this lake level is a widespread feature across the Ojibway basin and that it represents a stable phase of the lake. This redefinition of the Kinojévis lake stage provides a critical minimal constraint on a stable lake surface

that can be used to evaluate the connection between Lake Ojibway and the Ponton level in the Lake Agassiz basin.

Although the outlet associated with the late Kinojévis stage was presumably the last main outlet regulating southward meltwater overflow prior to the northward drainage of Lake Ojibway, the absence of stability in the development of shorelines across the basin and the ~11 m difference between the last Kinojévis-type lake level (level 1b) and the 300 m outlet suggest a rapid downcutting of the outlet. The presence of localized 30-m deep incisions in the vicinity of the present-day drainage divide at an elevation of ~300 m (Vincent and Hardy, 1979) supports this scenario, but it also questions the proposed correlation with the Ponton lake level across Ontario, thereby complicating the reconstruction of a pre-drainage lake surface for Lake Agassiz-Ojibway. This would imply that the surface of Lake Agassiz remained stable enough to develop shorelines across a large area at a time when the level of Lake Ojibway was dropping rapidly. To that effect, although varve records supposedly indicate a ~600 years connection between the two lakes (Breckenridge, 2004; Breckenridge et al., 2012), our shoreline data does not support this stable connection, which is also not reflected in the lake level history of both lakes.

The next period of significant shoreline formation in the basin is represented by the closely-related La Sarre lake levels (levels 2a, 2b). Using the latitude of La Sarre as a reference, this corresponds to a lake surface lowering of 26-28 m below the late Kinojévis outlet. The lake level sequence we report also outline a major lake level drop of 37-39 m between the Kinojévis-type lake level and the La Sarre lake level (Roy et al., 2015). Assuming that this lake surface drawdown represent a drainage event, our shoreline sequence clearly indicates that Lake Ojibway disappeared through a two-step drainage, which contrasts with classical reconstructions that depict a single rapid drainage of the lake (Leverington et al., 2002a). A two-step drainage of Lake Ojibway is also consistent

with a recent varve analysis in the Ojibway basin (Godbout et al., submitted) and marine records that document multiple outburst floods around the time of the drainage of the lake (Ellison et al., 2006; Hillaire-Marcel et al., 2007; Lajeunesse and St-Onge, 2008; Jennings et al., 2015), as well as a sedimentary sequence in James Bay that shows evidence for subglacial exchanges between Lake Ojibway and the Tyrrell Sea prior to the final lake drainage (Roy et al., 2011).

The shoreline sequence we report also indicates the occurrence of another lake level in the Lake Abitibi basin, which indicates that an important water body existed in the region following two lake drawdowns that led to the drainage of the Lake Agassiz-Ojibway. The LiDAR DTM does not show any distinct shoreline population indicative of a similar postglacial lake level east of the Harricana moraine. This suggests that the lake level continued to drop in the James Bay basin while it stabilized in the Lake Abitibi basin. This may be related to the fact that following the 26-28 m lake surface drop below the Kinojévis outlet, the Lake Abitibi basin became isolated. This scenario is supported by a GIS-based paleogeographic reconstruction of the areal extent involved by the different lake levels (Figs. 3.9; 3.10), which also implies that the subsequent 11-13 m drop down to the Palmarolle lake level (Fig. 3.11) would be associated with the downcutting of the River Abitibi outlet to the west. Although our results suggest that the La Sarre and Palmarolle lake stages should be present further to the west in Ontario and to the north in the James basin, the absence of LiDAR coverage in these regions prevent any firm support for this reconstruction at this moment. However, the quality of our data set and the lack of extensive topographic rises that could separate the Ojibway basin suggest that these stages should be present, as indicated by the occurrence of low-elevations shorelines in these regions (e.g., Paulen, 2001; Paradis et al., 2010; Paradis et al., 2017; Veillette et al., 2017b-e). Future work should concentrate on producing additional constraints on the areal extent of the reported lake levels and provide new estimates of the meltwater volumes involved.

Overall, our reconstruction outlines the occurrence of two marked drawdowns: a 37-39 m drop that took place from the Kinojévis-type lake level and another 11-13 m-drop from the La Sarre lake level. This scenario is supported by the presence of unconformities in the regional varve record (Hughes, 1959; 1965; Breckenridge et al., 2012), where two coarse-silt units separated by 65 years were recently documented in the Lake Abitibi basin and attributed to drainage events, including the final one (Godbout et al. submitted). This provides additional evidence that Lake Agassiz-Ojibway drained through a multi-step sequence with two major drawdowns, which is consistent with continental (Roy et al., 2011), marine (Ellison et al., 2006; Jennings et al., 2015) and relative sea level (RSL) records (Hijma and Cohen, 2010; Li et al., 2012; Törnqvist and Hijma, 2012; Lawrence et al., 2016) that document multiple meltwater outbursts around the 8.2 ka interval.

3.6 Conclusions

We mapped >3000 high-, intermediate- and low-elevation shorelines of Lake Ojibway on a high-resolution LiDAR DTM to identify lake levels using a GIS-based reconstruction that incorporates the paleotopography at 8.5 ka (ICE-6G model). This approach documents the following features in the history of lake levels:

- The shoreline-elevation data set shows a large cluster of intermediate-elevation shorelines features (around 299-350 m) that delineate two closely-spaced lake levels that show some similarities with the early and late Kinojévis lake levels reported in earlier studies (Vincent and Hardy, 1979; Veillette, 1994), although our reconstruction refines the elevation and geometry of the associated water planes. Indeed, the Kinojévis-type lake levels are separated by ~12 m and show comparable uplift gradients of 0.35 m/km (1a: highest level) and 0.37 m/km (1b: lowest level), indicating that the lake surface gradients defined in earlier studies and conveyed in subsequent reconstructions were overestimated.

- The last stable Kinojévis-type lake level was followed by a significant gap in the distribution of shorelines, which argues for the occurrence of an abrupt lake surface drawdown of at least 37 m. Scattered shorelines are present in this gap, but they likely represent short-lived and transient lake stages.

- This gap in shorelines is followed by another important concentration of shorelines that plot in a narrow elevation range. These shorelines consist in WCS carved into the Ojibway clay plain, thus consistent with the scenario of an abrupt lowering of the lake surface. These shorelines thus likely mark the reestablishment of stable water planes, which correspond to the late-stage lake levels defined in the Lake Abitibi region (Roy et al., 2015). Although our data set also identifies two low-elevation lake levels, the resolution of our reconstruction does not allow these lake levels to be distinguished since they form water planes separated by ~2 m. The La Sarre lake levels plot below the Kinojévis outlet system and also present near-similar uplift gradient of 0.36 m/km (2a: highest level) and 0.35 m/km (2b: lowest level).

- The La Sarre lake levels are followed by another 12 m drop that represents another significant lake drawdown. The shoreline elevation data show another concentration of shorelines that clusters mainly in the Lake Abitibi region. This low-elevation Palmarolle lake level records the presence of a post-glacial lake that occupied low-lying depressions in the region (Antevs, 1925; Daubois et al., 2014).

- The reconstruction thus presents firm evidence for a multi-step drainage of Lake Agassiz-Ojibway, which occurred through two large lake drawdowns, thus consistent with continental and marine records that indicate that the late deglacial

interval was marked by at least two significant meltwater outbursts (e.g., Jennings et al., 2015; Godbout et al., submitted).

- A Kinojévis outlet standing at an elevation of 300 m cannot be associated with a stable phase of Lake Ojibway and this raises questions about its use to reconstruct a pre-drainage lake surface of Lake Agassiz-Ojibway. Furthermore, the occurrence of two major lake drawdowns is also in contradiction with varve records arguing for a stable lake surface since their connection, an interval of ~600 years (Breckenridge, 2004; Breckenridge et al., 2012).

- These issues imply that the pre-drainage surface(s) of the coalesced Lake Agassiz and Lake Ojibway – and even their connection – should be revaluated. Future studies should focus on the record of shorelines present in the western (Agassiz) basin to see whether the extent of the late-stage lake levels and associated drawdowns can be identified. This work represents a critical step towards the establishment of reliable meltwater volumes, which are essential in paleoclimatic modeling studies.

Overall, this study refines the current understanding of the Lake Ojibway evolution during its late-stages, including the possible connection with Lake Agassiz and the northward drainage of the lake. Altogether, the results presented here have implications regarding the freshwater forcing that triggered the 8.2 ka-event.

Aknowledgements: This research was supported by a NSERC grant to MR and a FRQNT PhD fellowship to PMG.

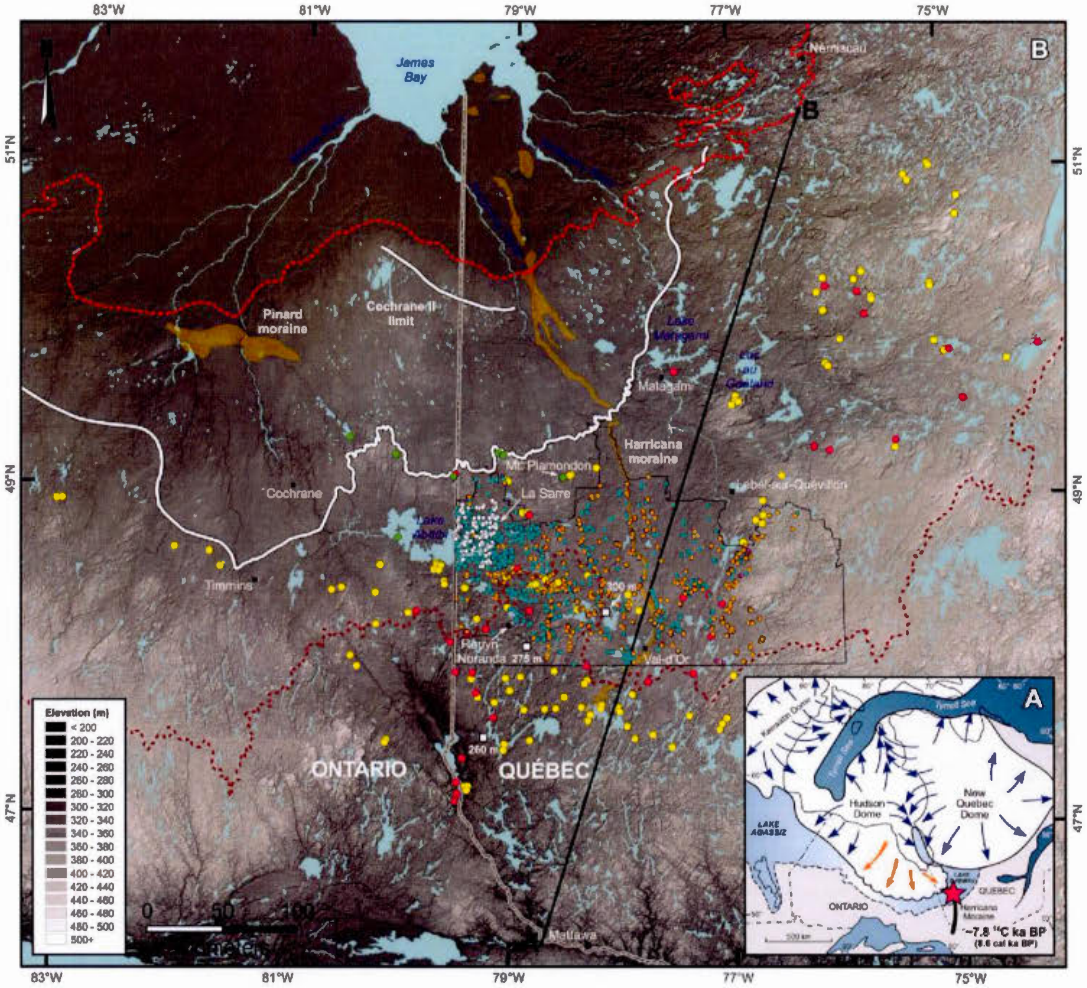

Figure 3.1 A) Schematic map showing the extent of Lake Agassiz-Ojibway and the Laurentide Ice Sheet during the last ~300 years of the lake's existence at the time of the Cochrane readvance (orange arrows) based on Dyke et al. (2003). Star shows the general location of the study area. **B)** General map of the study area showing the CDSM topography in shades of black. The LiDAR coverage is outlined in black where the elevation measurements on wave-cut scarps (small turquoise dots) and raised shorelines and lake limits are respectively symbolized by orange and red dots. The white dots refer to recent measurements (Roy et al., 2015) in the La Sarre area and the green ones to new field measurements presented in this study. **(continued)**

Figure 3.1 (continued) The reds dots correspond to Vincent and Hardy (1979) shoreline data while the yellow ones correspond to maximum lake levels recorded at 145 sites by Veillette (1994) using photogrammetry and/or altimetry, including 25 sites compiled by Vincent and Hardy (1979), 33 sites from Veillette (1983; 1988) and 1 site from Prichonnet et al. (1984). The regional tilt axis of N 17°E is represented by the thick black line starting at Mattawa. The main geomorphic (moraine) features in the basin (orange) are depicted according to Veillette et al. (2003), Veillette et al. (2017b) and Fulton (1995). The thick white line shows the southern limit of the Cochrane ice readvances (grounding line) obtained from surficial geology maps (Boissonneau, 1966; Veillette and Pomares, 2003; Thibaudeau and Veillette, 2005; Paradis, 2007a; 2007b; Veillette, 2007a; 2007b; Veillette and Thibaudeau, 2007; Paradis et al., 2017; Veillette et al., 2017d) while the Cochrane II limit is mapped accordingly to Hardy (1976). The Tyrrell sea limit is outlined by a red line (Dredge and Cowan, 1989; Vincent, 1989). The elevation above sea level (asl) of the outlets associated with the Angliers (260 m), early Kinojévis (275 m) and late Kinojévis (300 m) levels of Lake Ojibway are also shown (Vincent and Hardy, 1979). A maroon line marks the present-day drainage divide of the St. Lawrence River and Hudson Bay watersheds.

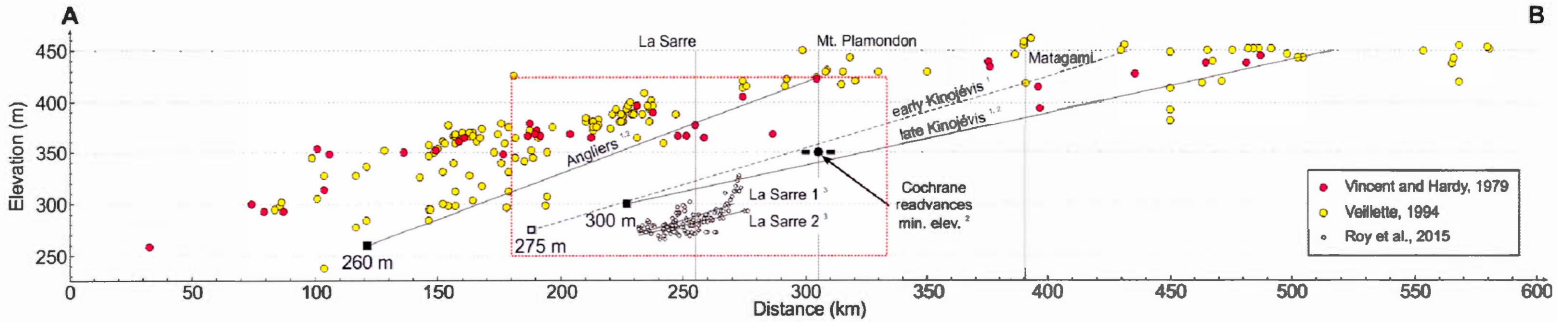

Figure 3.2 Distance-elevation diagram on a 600 km transect along the regional tilt axis (N 17°E) showing all the previous shoreline measurements recorded in the Lake Barlow-Ojibway basin. The elevation of the outlets is indicated with black (previous work) and white (proposed) squares along with their respective elevations. Lake levels from previous studies are shown with gray lines (see text for details). The red rectangular box corresponds to the limits of the LiDAR coverage used in this study. 1: Vincent and Hardy (1979); 2: Veillette (1994) and 3: Roy et al. (2015).

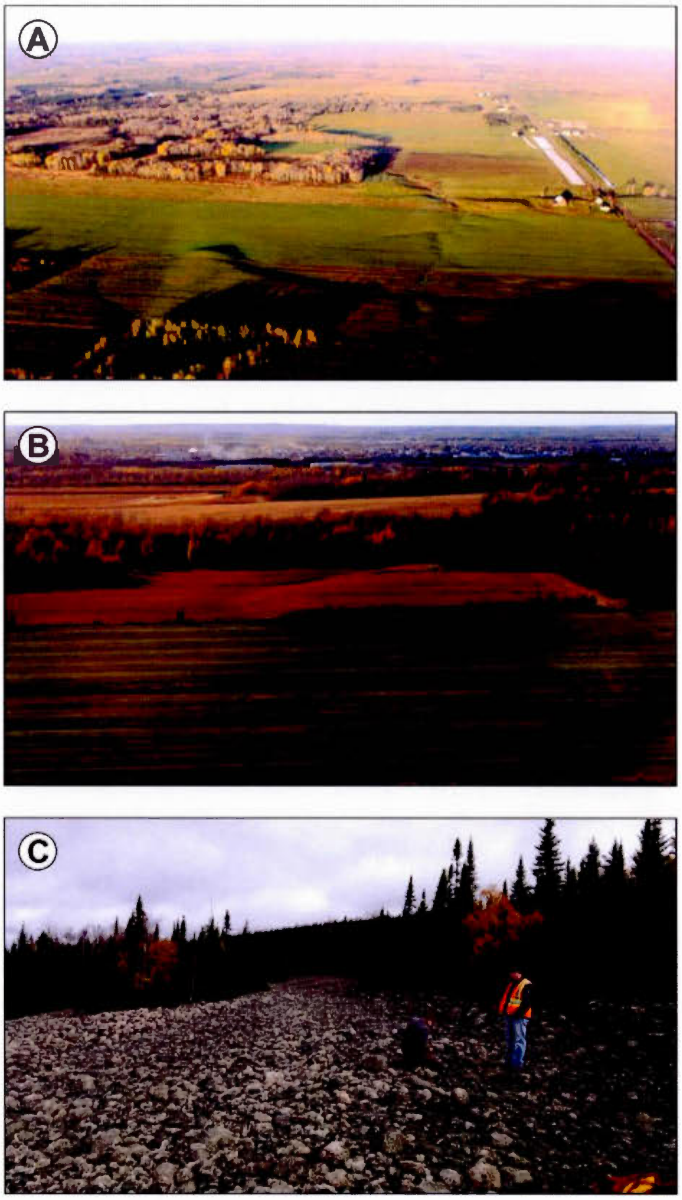

Figure 3.3 Examples of raised shorelines in the Ojibway basin. **A)** and **B)** are wave-cut scarps in the soft clayey Ojibway lake bed in the La Sarre area; the one shown in A is the same as the one exposed the upper middle portion of Fig. 3.4 B; **C)** Boulder beach resulting from the erosion of thick till on the western flank of Mt. Plamondon measured in the study.

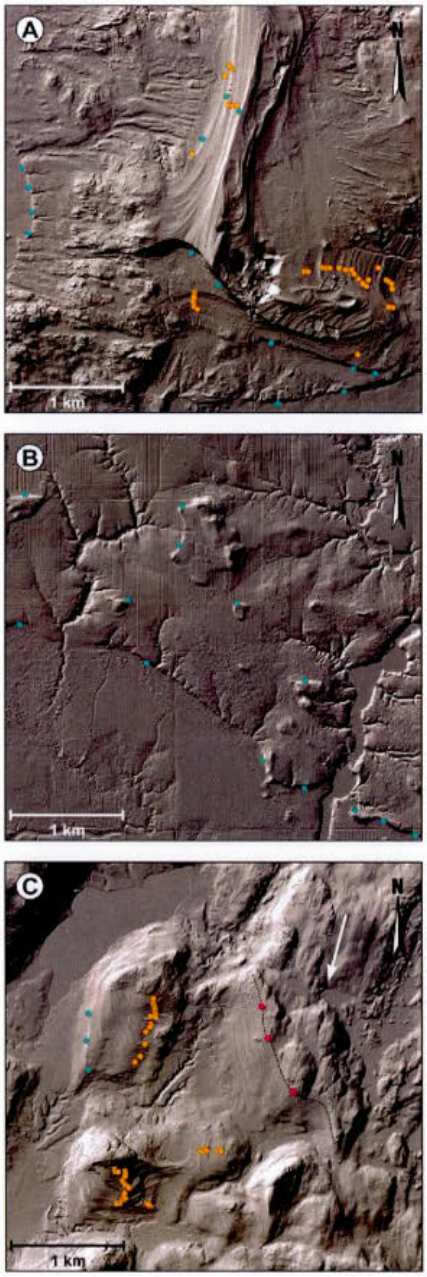

Figure 3.4 Close-up LiDAR views of Ojibway shorelines. **A)** Wave-cut scarps (turquoise) and numerous beaches (orange) along a major esker ridge located 42 km NE of Val-D'Or; **B)** Wave-cut scarps in the Lake Abitibi clay plain 7.5 km NNW of La Sarre; and **C)** Wave-cut scarps and beaches (orange) in an area located 42 km SSE of Lebel-sur-Quévillon. Note the well-defined lake-limit (black dashed line) indicated by the red dots that marks the contact with the fluted terrains (white arrow).

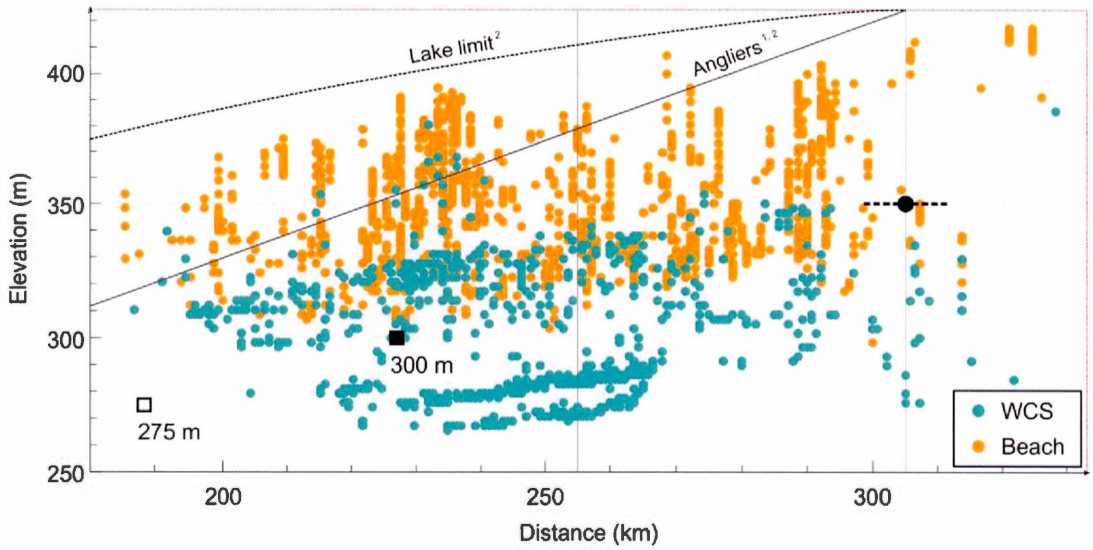

Figure 3.5 Close-up view of the Fig.3.2 red box. The selected 2139 LiDAR shoreline-elevation data points are divided between wave-cut scarps and raised beaches and are compared to the lake limit and the Angliers level. The minimum elevation reached by the Hudson Bay erratics at Mt. Plamondon is indicated by the black dot and dashed line (Veillette et al., 1991), the early (white square) and late Kinojévis outlets (black square) are also shown. 1: Vincent and Hardy (1979) and 2: Veillette (1994).

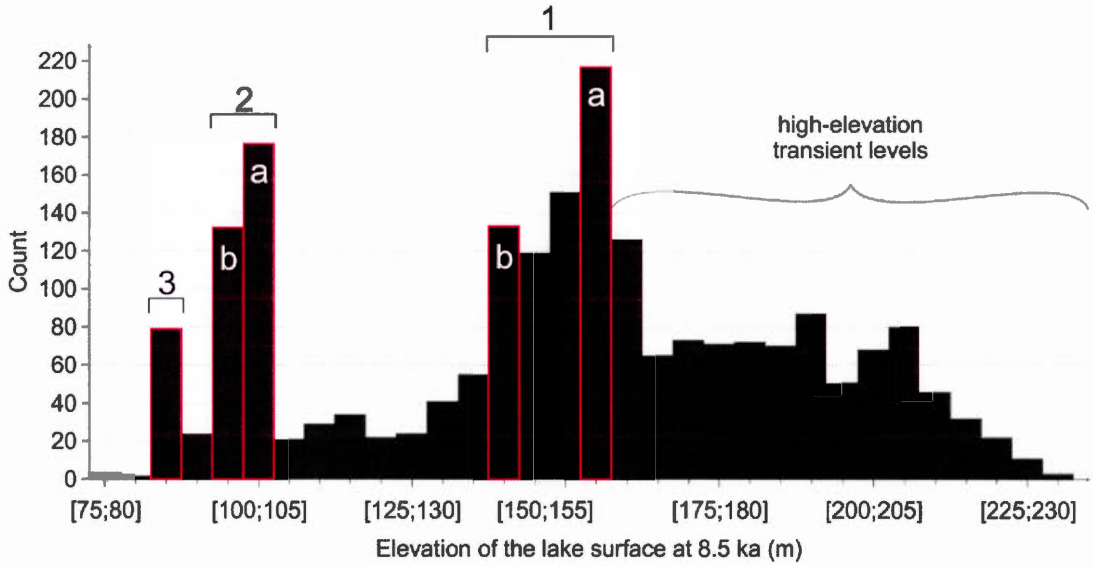

Figure 3.6 Histogram representing the population of 2139 LiDAR shoreline-elevation data on the 8.5 ka paleotopography. The interval 1 corresponds to the Kinojévis-type lake stage, interval 2 to the La Sarre lake stage and interval 3 to the Palmarolle lake stage. The lake levels defining each stage are highlighted in red (see text for details).

Table 3.1 Elevation data and uplift gradients of the reconstructed lake levels.

Interval	Uplift gradient (m/km)	Elevation of lake phases [a] (m)	[b] (m)	[c] (m)	n_{wcs}	n_{beach}	R^2
1a	0.35	334	352	382	113	104	0.86
1b	0.37	322	340	371	44	89	0.86
2a	0.36	285	303	334	176	0	0.93
2b	0.35	283	301	331	131	1	0.94
3	0.33	272	289	317	79	0	0.89

[a] Elevations measured at the latitude of La Sarre
[b] Elevations measured at the latitude of Mont Plamondon
[c] Elevations measured at the latitude of Matagami

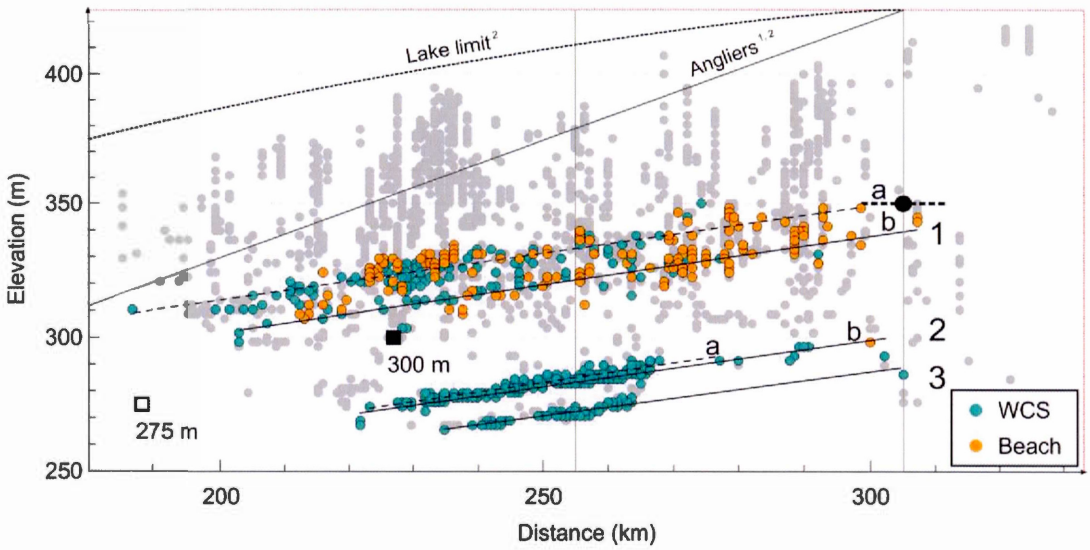

Figure 3.7 Lake levels associated with the 3 intervals shown in Fig. 3.6 where the black lines represent the trend of the associated shorelines.

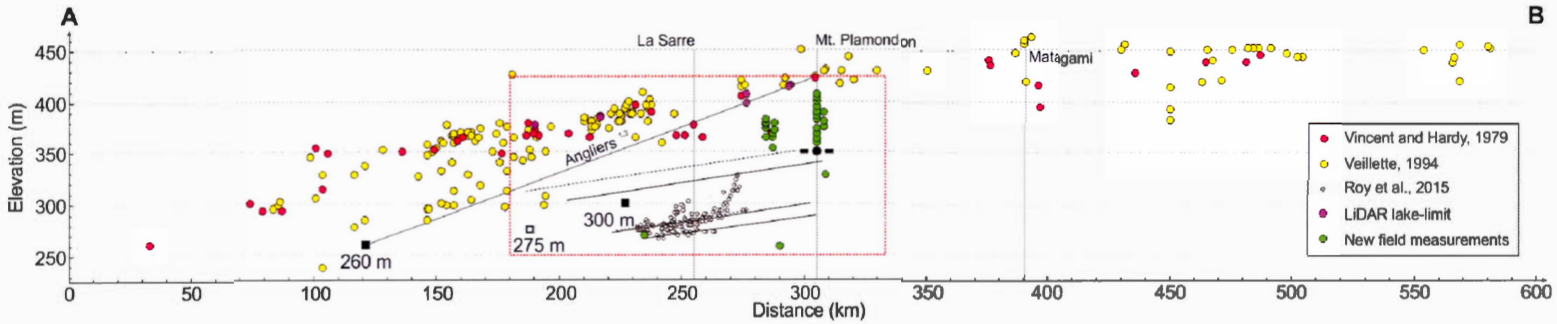

Figure 3.8 Distance-elevation diagram including the new field measurements and the lake levels described in this study.

3.7 Supplementary material

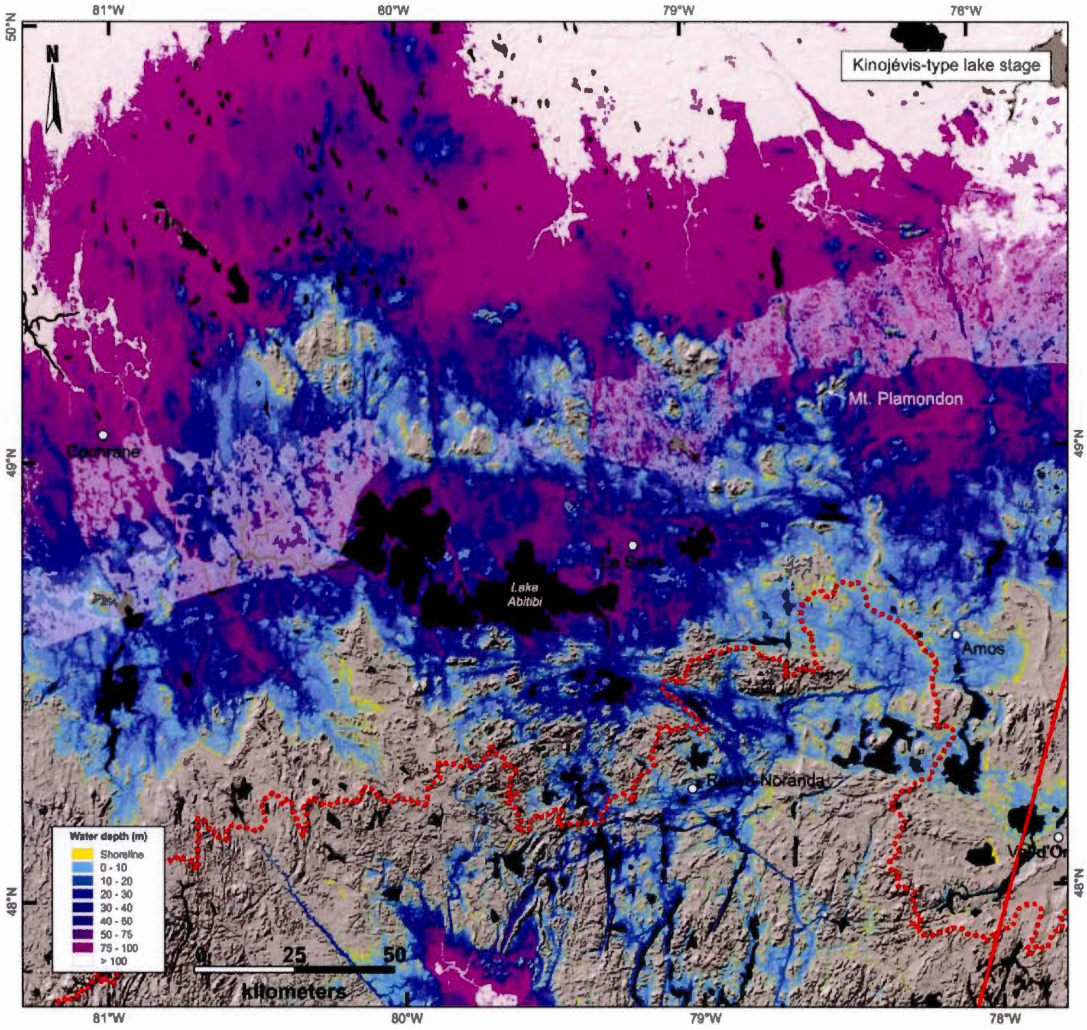

Figure 3.9 Reconstruction of the Kinojévis-type lake stage in the Lake Abitibi region. The white shaded areas correspond to the extent related to Cochrane readvances deposits where an ice-rafted debris-rich layer (gritty clay) is present at the top of the Ojibway sequence (Veillette and Pomares, 2003; Thibaudeau and Veillette, 2005; Paradis, 2007a; 2007b; Veillette, 2007a; 2007b; Veillette and Thibaudeau, 2007; Paradis et al., 2017; Veillette et al., 2017d).

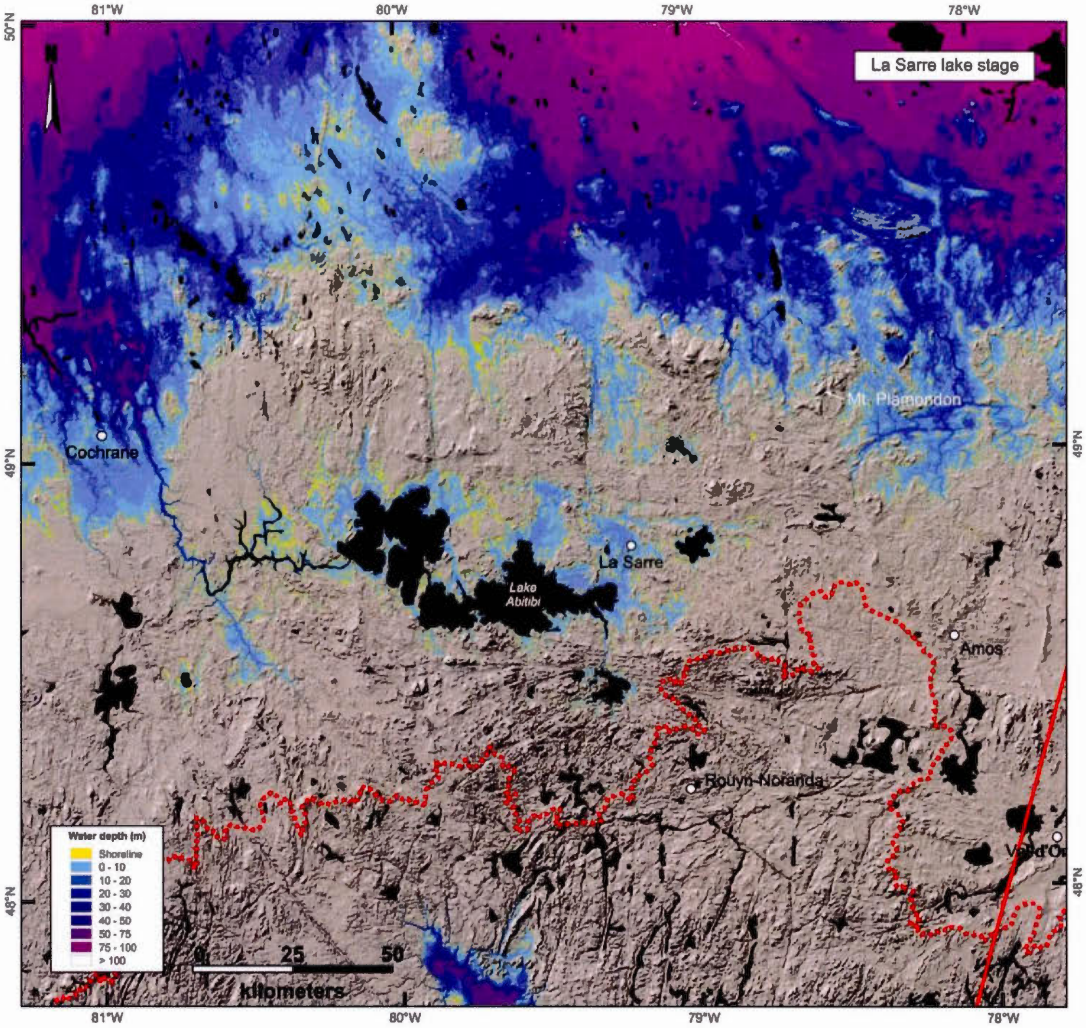

Figure 3.10 Reconstruction of the La Sarre lake stage in the Lake Abitibi region.

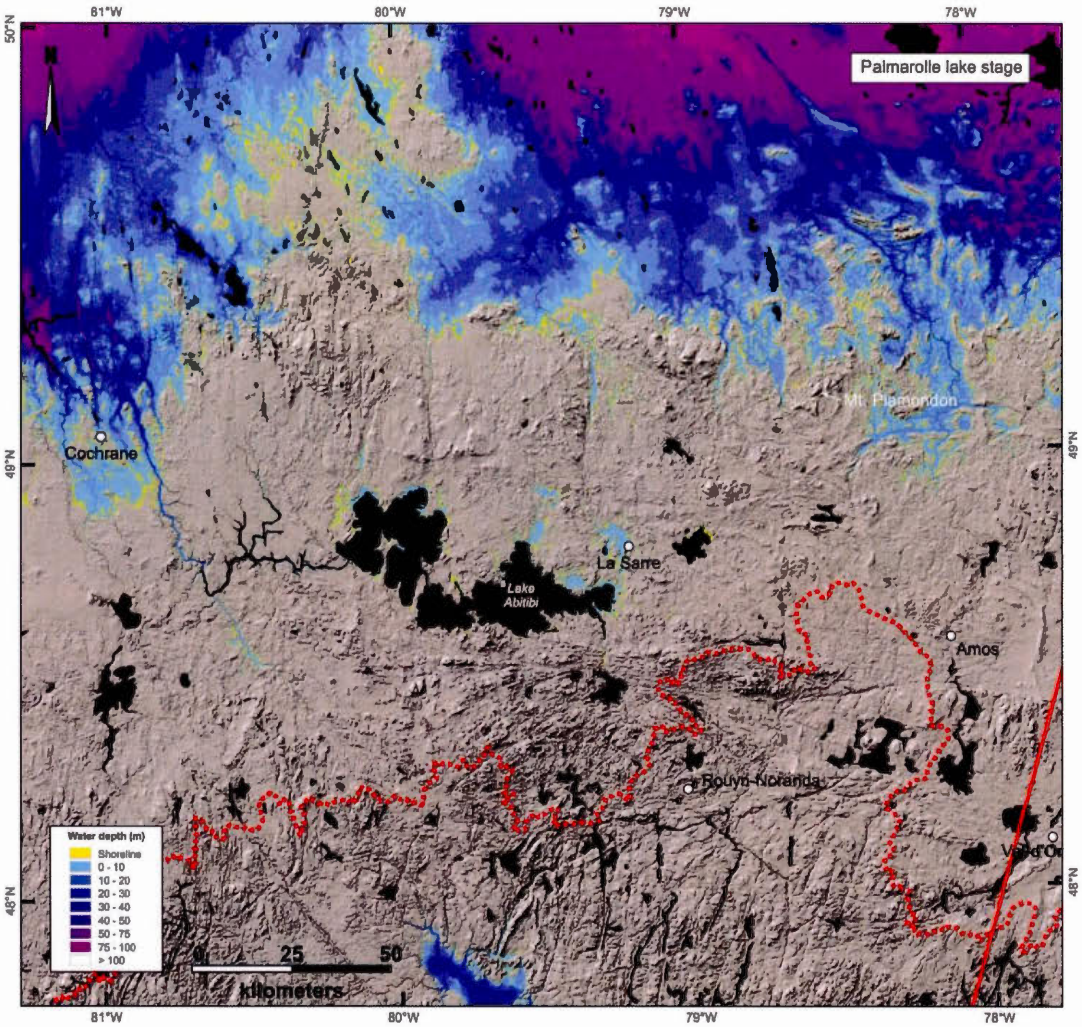

Figure 3.11 Reconstruction of the Palmarolle lake stage in the Lake Abitibi region.

CONCLUSIONS

Les données paléoclimatiques de la dernière déglaciation et du début de l'Holocène indiquent que des variations importantes du climat seraient principalement liées à l'évolution d'immenses lacs de barrage glaciaire qui se sont développés à la marge sud de l'inlandsis laurentidien lors de son retrait. C'est le cas d'un épisode abrupt de refroidissement survenu il y a 8,2 ka et qui aurait été vraisemblablement causé par la vidange catastrophique du Lac Agassiz-Ojibway lors de deux événements de drainage majeurs survenus suite à l'effondrement du barrage de glace formé par la masse résiduelle de l'inlandis laurentidien sur la baie d'Hudson. Cependant, malgré l'identification de ce forçage climatique important dans les archives sédimentaires et de niveaux marins relatifs datant de cet intervalle de la déglaciation, le lien avec les événements tardifs survenus dans les bassins Agassiz et Ojibway demeure mal défini en raison de la rareté des enregistrements géomorphologiques et sédimentaires, en plus du manque de contraintes chronologiques directes. Pour ces raisons, la compréhension des étapes ayant mené à la déglaciation finale et au drainage du Lac Agassiz-Ojibway est en grande partie basée sur des reconstructions du Lac Ojibway articulées à partir d'études régionales renfermant peu de données géologiques, notamment en ce qui a trait au nombre de phases du lac, de l'étendue de chacune et de leur chronologie.

Cette thèse avait pour objectif principal de déterminer le nombre et la chronologie des phases glaciolacustres, ainsi que des événements tardifs comme les drainages et réavancées glaciaires survenus dans le bassin Ojibway à partir des enregistrements géomorphologiques et sédimentaires afin de raffiner les reconstructions paléogéographiques couvrant l'évolution de ce lac de barrage

glaciaire. Les sous-objectifs spécifiques étaient 1) d'apporter de nouvelles contraintes géochronologiques sur la séquence de niveaux glaciolacustres Ojibway afin de cadrer l'évolution du lac dans un contexte temporel; 2) de raffiner la chronologie varvaire et la séquence des événements tardifs dans le bassin Ojibway à partir de l'étude de nouvelles séquences sédimentaires et 3) de reconstruire les niveaux et les différentes phases du Lac Ojibway à partir d'un inventaire exhaustif de rivages cartographiés sur un modèle numérique de terrain LiDAR. Pour ce faire, nous avons appliqué la datation par isotopes cosmogéniques sur des rivages associés à une phase majeure du Lac Ojibway, documenté à haute-résolution la composition et l'épaisseur des varves formant deux séquences prélevées au cœur du bassin et reconstruit la paléotopographie du bassin à partir d'un modèle de relèvement isostatique afin d'étudier les phases de stabilité documentées par les séquences de rivages glaciolacustres cartographiées à partir d'un LiDAR.

Premièrement, l'application de la datation par isotopes cosmogéniques (^{10}Be) sur des rivages perchés associés à une phase majeure du Lac Ojibway a permis de fournir les premières contraintes géochronologiques directes sur l'invasion glaciolacustre lors du retrait de l'inlandsis laurentidien dans le NE de l'Ontario et le NO du Québec. Les âges ^{10}Be indiquent que le niveau le plus élevé et associé à la phase Angliers s'est développé il y a 9.9 ± 0.7 ka. Ces résultats fournissent des indications importantes sur la chronologie des variations d'altitude de la surface du lac qui avaient traditionnellement été groupées dans une succession de trois niveaux d'altitude élevée à intermédiaire (Vincent and Hardy, 1979), dont le niveau inférieur est généralement associé au drainage du Lac Agassiz-Ojibway (Veillette, 1994; Thorleifson, 1996; Leverington et al., 2002a; Teller et al., 2002). Les âges ^{10}Be obtenus pour la phase Angliers associent les hauts niveaux au tout début de la déglaciation – tôt dans l'épisode glaciolacustre Ojibway – ce qui, considérant la présence de niveaux tardifs de basses altitudes dans les bassins Agassiz et Ojibway (Klassen, 1983; Roy et al., 2015), suggère une réévaluation des séquences de rivages

d'altitude intermédiaire et basse, notamment celles associées au drainage, et de leur chronologie respective. Conséquemment, l'application de la datation ^{10}Be sur des séquences clés de rivages devrait faciliter les corrélations qui définissent les niveaux glaciolacustres, en plus d'améliorer de manière générale la chronologie des stades finaux de ces deux lacs glaciaires. Enfin, ce type de datation fourni des âges limites minimums sur la déglaciation d'une vaste région caractérisée par l'absence d'éléments géomorphologiques marquants le retrait de la marge (e.g., moraines).

Cette étude démontre aussi que la datation ^{10}Be sur des rivages perchés représente une étape fondamentale dans l'amélioration des reconstructions paléogéographiques des lacs glaciaires, surtout dans un contexte où la rareté de matériel organique rend l'utilisation de la datation au radiocarbone impraticable. L'approche novatrice utilisée ici pourrait éventuellement être appliquée à d'autres étendues glaciolacustres d'importance qui se sont développées durant la déglaciation de l'inlandsis laurentidien (e.g., Lac Agassiz; Lac Algonquin; Lac Naskaupi, etc.), de même que sur les séquences de rivages afin d'obtenir de nouvelles contraintes sur des niveaux associés à des abaissements des plans d'eau (drainages). Il s'agit d'une étape importante afin de fournir des estimations réalistes des volumes d'eau de fonte pour des intervalles spécifiques de la dernière déglaciation.

Deuxièmement, l'analyse de deux séquences de varves provenant du cœur du bassin Ojibway a permis de documenter l'histoire tardive du lac. Les données compositionnelles et géochimiques d'une première séquence prélevée sur les rives du Lac Matagami et corrélée avec d'autres séquences régionales à partir des mesures d'épaisseur des varves indiquent qu'une seule réavancée majeure est survenue à l'échelle du bassin, laquelle a joué un rôle important dans l'évolution du Lac Ojibway. En effet, cette réavancée de Cochrane s'est produite ~310 ans avant le drainage final du lac et est caractérisée par la présence de varves proximales enrichies en carbonates détritiques et en matériel glaciel qui témoignent de l'avancée d'une importante plate-

forme de glace, dont l'évolution était contrôlée par la topographie et le niveau du lac, à partir de la baie d'Hudson dans le bassin Ojibway. La corrélation d'une seconde séquence de varves prélevées à La Reine dans le bassin du Lac Abitibi indique que les varves associées à cette réavancée de Cochrane sont surmontées par une série de rythmites à granulométrie grossière. La chronologie des varves associe cette unité à un important *hiatus* qui enregistre un abaissement majeur (drainage) du Lac Ojibway. Ce changement important dans le régime de dépôt est fort probablement lié à la réavancée rapide de la marge qui pourrait avoir déstabilisé le barrage de glace dans la baie d'Hudson et la Baie-James et permis l'ouverture de voie(s) de drainage vers le nord, produisant ainsi un abaissement du niveau du Lac Ojibway. La série de 65 varves épaisses sus-jacente à cette unité est corrélée avec les varves de Connaught (Hughes, 1959; 1965; Breckenridge et al., 2012) – une unité type qui a été documentée à d'autres endroits dans le bassin – ce qui suggère une reprise rapide de la sédimentation des varves dans un bassin peu profond.

Ces varves de Connaught sont surmontées par une unité de silts massifs à faiblement laminés associée au drainage final du Lac Ojibway sur la base de considérations stratigraphiques et de compositions contrastées en isotopes de l'oxygène entre l'unité de silt et l'argile massive sus-jacente (Daubois et al., 2014). Cet horizon marqueur partage plusieurs caractéristiques compositionnelles et sédimentologiques avec les rythmites à la base des varves de Connaught, ce qui suggère la présence de deux horizons de drainage dans la séquence de La Reine. La chronologie des varves indique que ces deux événements sont séparés par un minimum de 65 ans, ce qui est cohérent avec les enregistrements marins qui documentent au moins deux décharges d'eau de fonte et hausses du niveau marin relatif rapprochées durant l'intervalle de la déglaciation comprenant le drainage du Lac Agassiz-Ojibway (Jennings et al., 2015). Ces résultats fournissent des contraintes importantes basées sur des données de terrain à propos de la chronologie et le nombre de décharges d'eau douce en provenance du Lac Agassiz-Ojibway dans l'Atlantique

Nord durant les stades finaux de la déglaciation. Les travaux futurs devraient s'attarder à identifier les séquences de rivages associées à des baisses de niveau marquées ailleurs dans le bassin afin de quantifier les volumes d'eau de fonte impliqués lors de ces événements.

Troisièmement, un nouveau relevé LiDAR couvrant une portion importante du bassin du Lac Ojibway dans le NO du Québec a permis la cartographie exhaustive de rivages avec une résolution jusqu'ici inégalée. Les altitudes de plus de 3000 points de contrôle mesurés sur des plages et des terrasses (escarpements) d'érosion littorale ont été incorporées dans un SIG et combinées à un modèle numérique d'altitude tenant compte de la déformation isostatique du basin à 8.5 ka (modèle ICE-6G; Peltier et al., 2015) dans le but de reconstruire les niveaux de stabilité du lac. La distribution des altitudes mesurées montre une dispersion marquée pour les rivages de haute altitude (i.e., sous la limite maximale atteinte par le Lac Ojibway) et témoigne d'un abaissement graduel du niveau du lac durant les phases précoces d'inondation. Ceci reflète également le manque de stabilité généralisé dans le bassin lié aux réajustements isostatiques combinés au retrait progressif de la marge glaciaire vers le nord qui a permis l'expansion rapide du Lac Ojibway dans le bassin de la Baie-James.

Ces données d'altitude montrent aussi un regroupement marqué de rivages intermédiaires entre les altitudes de 299 et 350 m, lequel renferme deux niveaux distincts et rapprochés montrant des similarités avec les niveaux *early* et *late* Kinojévis documentés dans les études antérieures (Vincent and Hardy, 1979; Veillette, 1994). Notre reconstruction indique que les deux niveaux de type Kinojévis identifiés (c.f., 1a et 1b) sont séparés de 10 à 12 m et présentent des taux de gauchissement nettement distincts de ce qui a été suggéré dans les travaux antérieurs, avec 0.35 m/km (1a: niveau supérieur) et 0.37 m/km (1b: niveau inférieur), indiquant ainsi que les valeurs précédemment rapportées de 0.5 à 1.2 m/km et reprises dans les reconstructions subséquentes ont été surestimées. De plus, le niveau 1b qui marque la

dernière phase de stabilité à l'échelle du bassin Ojibway et l'écart significatif de 37 m avec le niveau inférieur, de même que le faible nombre de rivages entre ces deux niveaux, soutiennent l'hypothèse qu'une baisse abrupte du niveau du lac est à l'origine de cette distribution des rivages. La présence de quelques rivages dispersés dans cet intervalle de 37 m représente des phases transitoires et de courtes durées.

Cet abaissement significatif du plan d'eau est suivi par une seconde concentration importante de rivages s'alignant à l'intérieur d'un intervalle restreint d'altitudes se projetant sous le dernier exutoire connu du Lac Ojibway qui acheminait les excès d'eau de fonte vers le sud. La quasi-totalité de ces éléments a été cartographiée comme des terrasses (escarpements) d'érosion littorale sculptées dans la plaine argileuse qui sont vraisemblablement associées au rétablissement d'un plan d'eau stable dans le cœur du bassin suivant la baisse abrupte du niveau Ojibway. Deux paléosurfaces semblent présentes dans ce regroupement de rivages. Les valeurs de gauchissement de 0.36 m/km (2a: niveau supérieur) et 0.35 m/km (2b: niveau inférieur) similaires à celles déterminées pour les niveaux 1a et 1b indiquent que cette baisse s'est produite sur un cours laps de temps. Cependant, même si nos données montrent deux niveaux séparés de 2 m, la résolution de notre reconstruction (± 5 m) ne permet pas d'identifier de façon statistiquement significative deux plans d'eau distincts. Néanmoins, la présence de cette population de rivages correspond aux niveaux tardifs récemment définis dans la région de La Sarre et témoigne de l'existence d'un niveau de stabilité dans le bassin Ojibway suite à un abaissement important de la surface du lac (Roy et al., 2015). Ces niveaux de La Sarre sont suivis d'une deuxième baisse de 11 m qui suggère une diminution marquée du niveau du Lac Ojibway. Les rivages constituant le plus bas niveau documenté dans cette étude sont confinés aux abords du Lac Abitibi et la reconstruction du plan d'eau associé trace les limites du lac postglaciaire qui a occupé la région tel que précédemment rapporté dans les enregistrements sédimentaires (Antevs, 1925; Daubois et al., 2014).

Cette reconstruction présente des preuves solides que le drainage du Lac Agassiz-Ojibway s'est produit par étapes, via au moins deux abaissements majeurs du plan d'eau, établissant par le fait même un lien direct entre les enregistrements marins et continentaux (cette thèse) qui indiquent deux décharges massives d'eau de fonte au cours de cet intervalle de la déglaciation. Les niveaux de type Kinojévis documentés à partir des données LiDAR montrent que le dernier exutoire connu à avoir drainé l'excès d'eau de fonte vers le sud et situé à une altitude de 300 m n'est pas associé à un plan d'eau stable dans le bassin Ojibway, ce qui soulève des questions quant à son utilisation pour reconstruire le niveau prédrainage du Lac Agassiz-Ojibway (Thorleifson, 1996; Leverington et al., 2002a). De plus, l'occurrence de deux abaissements majeurs du Lac Ojibway est en contradiction avec les enregistrements de varves suggérant une stabilité du plan d'eau à partir de la connexion entre le Lac Agassiz et le Lac Ojibway, un intervalle de ~600 ans (Breckenridge, 2004; Breckenridge et al., 2012). Ces nouvelles données impliquent que la surface prédrainage utilisée dans les reconstructions du Lac Agassiz-Ojibway, de même que la connexion entre les deux bassins, devraient être réévaluées. Les travaux futurs devraient s'efforcer de vérifier si les niveaux tardifs et les abaissements associés peuvent être retracés à travers l'ensemble du bassin, notamment dans le secteur du Lac Agassiz.

En conclusion, ce travail contribue de manière importante à réduire les incertitudes liées à la chronologie et au nombre d'événements associés au drainage final du Lac Agassiz-Ojibway et devrait contribuer à raffiner les reconstructions utilisées dans les calculs de volumes d'eau de fonte. Ces données constituent des intrants essentiels dans les modèles océaniques et paléoclimatiques qui visent à évaluer les impacts des décharges d'eau douce de la dernière déglaciation sur la circulation thermohaline de l'Atlantique Nord. Ultimement, les résultats présentés dans cette thèse ont de sérieuses implications dans l'évaluation du forçage climatique

produit par ces apports massifs d'eau douce, un élément critique dans le contexte actuel de fonte accélérée des glaces du Groenland et des glaciers de l'Arctique.

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