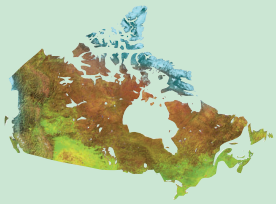
Natural Resources Canada
Ressources naturelles Canada



Geological Survey of Canada
Bulletin 600

Glacial stratigraphy of northern and central Manitoba

L.A. Dredge and I. McMartin

2011

Canada

The CD-ROM accompanying this publication contains the full report, including any oversized figures and/or A-series maps, in Portable Document Format (PDF). Oversized items may be purchased separately as paper plots from any Geological Survey of Canada Bookstore location:

Geological Survey of Canada Bookstore (Ottawa)
615 Booth Street
Ottawa, Ontario
K1A 0E9
Tel.: (613) 995-4342
Tel.: (888) 252-4301 (toll-free)
Fax: (613) 943-0646
E-mail: gscbookstore@nrcan.gc.ca
Web: http://gsc.nrcan.gc.ca/bookstore/index_e.php

Geological Survey of Canada Bookstore (Vancouver)
101-605 Robson Street
Vancouver, B.C.
V6B 5J3
Tel.: (604) 666-0271
Fax: (604) 666-1337
E-mail: gscvan@gsc.nrcan.gc.ca
Web: http://gsc.nrcan.gc.ca/org/vancouver/bookstore/index_e.php

Geological Survey of Canada Bookstore (Atlantic)
1 Challenger Drive
P.O. Box 1006
Dartmouth, Nova Scotia
B2Y 4A2
Tel.: (902) 426-4386
Fax: (902) 426-4848
E-mail: Jennifer.Bates@nrcan-rncan.gc.ca
Web: http://gsca.nrcan.gc.ca/pubprod/pubprod_e.php

Geological Survey of Canada Bookstore (Québec)
490, rue de la Couronne
Québec, Quebec
G1K 9A9
Tel.: (418) 654-2677
Fax: (418) 654-2660
E-mail: cgcq_librairie@rncan.gc.ca
Web: http://www.gscq.nrcan.gc.ca/bibliotheque/

Le CD-ROM qui accompagne cette publication renferme le rapport au complet, y compris les figures surdimensionnées ou les cartes de série A, en format PDF. Pour acheter des copies papier des éléments surdimensionnés, adressez-vous à la Librairie de la Commission géologique du Canada :

Librairie de la Commission géologique du Canada (Ottawa)
615, rue Booth
Ottawa (Ontario)
K1A 0E9
Tél. : (613) 995-4342
Tél. : (888) 252-4301 (sans frais)
Télécopieur : (613) 943-0646
Courriel : librairiecgc@nrcan.gc.ca
Web : http://cgc.rncan.gc.ca/librairie/index_f.php

Librairie de la Commission géologique du Canada (Vancouver)
101-605 Robson Street
Vancouver (C.-B.)
V6B 5J3
Tél. : (604) 666-0271
Télécopieur : (604) 666-1337
Courriel : gscvan@gsc.nrcan.gc.ca
Web : http://cgc.rncan.gc.ca/org/vancouver/bookstore/index_f.php

Librairie de la Commission géologique du Canada (Atlantique)
1 Challenger Drive
P.O. Box 1006
Dartmouth (Nouvelle-Écosse)
B2Y 4A2
Tél. : (902) 426-4386
Télécopieur : (902) 426-4848
Courriel : Jennifer.Bates@nrcan-rncan.gc.ca
Web : http://gsca.nrcan.gc.ca/pubprod/pubprod_f.php

Librairie de la Commission géologique du Canada (Québec)
490, rue de la Couronne
Québec (Québec) G1K 9A9
Tél. : (418) 654-2677
Télécopieur : (418) 654-2660
Courriel : cgcq_librairie@rncan.gc.ca
Web : http://www.cgcq.rncan.gc.ca/bibliotheque/

Geological Survey of Canada
Bulletin 600

Glacial stratigraphy of northern and central Manitoba

L.A. Dredge and I. McMartin

2011

ISSN 0068-7626
Catalogue No. M42-600E-MRC
ISBN 978-0-660-20037-8
doi: 10.4095/288561

Available in Canada from the Geological Survey of Canada Bookstore
(see inside front cover for details)

A copy of this publication is also available for reference in depository libraries across Canada through access to the Depository Services Program's Web site at http://dsp-psd.pwgsc.gc.ca

A free digital download of this publication is available from GeoPub: http://geopub.nrcan.gc.ca/index_e.php

Recommended citation

Dredge, L.A., and McMartin, I., 2011. Glacial stratigraphy of northern and central Manitoba; Geological Survey of Canada, Bulletin 600, 27 p. doi: 10.4095/288561

Cover illustration
Terrain and stratigraphic sections along Churchill River at Mountain Rapids. Photograph by L.A. Dredge. 2010-214

Critical review
B. McClenaghan
J. Campbell

Authors
L.A. Dredge (Lynda.Dredge@NRCan-RNCan.gc.ca)
I. McMartin (Isabelle.McMartin@NRCan-RNCan.gc.ca)
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario
K1A 0E8

CONTENTS

Figures

Glacial stratigraphy of northern and central Manitoba

Abstract

Stratigraphic sections exposed along river banks and road cuts, and in boreholes across northern and central Manitoba, reveal a record of multiple glaciations and at least two interglaciations. The sections in northeast Manitoba contain the most complete records, whereas those in the west more commonly relate to late Wisconsin events and ice retreat phases. Evidence exists for separate early Keewatin and Labradorean ice flows that extended farther south and west than those of the late Wisconsin glaciation. During the late Wisconsin glaciation, carbonate content in the upper till suggests an intermingling of Keewatin and Labradorean ice in the area, and a shifting zone of convergence that ultimately lay along the Etawney-Settee moraine. Small amounts of matrix carbonate and limestone clasts in the uppermost till sheet in the Leaf Rapids area are thought to have been incorporated from underlying tills. There is a record of several readvances of Keewatin and Labradorean ice into glacial Lake Agassiz, both of which incorporated calcareous glaciolacustrine silt into the upper till unit.

Résumé

Des coupes stratigraphiques exposées le long des berges de cours d'eau et des tranchées de route ainsi que dans des sondages dans le nord et le centre du Manitoba préservent les traces de plusieurs glaciations et d'au moins deux périodes interglaciaires. Les coupes dans le nord-est du Manitoba renferment les séquences les plus complètes, tandis que celles à l'ouest sont souvent associées à des événements et à des phases de retrait des glaces qui datent du Wisconsinien tardif. Certaines données indiquent que lors d'une phase précoce, des écoulements glaciaires distincts à partir des centres de dispersion du Keewatin et du Labrador s'étendaient plus loin vers le sud et l'ouest que lors de la glaciation du Wisconsinien tardif. La teneur en carbonates du till supérieur indique un mélange des glaces du Keewatin et du Labrador dans la région pendant la glaciation du Wisconsinien tardif, ainsi qu'une zone de convergence mobile qui s'étendait en dernier lieu le long de la moraine d'Etawney-Settee. Dans la région de Leaf Rapids, de petites quantités de matrice carbonatée et de clastes de calcaire dans la nappe de till sommitale proviendraient de tills sous-jacents. Plusieurs réavancées des glaces du Keewatin et du Labrador dans le Lac glaciaire Agassiz sont documentées, au cours desquelles ces deux entités ont introduit des silts glaciolacustres calcareux dans l'unité supérieure de till.

SUMMARY

This is the first regional synthesis of the stratigraphy of northern and central Manitoba. The stratigraphic record and its interpretation presented here indicate that the Laurentide Ice Sheet and its precursors have had a long and complicated history, with both minor and major shifts in ice flow occurring not only at the southerly limits of glaciation, or during deglaciation, but also at the heart of the Laurentide Ice Sheet and throughout the course of at least the last several glaciations.

The stratigraphic record across central and northern Manitoba consists of a sequence of tills and intertill sediments representing a series of ice-flow events spanning a number of glaciations and interglaciations. The exposures containing the longest records are found along the large rivers in the Hudson Bay Lowlands, where two interglacial periods are recorded. Most sections farther north and west contain sediments related to the last glacial, and mainly to deglacial events, although striation sequences in that area preserve a longer record.

Based on the stratigraphic records presented above, we interpret the sequence of glacial and nonglacial events to be as follows:

1. An early major ice flow from the east, inferred by Omarolluk erratics in the lowermost tills along Nelson River.

2. A major flow of Keewatin ice across northern and central Manitoba, emplacing the Sundance till on Nelson River, and Keewatin erratics regionally.

3. A pre-Sangamon interglacial event consisting of both warm and cold climate phases, indicated by soil horizons at the top of the Sundance till, and correlative clay-rich sediments.

4. A major flow of Labradorean ice westward, emplacing the Amery till on Nelson River and areas south in the Hudson Bay Lowlands, and accounting for westward striae in the Lynn Lake and Flin Flon areas, and in Saskatchewan farther west (e.g. Campbell and McMartin, 2008). This ice flow is tentatively assigned to the Illinoian Glaciation.

5. An interglaciation with climates and biomes similar to present, as evidenced by peat, alluvium, and glaciolacustrine deposits along rivers in the Hudson Bay Lowlands and as far north as Seal River in eastern Manitoba. These deposits are considered to represent the Sangamon interglaciation. Radiocarbon dates are nonfinite and greater than 59 ka, and optical dates are about 121 ka.

SOMMAIRE

Cette étude constitue la première synthèse régionale de la stratigraphie du nord et du centre du Manitoba. Cette stratigraphie, et l'interprétation qui en est faite dans ce rapport, démontrent que l'Inlandsis laurentidien et ses précurseurs ont eu une histoire longue et complexe, comprenant des déplacements mineurs et majeurs de l'écoulement glaciaire, non seulement aux limites sud de la glaciation ou pendant la déglaciation, mais également au cœur de l'Inlandsis laurentidien, et au cours des quelques dernières glaciations tout au moins.

La stratigraphie du centre et du nord du Manitoba est constituée d'une séquence de tills et de sédiments intertill reflétant une série d'événements d'écoulement glaciaire répartis sur plusieurs glaciations et périodes interglaciaires. Les coupes exposées qui représentent les plus longs intervalles se trouvent en bordure des grands cours d'eau dans les basses terres de la baie d'Hudson, et renferment l'évidence de deux périodes interglaciaires. Plus au nord et à l'ouest, la plupart des coupes contiennent des sédiments associés aux derniers événements glaciaires, et principalement aux événements de déglaciation, bien que les séquences de stries dans cette zone couvrent un intervalle plus long.

D'après cette stratigraphie, nous avons interprété la séquence d'événements glaciaires et non glaciaires comme suit :

1. Un important écoulement initial des glaces en provenance de l'est, déduit d'après la présence de blocs erratiques de la Formation d'Omarolluk dans les tills basaux le long du fleuve Nelson.

2. Un important écoulement des glaces du Keewatin dans le nord et le centre du Manitoba, entraînant le dépôt du till de Sundance le long du fleuve Nelson et de blocs erratiques de la région de Keewatin à l'échelle régionale.

3. Un interglaciaire pré-Sangamonien comprenant des phases de climat chaud et de climat froid, déduit d'après les horizons pédologiques au sommet du till de Sundance ainsi que des sédiments corrélatifs riches en argile.

4. Un important écoulement des glaces du Labrador vers l'ouest, entraînant le dépôt du till d'Amery le long du fleuve Nelson et plus au sud dans les basses terres de la baie d'Hudson, et expliquant la présence de stries orientées vers l'ouest dans les régions de Lynn Lake et de Flin Flon, ainsi qu'en Saskatchewan plus à l'ouest (p.ex. Campbell et McMartin, 2008). Cet écoulement glaciaire est provisoirement attribué à la Glaciation illinoienne.

5. Une période interglaciaire dont les climats et les biomes étaient similaires à ceux d'aujourd'hui, comme en témoignent des dépôts de tourbe, d'alluvions et de sédiments glaciolacustres le long des cours d'eau des basses terres de la baie d'Hudson et, vers le nord, jusqu'à la rivière Seal dans l'est du Manitoba. Nous estimons que ces dépôts représentent l'Interglaciaire sangamonien. Les dates radiocarbone obtenues sont non finies et supérieures à 59 ka, tandis que les dates déterminées par méthode optique sont d'environ 121 ka.

6. Early to main Wisconsinan flow of Keewatin ice southeast, inferred from crosscutting striae in the Lynn Lake area (Kaszycki et al., 2008), The Pas (McMartin, 1994, 2000) and eastern Saskatchewan (Henderson, 1995; McMartin et al., 1996; Campbell and McMartin, 2008), and from numerous Proterozoic Dubawnt clasts in the base of the Long Spruce till in the Hudson Bay Lowlands. However, there is no actual corresponding till unit in the lowlands.

7. There were shifts in ice flow within both the Keewatin and Labradorean sectors of the Laurentide Ice Sheet during the main to late Wisconsin Glaciation. Also, there was a westward shift in the confluence of Keewatin and Labradorean ice during this glacial period. A major Labradorean ice flow westward emplaced the Long Spruce till/Wigwam Creek till in the Hudson Bay Lowlands. Kaszycki (*in* Kaszycki et al., 2008) thought that Labradorean ice of this age followed an arcing flow path, creating striae at about 210°, and stopped in the Leaf Rapids area. We conclude, however, that it extended westward somewhat farther, into the Lynn Lake area and west of The Pas moraine near Flin Flon, as reflected by silty and/or calcareous tills. Also, more recent compilations of ice-flow datasets (McMartin et al., 2010) suggest that the 210° ice flow that Kaszycki attributed to a Labradorean source is just as likely, or more likely, to be of Keewatin provenance. The northern extent of Labradorean ice at this time was probably somewhat north of Seal River, as inferred from the presence of reworked Paleozoic carbonate clasts in later Keewatin tills.

8. Eastward migration of the Keewatin Ice Divide caused shifting ice-flow patterns during the late Wisconsin glaciation and during deglaciation. In northeastern Manitoba, both striation records and till stratigraphy indicate that the northern limit of the Keewatin/Labradorean convergence shifted between Churchill River and North Knife River. Areas north of this zone lay in the Keewatin ice domain. South of this zone of interplay, Labradorean ice deposited the Sky Pilot till. South of the Flin Flon area, Keewatin flow dominated in areas west of the The Pas moraine, which marks the westerly limit of Labradorean ice during deglaciation.

   North of the Cree Lake moraine, Kaszycki (*in* Kaszycki et al., 2008) interpreted the Leaf Rapids moraine area to mark the westward limit of convergence of Labradorean and Keewatin ice, with converging flow recorded in till fabrics and local striae. She interpreted the Settee-Etawney

6. Un écoulement des glaces du Keewatin vers le sud-est, depuis la phase initiale jusqu'à la phase principale de la glaciation du Wisconsinien, est déduit d'après des stries entrecroisées dans les régions de Lynn Lake (Kaszycki et al., 2008) et de The Pas (McMartin, 1994, 2000), et dans l'est de la Saskatchewan (Henderson, 1995; McMartin et al., 1996; Campbell et McMartin, 2008), ainsi que d'après de nombreux clastes du Supergroupe de Dubawnt (Protérozoïque) à la base du till de Long Spruce dans les basses terres de la baie d'Hudson. Il n'existe cependant aucune unité de till correspondante dans les basses terres.

7. Des déplacements de l'écoulement glaciaire se sont produits dans les secteurs du Keewatin et du Labrador de l'Inlandsis laurentidien pendant les phases principale et terminale de la glaciation du Wisconsinien. De plus, la confluence des glaces du Keewatin et du Labrador s'est déplacée vers l'ouest pendant cette période glaciaire. Un écoulement majeur des glaces du Labrador vers l'ouest a entraîné le dépôt du till de Long Spruce/till de Wigwam Creek dans les basses terres de la baie d'Hudson. Kaszycki (*in* Kaszycki et al., 2008) pensait que les glaces du Labrador de cet âge s'étaient écoulées suivant une trajectoire en arc, laissant des stries à environ 210°, et s'étaient arrêtées dans la région de Leaf Rapids. Nous concluons, cependant, que ces glaces se sont étendues un peu plus loin vers l'ouest, jusque dans la région de Lynn Lake, et à l'ouest de la moraine de The Pas près de Flin Flon, comme le démontrent des tills silteux ou calcareux. En outre, des compilations plus récentes de jeux de données sur les écoulements glaciaires (McMartin et al., 2010) indiquent que l'écoulement glaciaire à 210° que Kaszycki attribuait à une source du secteur du Labrador est tout aussi probablement, ou plus probablement, de provenance du secteur du Keewatin. La limite nord des glaces du Labrador à cette époque se situait probablement un peu au nord de la rivière Seal, comme le laisse supposer la présence de clastes carbonatés remaniés du Paléozoïque dans des tills déposés par les glaces du Keewatin lors de phases tardives.

8. La migration vers l'est de la Ligne de partage glaciaire du Keewatin a entraîné un changement de la configuration des écoulements glaciaires pendant la glaciation du Wisconsinien tardif et pendant la déglaciation. Dans le nord-est du Manitoba, tant la configuration des stries que la stratigraphie du till indiquent que la limite nord de la convergence des glaces du Keewatin et du Labrador s'est déplacée entre la rivière Churchill et la rivière North Knife. Les régions au nord de cette zone se trouvaient dans le domaine des glaces du Keewatin. Au sud de cette zone d'influence réciproque, les glaces du Labrador ont déposé le till de Sky Pilot. Au sud de la région de Flin Flon, l'écoulement du Keewatin a dominé les zones à l'ouest de la moraine de The Pas, laquelle marquait la limite occidentale des glaces du Labrador pendant la déglaciation.

   Au nord de la moraine de Cree Lake, selon l'interprétation de Kaszycki (*in* Kaszycki et al., 2008), la moraine de Leaf Rapids marquerait la limite ouest de la convergence des glaces du Labrador et du Keewatin, avec des écoulements convergents apparents dans les stries à l'échelle locale et la structure du till. Toujours selon Kaszycki, les moraines de Settee-Etawney

moraines to be recessional moraines that developed after retreat of Labradorean ice from the Leaf Rapids moraine.

Klassen (1986), however, interpreted the Etawney moraine to be the deglacial interlobate zone between the Keewatin and Labradorean ice masses. Streamlined landforms, esker patterns, and the composition of surface till sheets (Dredge and Nixon, 1992; McMartin et al., 2010), suggest confluent flow of Keewatin and Labradorean ice during deglaciation in the area east of North Knife Lake. Thus, it is likely that the Etawney and contiguous North Knife kame moraines mark a major zone of convergence. Either these moraines mark a major convergence after the confluent ice margins had retreated north and east of Leaf Rapids, or they were the major convergence, and the Leaf Rapids moraine is essentially an esker that was large enough to pull ice toward it, thus accounting for the till fabric and striation rotations along its flanks. At present, we conclude that the latter scenario is more likely, in which case the Labradorean ice flow that reached as far as, or beyond Leaf Rapids, was an earlier ice flow mentioned above (event 7 or 4), and the late Labradorean ice did not extend west of the Etawney moraine. The sandy Limestone moraine, oriented east-west, is considered to be a radial kame moraine feature within the Labradorean ice sheet that is parallel to the regional ice flow.

During deglaciation, stacked tills in the Lynn Lake–Leaf Rapids area, intercalated with glacial lake sediments, indicate small glacial readvances into glacial Lake Agassiz. Similar intercalated till and glaciolacustrine sediment sequences are also present in the lowlands. A major regional fanning pattern of sandy, noncalcareous till with drumlinoidal surface landforms, representing the Quinn Lake readvance, marks a major surge of Keewatin ice into the northern margin of glacial Lake Agassiz. Similar readvances into glacial Lake Agassiz from the receding Keewatin ice margin may account for south-southwestward striation patterns along Southern Indian Lake.

9. Accompanying deglaciation, the Keewatin ice margin retreated northward, while the Labradorean ice margin retreated eastward. Diamictic and substratified till-like deposits, as well as distal-facies, clay-rich, varved sediments, were deposited into glacial Lake Agassiz. Following breakup of Hudsonian ice, marine waters inundated lowland areas surrounding Hudson Bay, depositing a coarsening-upward sequence of postglacial marine deposits.

seraient des moraines de retrait qui se seraient formées après que les glaces du Labrador se soient retirées de la moraine de Leaf Rapids.

Toutefois, selon l'interprétation de Klassen (1986), la moraine d'Etawney marquerait la zone interlobaire de déglaciation entre les masses de glace du Keewatin et du Labrador. Les formes de terrain fuselées, la configuration des eskers et la composition des nappes de till de surface (Dredge et Nixon, 1992; McMartin et al., 2010) laissent supposer un écoulement confluent des glaces du Keewatin et du Labrador pendant la déglaciation dans la région à l'est du lac North Knife. Ainsi, il est probable que les moraines de kame contiguës d'Etawney et de North Knife marquent une zone de convergence majeure. Ou bien ces moraines marquent une convergence majeure après que les marges glaciaires confluentes se soient retirées au nord et à l'est de Leaf Rapids, ou bien ces moraines constituaient cette convergence majeure, et la moraine de Leaf Rapids est essentiellement un esker qui était suffisamment important pour amener la glace vers lui, expliquant ainsi la structure du till et les rotations des stries le long de ses flancs. À l'heure actuelle, nous concluons que le second scénario est le plus probable; dans ce cas, l'écoulement des glaces du Labrador qui a atteint, voire dépassé, Leaf Rapids était un écoulement glaciaire plus ancien mentionné précédemment (événement 7 ou 4) et les glaces du Labrador de cette phase tardive ne s'étendaient pas à l'ouest de la moraine d'Etawney. La moraine sableuse de Limestone, orientée est ouest, est interprétée comme une moraine de kame radiale dans la nappe glaciaire du Labrador qui est parallèle à l'écoulement glaciaire régional.

Des tills empilés dans la région de Lynn Lake–Leaf Rapids, à interstrates de sédiments de lac glaciaire, indiquent de petites réavancées glaciaires dans le Lac glaciaire Agassiz pendant la déglaciation. Des séquences similaires de till et de sédiments glaciolacustres interstratifiés sont également présentes dans les basses terres. Une importante configuration régionale en éventail de till sableux non calcareux à relief drumlinoïde, représentant la réavancée de Quinn Lake, marque une crue majeure des glaces du Keewatin jusque dans la marge nord du Lac glaciaire Agassiz. Des réavancées similaires dans le Lac glaciaire Agassiz de la marge en retrait des glaces du Keewatin peuvent expliquer les configurations de stries orientées sud–sud-ouest le long du lac Southern Indian.

9. Pendant la déglaciation, la marge des glaces du Keewatin s'est retirée vers le nord, tandis que la marge des glaces du Labrador se retirait vers l'est. Des dépôts diamictiques et des dépôts quasi-stratifiés s'apparentant à du till, ainsi que des sédiments varvés de faciès distal riches en argile, se sont déposés dans le Lac glaciaire Agassiz. À la suite de la dislocation des glaces d'Hudson, l'eau de mer a inondé les basses terres ceinturant la baie d'Hudson, y déposant une séquence de sédiments marins postglaciaires à granocroissance ascendante.

INTRODUCTION

This paper is the first regional synthesis of the glacial stratigraphy of northern and central Manitoba. It combines previously published data from a variety of sources, and includes unpublished results based on fieldwork by the authors. An understanding of the glacial stratigraphy of this area is important in reconstructing the glacial history of the central part of the Laurentide Ice Sheet, and provides a much longer glacial record than reconstructions derived primarily from surface features. The stratigraphic record is also important for drift dispersal aspects of mineral exploration, because it reveals the complex pattern of ice flow in this area, and indicates the degree of inheritance of old materials in the surface till.

Glacial setting

Northern and central Manitoba have been glaciated by two major ice masses within the Laurentide Ice Sheet (Dredge and Cowan, 1989) and its precursors. Ice flow was influenced at various times by the Keewatin ice centre, which resulted in basically southward ice flow across the area, and tills that were derived primarily, but not exclusively, from Precambrian Shield source rocks. At other times, ice flow was dominantly from a Labradorean centre of outflow, resulting in westward ice flow that produced tills derived from both Shield terrane and the Paleozoic carbonate bedrock that underlies and surrounds Hudson Bay. The stratigraphic record shows that during the late Wisconsin glaciation, the area lay in the zone of convergence of these two ice sheets, thereby producing complex ice-flow and drift dispersal patterns. It further shows that during previous glacial events, one ice mass, or the other, or both, dominated the region.

Stratigraphic setting

Stratigraphic sections exposed along rivers and roadcuts in central and northern Manitoba (Fig. 1), together with sporadic borehole data, provide a record of regional glacial events and ice-flow sequences. As well as the large sections, which reveal major glacial and interglacial events, many small sections shed light on late-glacial ice flows. The late-glacial stratigraphic record is especially significant in the extensive areas that are mantled by glacial Lake Agassiz sediments, postglacial marine deposits, and peat blankets: in these areas, till and striations are rarely seen.

In northern Manitoba, sections that record a number of glaciations as well as nonglacial intervals occur in the Hudson Bay Lowlands, mainly along the lower 100 km of large rivers draining into Hudson Bay. The principal rivers exposing a long stratigraphic record in their banks are the Gods, Hayes, Stupart, Fox, Nelson, Little Churchill, Churchill, Little Beaver, South and North Knife, and Seal. Shorter stratigraphic records are found in Shield terrain farther west along South Seal and Muskwesi rivers; and late-glacial or deglacial records are preserved in roadcuts and small exposures between Thompson, Lynn Lake, and Flin Flon.

The stratigraphic record described here provides a long glacial record for the region. It also complements and elucidates last-glacial chronologies determined from glacial landforms, carbonate/geochemical element dispersal in the surface till, and the striation record on bedrock outcrops (Kaszycki et al., 2008; McMartin et al., 1996, 2010, work in progress). The longest well-studied records occur along the Nelson River, and are treated first. Other sections within the Hudson Bay Lowlands that include interglacial deposits, from south to north, are then discussed. Finally, shorter records from limited exposures in western Manitoba are described.

Previous work

Although initial concepts on ice flow within the Laurentide Ice Sheet in northern and central Manitoba were envisaged by Bell (1879, 1880) and Tyrrell (1898) using striation orientations as early as 1898, most of the detailed work was conducted by the Geological Survey of Canada (GSC) in the 1970s and 1980s. Klassen (1986) and Netterville (1974) documented a sequence of tills and nonglacial sediments along the Nelson and Gods rivers during mapping projects in north-central Manitoba. Later, Dredge and Nielsen (1985) and Dredge and Nixon (1992), with others, elaborated on these findings across northeastern Manitoba extending from Seal River in the north, to Shamattawa river near the Ontario provincial boundary. Records from Polar Gas (1976) boreholes along a proposed pipeline route provided additional data between rivers. More recently, the documentation and interpretation of Kaszycki et al. (2008) and McMartin (2000) of short river sections, roadcuts and backhoe trenches in west-central Manitoba have added significant details to the regional stratigraphic framework. Roy (1998) intensively studied four sections along the Nelson River as part of an M.Sc. thesis, and a recent map compilation by Matile (*in* Anderson et al., 2005) of northernmost Manitoba has contributed additional data on penultimate glacial events in the vicinity of Nejanilini Lake.

INDICATORS OF ICE-FLOW EVENTS AND PROVENANCE

In northern and central Manitoba, pebble-sized clasts in till are the main indicators of ice provenance, although theoretically, textural composition and matrix elemental geochemistry should also provide a means of distinguishing between till sheets as a result of differences in till characteristics derived from granitic Precambrian terrain and Paleozoic carbonate terrain. Northern provenance Shield

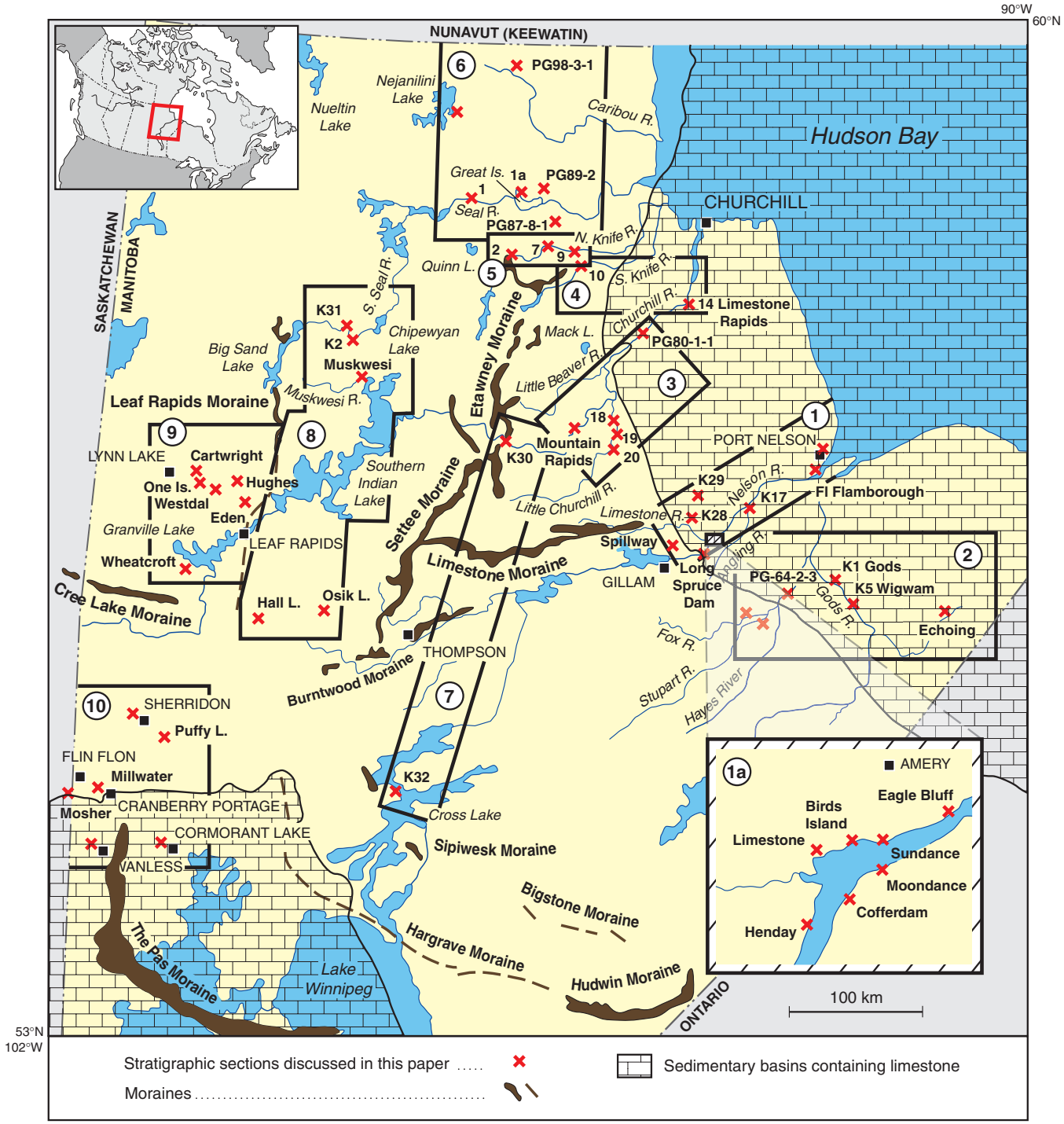


Figure 1. Location map. Sets of stratigraphic sections described in the text are outlined.

tills tend to be sandy textured and characterized by greater concentrations of lithophile elements (Al, K, Si, etc.), whereas those of eastern provenance are silty, and contain much higher quantities of Ca, Mg, Zn, Mn, and Te (Dredge and Pehrsson, 2006). However, distinguishing between till units and interpreting ice provenance based on matrix composition is difficult in most stratigraphic sections because ice from both the Keewatin and the Labradorean ice centres crossed both bedrock terrains, thereby creating overlapping textural characteristics. Interpretation is further complicated by the reworking of tills during successive ice-flow events.

Several major diagnostic suites of glacial erratics have been recognized in the coarse fractions of tills, and indicate ice flow from, or across, Keewatin, southern Hudson Bay, northern Ontario, and central Hudson Bay (Fig. 2). The northern suite of distinct rock types includes red to pink arkose and sandstone (Thelon Fm), reddish pebble conglomerate (South Channel fm, Fig. 3a), red-brown rhyolite porphyry with white feldspar phenocrysts and glassy quartz phenocrysts (Pitz Fm), and volcaniclastics with phlogopite phenocrysts (Christopher Island Fm), all from the Paleoproterozoic Dubawnt Supergroup in central Keewatin and adjacent Northwest Territories (Rainbird et al., 2003). Rock suites of eastern provenance include dark grey greywacke with light grey concretions deriving from the Proterozoic Omarolluk Formation in the Belcher Group (Fig. 3b) in eastern Hudson Bay, red oolitic red jasper derived from Sutton Ridges (Kipalu Fm) in northern Ontario, porphyritic basalt with a fine greenish groundmass and yellow phenocrysts from the Belcher Islands area (Fig. 2), and red sandstone from the Loaf Formation of the Belcher Group (Bostock, 1971; Prest et al., 2000). Rock suites of eastern or northeastern provenance include brick red siltstone (Williams Island and Long Rapids fms) from Devonian outcrops in Hudson Bay, and black Cretaceous shale containing marine fossils, presumably from central Hudson Bay (Norris, 1993). In addition, Paleozoic corals and Quaternary shell fragments and foraminifera from Hudson Bay occur as clasts in some till units.

Other clasts in the till—Precambrian granite, gneiss and minor volcanics, and Paleozoic limestone and dolomite—are present in greater abundance and may be either of local or distant origin. In northern Manitoba, the Paleozoic clasts

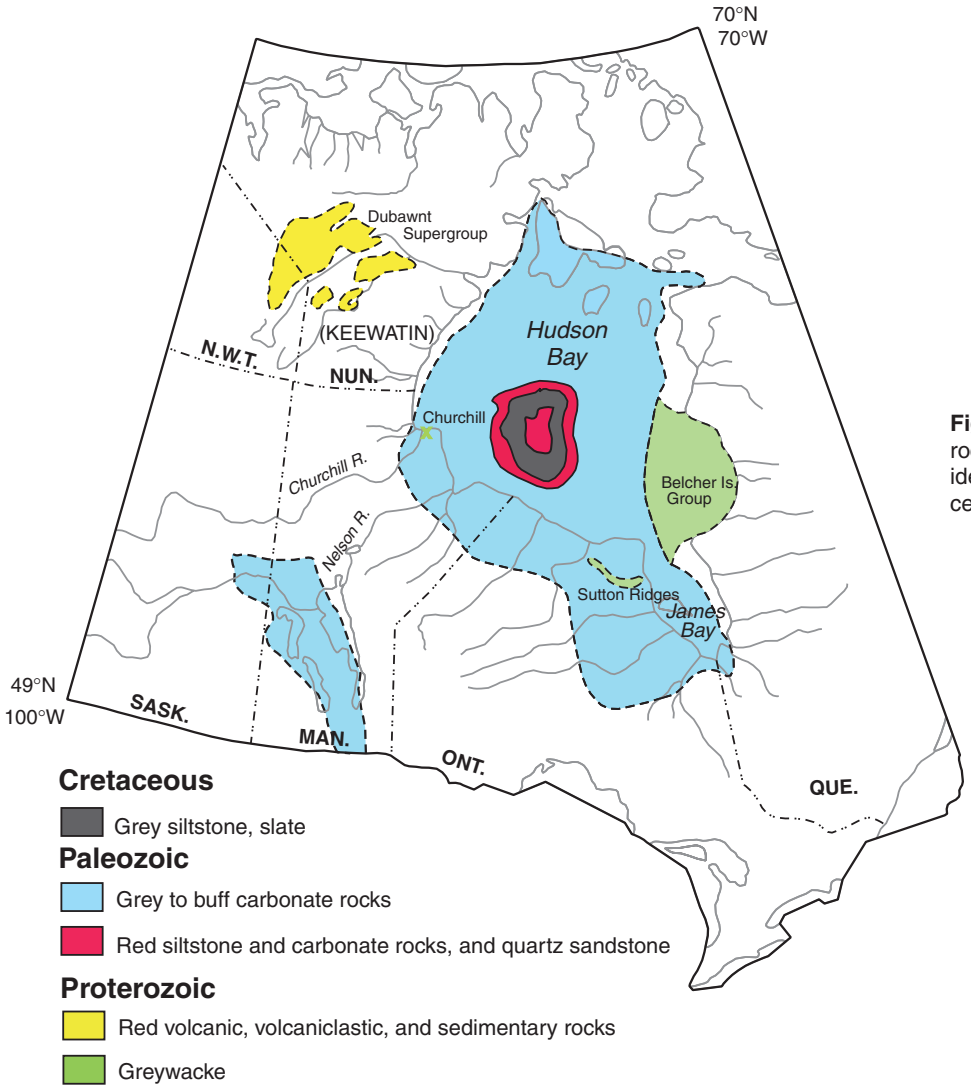


Figure 2. Locations of distinct bedrock lithologies that can be visually identified in till across northern and central Manitoba.

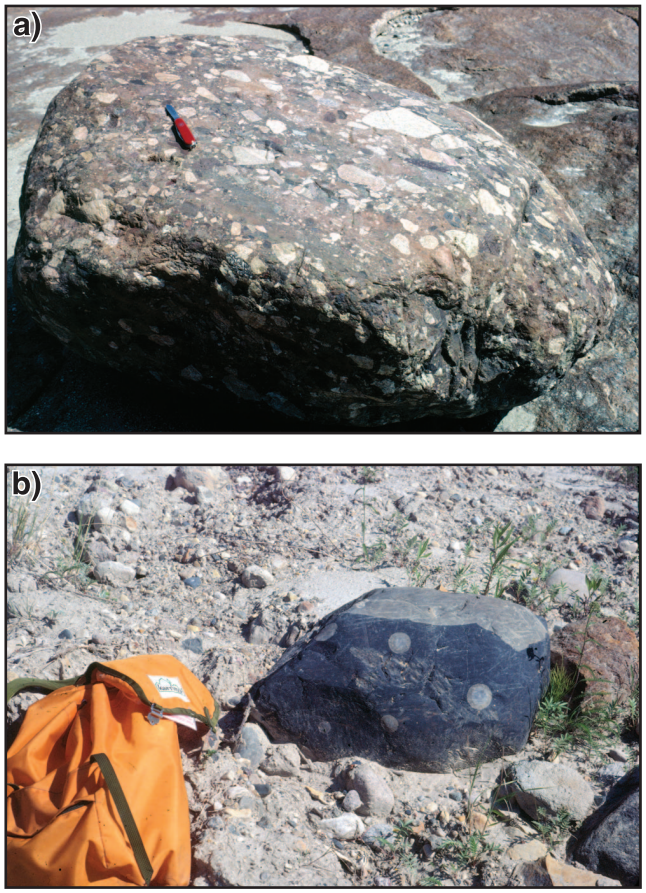


Figure 3. Photographs of indicator clasts: **a)** Proterozoic Dubawnt erratic (South Channel formation) from Keewatin found along Churchill River; **b)** Omarolluk Formation erratic and silty till from eastern Hudson Bay, found along Nelson River. Photographs by L.A. Dredge. 2010-202, 203

are derived from Hudson Platform rocks, and are generally indicators of eastern provenance, but farther to the southwest, they may also come from Williston Basin. Local lithological or geochemical indicators of ice-flow direction occur near mineralized bedrock, examples being arsenic in the till at Wheatcroft Lake (Kaszycki et al., 1988, 2008), arsenic/gold in till at Great Island along the Seal River (Dredge and Nielsen, 1986; Nielsen, 1987) and chrome/nickel in till at Osik Lake (DiLabio and Kaszycki, 1988).

STRATIGRAPHIC RECORD ALONG THE NELSON RIVER

Sections along the lower Nelson River (Fig. 1, area 1a) contain multiple tills and intervening non-till sediments, providing a long record of glacial and interglacial events. Attempts to recognize different till units along the Nelson River by major clast lithology, matrix colour, degree of weathering, texture, matrix carbonate content, trace element geochemistry, fabric and related striae, and by determining 'absolute' ages have met with limited success. There is substantial variability of each parameter within each till sheet from area to area, and even within a single section. To date, sediment sequence and indicator clast content, combined with one or more other parameters, have been the diagnostic criteria for recognition of till units. Absolute age determinations have been attempted for both till and intertill nonglacial sediments. Methods include paleomagnetism and magnetic susceptibility, radiocarbon dating of interglacial organic deposits and shell 'clasts' in till, amino acid dating of shell and wood, U/Th isotope dating, and thermal and optical luminescence dating. Results have been equivocal, except where noted below. The determination of the ice-flow record, and correlation from one section to another therefore relies heavily on sequence stratigraphy.

Cliff faces more than 30 m (50 m at Eagle Bluff) high are exposed intermittently along a considerable length of the Nelson River between Long Spruce Dam near Gillam, and Hudson Bay. They reveal a sequence of sediments, including multiple tills and interglacial deposits (Fig. 4).

Sundance till and an older event

The lowermost and oldest recognized till unit is the Sundance till, which overlies Paleozoic bedrock at Sundance and Moondance (Fig. 1), and is also exposed several kilometres upstream of the mouth of Limestone River. It also outcrops at river level on the tidal flats at Port Nelson. At the type section (Fig. 5) the till is separated from the overlying till by a boulder pavement and a paleosol (Nielsen and Dredge, 1982; Nielsen et al., 1986; Roy, 1998).

The Sundance till is olive grey, compact, and fissile, with oxidation along joint surfaces. The till contains roughly 45% sand, 45% silt and 10% clay. Pebble (1–4 cm size) clasts are about 55% Precambrian lithologies and 45% Paleozoic carbonate. Matrix carbonate content in the <0.063 mm fraction ranges between 16 and 31%. The till contains small quantities of red Dubawnt clasts from central Keewatin and greywacke erratics derived from eastern Hudson Bay. The till also contains some foraminifera.

Striae on bedrock below the till at the Sundance section trend 245°, but upstream of the section, striae and rat-tails on Paleozoic outcrop trend 145°. Fabrics within the till dip northwest, suggesting southeast ice flow.

The sandy texture, abundance of Precambrian granitic clasts, relatively low quantities of matrix carbonate, southeast-trending striae, and till fabric suggest ice flow southward from central Keewatin. The striae directly underlying the till at Sundance, small quantities of Proterozoic greywacke clasts from eastern Hudson Bay, and a few foraminifera in the till suggest that there are reworked components from an earlier glacial event, in which ice flow was westward across Hudson Bay. However, the till related to this earlier westerly event has not been recognized at any site.

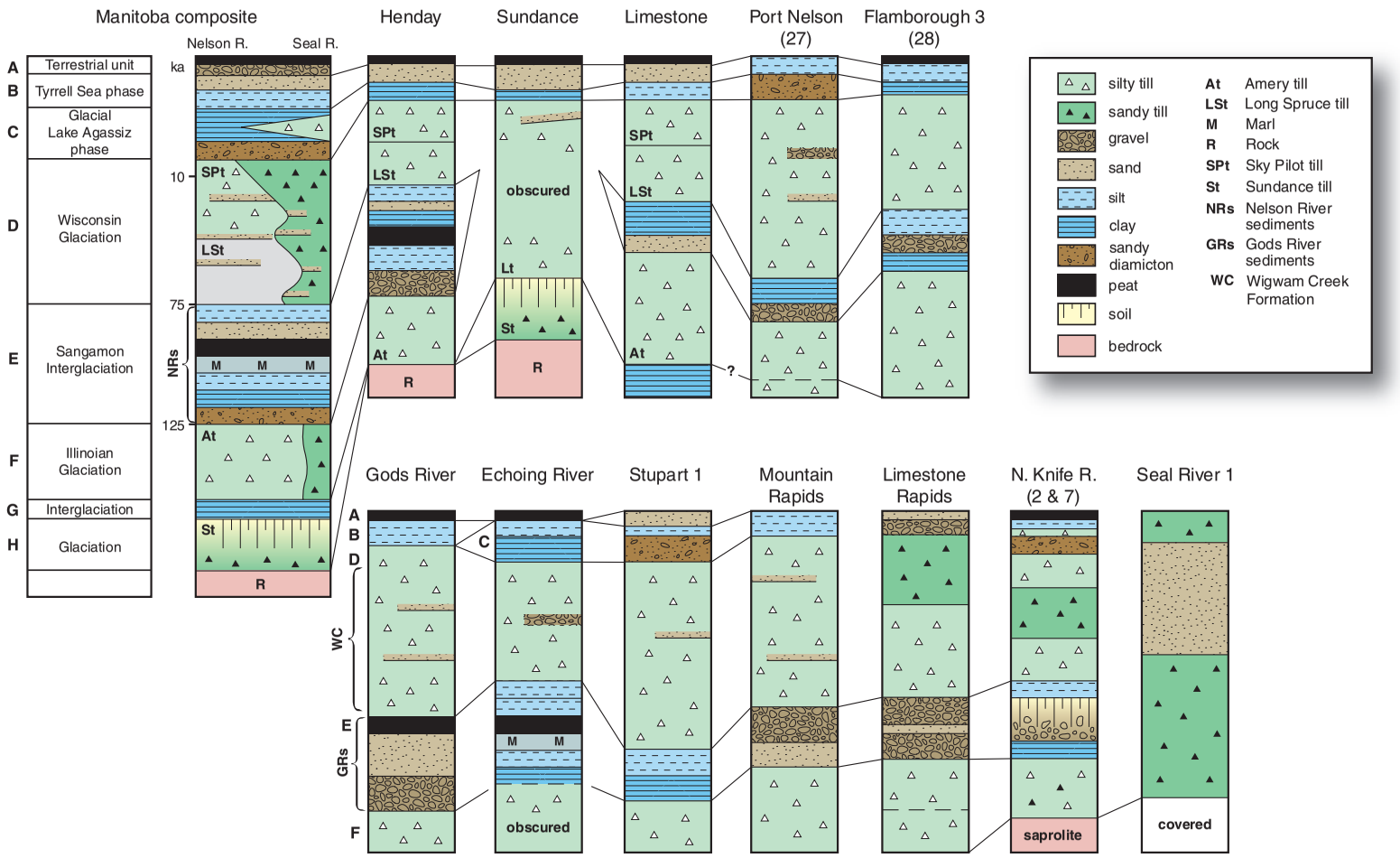


Figure 4. Representative stratigraphic sections from northeastern Manitoba.

Figure 5. The Sundance section on Nelson River: **a)** Paleozoic bedrock, **b)** Sundance till, **c)** paleosol, **d)** Amery till, and **e)** postglacial sediments. Photograph by L.A. Dredge. 2010-204

The uppermost part of the Sundance till at Sundance is marked by a pavement of facetted boulders and limestone clasts. The surfaces of the boulders have striations consistent with the ice-flow direction inferred for the overlying till.

Paleosol and interglacial deposits

The upper part of the Sundance till is leached and oxidized (Nielsen and Dredge, 1982; Nielsen et al., 1986; Dredge et al., 1990; Roy, 1998). The upper part is leached of ferromagnesian minerals and other metallic elements, whereas the zone directly below shows corresponding enrichment (Fig. 6). This unit is interpreted as a paleosol. The A0 horizon, which would have been part of this soil profile, is believed to have been incorporated into the overlying till, which contains elevated (0.6%) organic carbon levels in its lowermost part. Organic fragments and pollen of herbaceous tundra taxa in the lower part of the overlying till suggest tundra conditions. The thickness of the paleosol, however, exceeds that of postglacial soils, and may represent a long interglacial period.

In sections at the mouth of the Limestone River (Dredge et al., 1990; Roy, 1998) and at Eagle Bluff east of Sundance, the lowermost exposed unit consists of 4 m of laminated to massive clay containing dropstones. This clay unit is correlated with the Sundance paleosol on the basis of its stratigraphic position below Amery till. Pollen in the clay is consistent with a cool tundra environment. The sediment includes sparse foraminifera indicating cold-water conditions. These, and elevated Na, Mg, and B concentrations in the sediment suggest a marine origin. If so, then sea level was at least 58 m above present during this interglacial period (45 m at Eagle Bluff).

Amery till

The Amery till (Fig. 4) is well exposed around Limestone dam and downstream to the mouth of Angling River (Nielsen and Dredge, 1982; Klassen, 1986; Nielsen et al., 1986; Dredge et al., 1990; Roy, 1998), and at Flamborough near the mouth of the Nelson River (Dredge and Nielsen, 1985). In many places it is overlain by nonglacial sediments. It is the oldest till that is widespread in the region. At Sundance, where it reaches a thickness of 18 m, the till is separated from the Sundance paleosol by a boulder and cobble pavement, with striae trending 225° on the tops of the boulders. The Amery till is olive grey, calcareous, silty, and moderately stony. It is compact, fissile and jointed, and shows brown oxidation (in places red) along joint surfaces. Fabrics and striated clasts within the till trend southwest (Moondance,

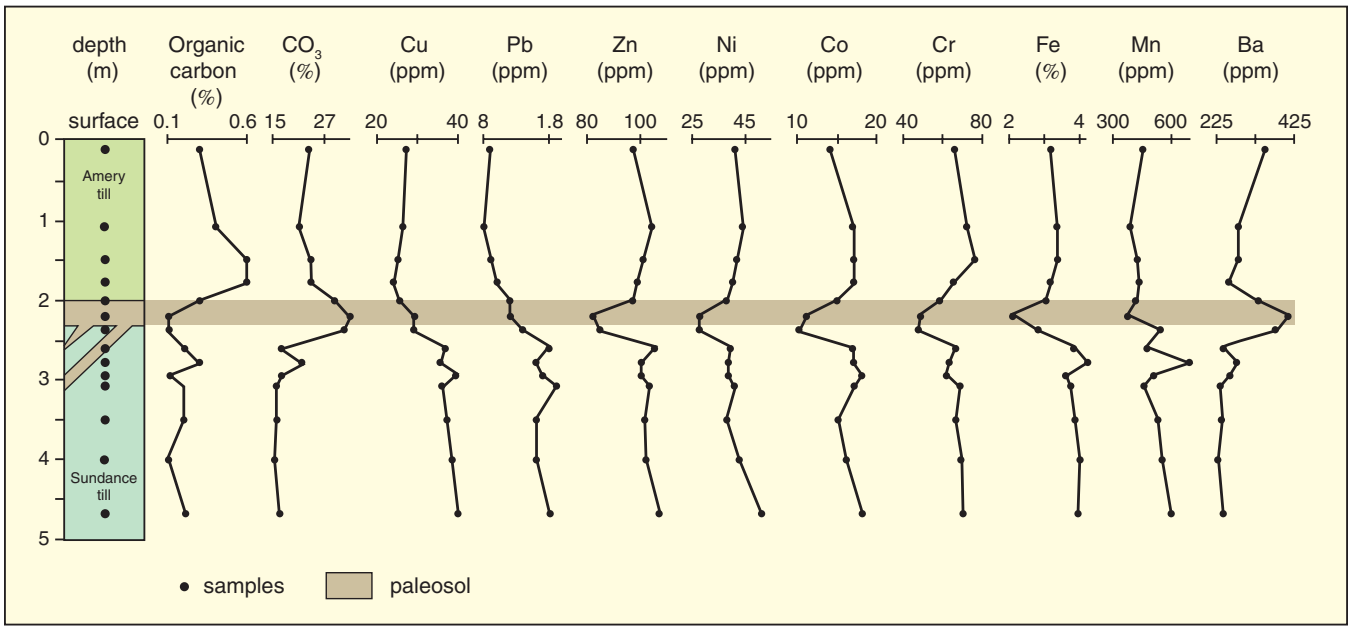


Figure 6. Geochemistry of the paleosol (brown) developed on Sundance till.

Birds Island, Sundance sites), west, or, in one case, northwest. Structurally, the Amery till contains subhorizontal and tectonically deformed intratill sand and gravel beds ranging from a few centimetres to one metre in thickness. Some of these beds have been injected into the till below them. The till texture averages 28% sand, 66% silt, and 7% clay. Matrix carbonate content ranges between 25 and 40% by weight. The pebbles consist of 77% Paleozoic limestone or dolomite, and 23% Precambrian clasts. Up to 7% of the pebble clasts are Omarolluk greywacke. Red carbonate and Dubawnt clasts are present in small amounts (<1%). The Amery till contains abundant cold-water foraminifera and mollusc fragments with species that indicate an ice advance across marine sediments.

The till fabric, striated clasts, and large number of greywacke clasts, presumably derived from the Omarolluk Formation, and the relatively abundant incorporated shell fragments indicate west or southwest ice flow out of or across Hudson Bay. The presence of abundant marine shell fragments of Quaternary species in this till suggests that the till originated in part from interglacial beds in the Hudson Bay area. Aspartic (D/L) acid ratios on shell fragments average 0.42 (Nielsen et al., 1986). The intratill sand beds and glaciotectonic structures suggest active ice that was warm-based when the till was deposited.

Nelson River sediments

A sequence of nonglacial sediments 2 to 4 m thick overlies the Amery till both west and east of Limestone dam (Nielsen et al., 1986; Roy, 1998), and at Flamborough near the mouth of the Nelson River (Dredge and Nielsen, 1985; Dredge et al., 1990; Dredge and Nixon, 1992, sections 27, 28). They are well exposed at the Henday, Limestone, and Moondance sites. Correlative deposits were earlier observed by Klassen (1986) along Gods River, where they were named 'Gods River sediments'. The top of the unit is in sharp contact with (i.e. truncated by) overlying till.

The lowest part of the sequence consists of fluvial sand and gravel, with climbing ripples that indicate water flow to the east. A layer of peat containing wood, pollen, and insect remains characterizes the middle unit (Fig. 7). These beds are overlain by massive and bedded silt, possibly with dropstones near the top. Together, the sequence of sediments is thought to represent fluvial, terrestrial, and lacustrine environments. Radiocarbon dating of organics yielded non-finite ages greater than 49 ka. An infrared stimulated luminescence (IRSL) date from Moondance section, considered to be valid, yielded an age of 121 ka on feldspars in sand (Roy, 1998). U-Th dating, thermoluminescence techniques, and other IRSL dates gave variable results ranging from 22 ka to more than 200 ka (Roy, 1998).

Palynological studies of the peat and sediment detected the presence of arboreal and herbal taxa indicative of forest-tundra transitions. Beetle data indicate both forest-tundra and tundra conditions. On the whole, the environmental indicators suggest a climate similar to that of today, but not completely analogous, as there is less spruce than at present, and deposition took place in an open tundra forest near the tree line. Bedding directions in the fluvial gravels indicate drainage toward an open Hudson Bay. The pollen spectra and aspartic amino acid ratios on wood from peat (0.18–0.22) are similar to those from the interglacial Missinaibi beds of northern Ontario (Nielsen et al., 1986).

Figure 7. Nelson River sediments from the Sangamon Interglaciation exposed at Port Nelson: **a)** Amery till, **b)** peat and **c)** sand of the Sangamon Interglaciation, and **d)** Long Spruce till. Photograph by L.A. Dredge. 2010-205

Long Spruce till(s?)

The Long Spruce till is prevalent along the Nelson River valley (Klassen, 1986; Dredge and Nielsen, 1985; Dredge et al., 1990; Dredge and Nixon, 1992; Nielsen and Dredge, 1982; Nielsen et al., 1986; Roy, 1998). It is commonly 2 to 6 m thick, but reaches 20 m at the mouth of Angling River. The Long Spruce till lies above the Amery till, or the Nelson River Sediments (Fig. 8, 9), and is injected into them in some places. The till is olive-grey, compact and fissile,

Figure 8. Amery and Long Spruce tills in the Cofferdam section on Nelson River: **a)** Amery till, **b)** Nelson River sediments (Sangamon Interglaciation), **c)** Long Spruce till grading upward to Sky Pilot till, and **d)** postglacial marine sediments. Geologist at the base of the section for scale. Photograph by L.A. Dredge. 2010-206

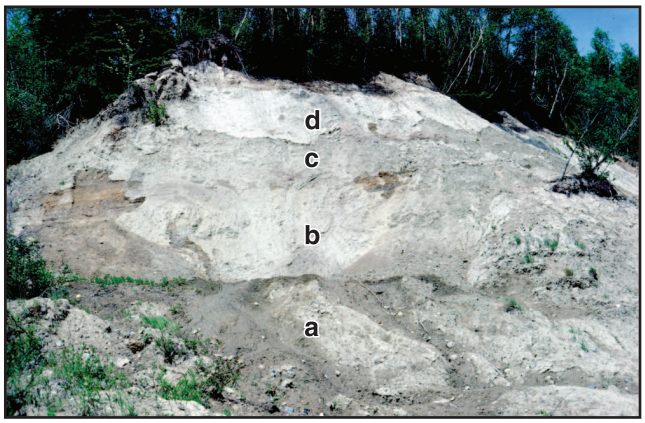


Figure 9. Amery and Long Spruce tills in the Henday section on Nelson River: **a)** Amery till, **b)** Nelson River sediments (Sangamon Interglaciation), **c)** Long Spruce till, and **d)** postglacial marine sediments. Photograph by L.A. Dredge. 2010-207

with thin oxidation rinds along joint surfaces; it is less fissile and less oxidized than the underlying Amery till, and till faces are less steep. The texture is similar to that of other tills of Labradorean origin: typically 25% sand, 68% silt, and 8% clay. The pebbles are 70% Paleozoic and 28% Precambrian, of which about 8% are commonly Omarolluk greywacke. West of Limestone dam, however, greywacke clast content exceeding 23% is common. Oolitic jasper was also identified at the Birds Island site, and red carbonate and Dubawnt clasts are also present. The silt-clay fraction typically contains 24 to 40% carbonate. Foraminifera and mollusc fragments are present as clasts, but are less abundant than in the Amery till. Aspartic acid D/L ratios average about 0.30 (Dredge et al., 1990), indicating a substantially younger age than the Amery Till.

Till fabrics are variable, ranging from northwest to southwest, but they generally indicate a westward ice flow. Roy (1998) interpreted the ice flow to be northwestward on the basis of the fabric, the orientation of striated boulders in the till at Moondance and Sundance, and the presence of oolitic jasper at Birds Island, presumably from Sutton Ridges west of James Bay. However, at the Birds Island site, the fabric trends southwest in the upper part of the till, not northwest, and there are red carbonate clasts in the till derived from central Hudson Bay. The Proterozoic Dubawnt clasts of red sandstone and quartzite could have been derived from a southerly Keewatin ice flow that occurred after the deposition of the Nelson River sediments, but before the emplacement of the Long Spruce till; however, these erratics could also be simply recycled from older tills (e.g. the Sundance till).

The Long Spruce till sheet contains up to three till layers separated in some places by as many as three thin, distinct, nonfossiliferous sand or gravelly sand layers lacking sedimentary structures. These beds extend for tens to hundreds of metres. The origin of these layers is problematic. Although the sand layers are present in many exposures, there are no data to indicate their continuity or correlation from one section to another. Netterville interpreted them to be interstadial deposits, whereas others, including the present authors, consider them more likely to have been deposited by subglacial meltwater. The sediments could have been deposited directly from the base of a warm-based ice sheet, or could equally be the remnants of esker or interlobate deposits, subsequently eroded by overriding ice. The presence of sand bodies, as well as the variation in till carbonate content, fabrics, and clast lithologies, suggest that there were ice-flow shifts during the glacial events that deposited the Long Spruce till, but that these shifts all were associated with a Labradorean ice centre.

Sky Pilot till(s)

The Sky Pilot till(s) is the surface till in the area, and is associated with southwest-oriented, streamlined, surface till landforms, and west- and southwest-trending eskers. The till is overlain by, or grades into, sediments associated with glacial Lake Agassiz, and Tyrrell Sea deposits. It

is distinguished from other tills in the region by its stratigraphic position, colour, density, and clast lithology (Nielsen and Dredge, 1982; Dredge and Nielsen, 1985; Nielsen et al., 1986; Dredge and Nixon, 1992; Roy, 1998).

The till ranges in thickness from 4 to 13 m, and is calcareous, and olive brown to brown. Textural analyses show a wide range of grain sizes, typically 15% sand, 75% silt, and 10% clay. Pebbles consist of about 75% Paleozoic carbonate, of which about 4% are red siltstone derived from central Hudson Bay. Greywacke clast content ranges from 5 to 20% of the pebble fraction (Nielsen and Dredge, 1982). Matrix carbonate content averages 38%. Till fabrics display westerly and southwesterly orientations. Mollusc fragments and foraminifera are present in small amounts.

The Sky Pilot till can be divided into two units or facies. The lower unit is a stony, calcareous, silty till that is moderately compact, slightly fissile, and has traces of brown oxidation along joints. A similar upper unit is brown, less stony, soft to crumbly, lacks joints, tends to contain more clay, and has fewer greywacke clasts. The upper unit contains till wedges glaciotectonically injected southwestward into intra-till sand layers (Dredge and Nielsen, 1985. The two units have been seen together only at Port Nelson and the Limestone River spillway; elsewhere, either one or the other is present. Along the bluff at Port Nelson the two units are separated in some places by an imbricated cobble lag, with clasts dipping to the east, indicating ice flow from Hudson Bay.

The Sky Pilot till appears to have been deposited from ice moving across Hudson Bay during the latter part of the last glaciation. Changes in composition, colour, and fabric within the till in the Nelson River valley suggest that ice flow shifted from westward to southwestward.

Stratigraphic units related to glacial Lake Agassiz

The uppermost sediment layers along the Nelson River and in other parts of northern Manitoba consist of transitional till/glaciolacustrine deposits, postglacial lake and marine deposits, and peat. Several different glacial and ice-proximal units related to glacial Lake Agassiz are mentioned briefly here: 1) melt-out till thought to have been deposited from below ice ramps in the lake, 2) glaciofluvial gravel, 3) turbidity flow and grain-flow sand and gravel, 4) silty rhythmites and massive clay, and 5) readvance tills.

1. In the Nelson River area, basal melt-out till from ice ramps was not definitively identified in section, but it is one possible interpretation for the deposits lying directly above the Sky Pilot till, described above. These deposits are calcareous, brown, till-like diamictons that contain small red siltstone clasts in a stony, gritty, silt diamicton matrix (Nielsen et al., 1986; Nielsen and Dredge, 1982). The deposits resemble, or may be, an upper facies of the Sky Pilot till. They differ from typical till in the region in that they are loose and poorly compacted, and tend to contain more silt and clay than typical Sky Pilot till. They may have been deposited into glacial Lake Agassiz from frontal ice ramps that projected into the lake. This unit is considered to be gradational between till and glaciolacustrine sediment. It was encountered in surface deposits between the Nelson and Seal rivers, and in a section at Port Nelson (Dredge and Nielsen, 1985; Dredge and Nixon, 1992).
2. At several sites near Long Spruce dam, the tills are unconformably capped by up to 12 m of coarse sand and rounded boulder and cobble gravel. Crossbedding indicates flow toward the northwest. The deposits seen in section are considered to be glaciofluvial, and are spatially correlated with the Limestone interlobate moraine (Fig. 1). They are thought to have been laid down by westward-flowing meltwater currents from the eastward-receding ice margin. At one section, this unit grades upward into sandy diamicton.
3. Along the Nelson River, a sandy diamicton (Fig. 10) lies disconformably atop the tills in some secions. This unit forms vertical exposures 3 to 6 m thick. The

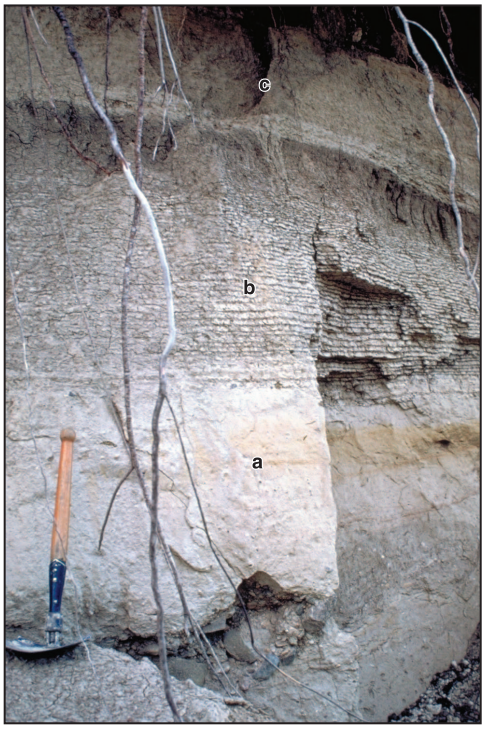


Figure 10. Section at Long Spruce Dam on Nelson River:**a)** sandy diamicton, **b)** overlying glacial Lake Agassizrhythmites, and **c)** Tyrrell Sea sediments. Photograph by L.A. Dredge. 2010-208

Figure 11. Tyrrell Sea sands with molluscs near Limestone Rapids on Nelson River. Photograph by L.A. Dredge. 2010-209

basal part of this unit consists of matrix-supored pebbles suspended in tan-coloured sand. At the base the unit is massive, but contains some flow folds. The unit becomes substratified to stratified upward, and in some places it grades into overlying lacustrine rhythites. The unit is considered to be a grain-flow deposit associated with turbidites generated by meltwater entering glacial Lake Agassiz near the front of the receding ice sheet. In some places the sandy diamicton is overlain or interlayered with readvance till (5). The readvance unit resembles the Sky Pilot till in colour and compaction, except that it is sandier or more clay-rich, depending on the material that was overridden by the glacier.

4. The sandy diamicton, or in places the Sky Pilot till, is overlain by up to 2 m of calcareous, brown and grey, silty clay rhythmites (Dredge and Nielsen, 1987; Nielsen et al., 1986; Klassen, 1986; Fig. 10). The brown clay layers contain rip-up clasts of the siltier grey beds. The rhythmites are 1 to 2 cm thick at the base and thin upward, becoming microlaminated to massive, red-brown, silt-clay deposits at the top. Ostracodes are present in the massive unit, but are scarce. The rhythmites and massive, red-brown, silty clay are typical of glacial Lake Agassiz deposits, and form the surface deposits over extensive areas of northeastern Manitoba. Iceberg furrows inscribed into the surface of the clay are consistent with interpretation of these deposits as glaciolacustrine.

Tyrrell Sea sediments

The uppermost lithostratigraphic unit is associated with deposition in the postglacial Tyrrell Sea. Deposits are 1 to 2 m thick at their inland limit, and thicken to 10 m at exposures near Hudson Bay (Klassen, 1986; Nielsen and Dredge, 1982; Dredge and Nixon, 1992). A basal unit of calcareous, grey silt-clay grades upward into horizontally stratified sand (Fig. 11). This unit is the main surficial sediment in the Nelson River valley below an elevation of 122 m, and elsewhere in northern Manitoba below an elevation of 180 m. The deposits are fossiliferous, and radiocarbon dates on marine molluscs from the Gillam area indicate that the sea inundated the Hudson Bay Lowlands about 7780 ± 80 years ago (GSC-3916, Dredge and Cowan, 1989). The Tyrrell Sea sediments constitute a regressive marine sequence, characterized by blankets of deep-water clay and sublittoral sand interspersed with beach ridges.

Lack of evidence of a major unconformity between glaciolacustrine deposits and Tyrrell Sea sediments suggests that the two water bodies might have been at about the same surface water elevation at the time of changeover.

Summary of ice-flow events based on stratigraphy along the lower Nelson River (Fig. 4.)

1. Early ice flow from eastern Hudson Bay is inferred from the presence of Omarolluk clasts in the Sundance till, and from southeast-trending striae on bedrock below the till.

2. Sundance till containing Proterozoic Dubawnt clasts and sandy texture indicates southward flow from a Keewatin ice centre.

3. Massive clay deposits indicate an interglacial period and ice-free Hudson Bay. The clays contain cold-water foraminifera, but a correlative paleosol suggests warmer conditions (or a long warm interval) as well. Sea level would have been as much as 45 to 58 m above present.

4. The Amery till, with silty texture, 16 to 30% matrix carbonate, fabric, and relatively abundant Omarolluk clasts, indicates ice flow west or southwest across Hudson Bay. One fabric at Birds Island suggests northwest flow.

5. Nelson River sediments represent an interglaciation with drainage toward an open Hudson Bay. Pollen and macrofossil remains indicate terrestrial and shallow freshwater aquatic environments in a treeline forest-tundra biome similar to today. Radiocarbon age is greater than 49 ka, and IRSL (infrared stimulated luminescence) age is 121 ka, but results are variable.

6. There may have been a southward ice-flow event, based on the presence of Dubawnt clasts in the base of the Long Spruce till.

7. Long Spruce till and intratill sand beds represent flow that is generally westward from Hudson Bay, based on silty texture and 24 to 40% carbonate content. Oolitic red jasper clasts originating in Sutton Ridges, Ontario suggest a northwest ice flow, as do some of the fabrics. Fabrics in the upper till, and the presence of red siltstone clasts, suggest a southwest flow. Intratill sand beds may be associated with the shifting ice flows.

8. The Sky Pilot till was deposited by ice flow to the southwest, based on the brown colour and inclusion of brick-red siltstone clasts from central Hudson Bay. There may be two different till units or two facies, with the upper till being of low compaction. The Sky Pilot till is the surface till in the region. Streamlined till forms and orientation of eskers are in accord with southwestward and westward ice flows.

9. Subaquatic glaciofluvial deposits, substratified sandy diamictons, and stratified to massive clays indicate inundation by glacial Lake Agassiz. There are thin till layers that represent minor ice readvances into the glacial lake basin.

10. Marine sediments dating from about 7800 ka BP (^{14}C) occur up to an elevation of 122 m and indicate inundation by the postglacial Tyrrell Sea. These consist of stony glaciomarine diamictons, fossiliferous marine clay, and sand. Postglacial terrestrial peat caps most of the stratigraphic sections.

STRATIGRAPHY SOUTHEAST OF NELSON RIVER

Major sections along the Gods, Hayes, and Angling rivers, as well as the Nelson River (Fig. 1, area 2), were first studied in some detail by Netterville (1974) and Klassen (1986). Other exposures along these rivers, as well as along the Stupart, Fox, and Echoing rivers, were later studied by Dredge and Nielsen (1985) and Dredge et al. (1990). The sequence of deposits is similar to that reported above for the Nelson River. However, there are several differences: 1) there is no evidence for the presence of the Sundance till, 2) till units were grouped differently by Klassen (1986) and Netterville (1974), and 3) ice-flow directions based on fabric differ somewhat from those on the Nelson River. The intratill sand beds (within Long Spruce unit) were also interpreted differently by Netterville (1974).

Amery till

The Amery till is exposed along the Gods and Hayes rivers, and was described by Klassen (1986; Fig. 1, section K-1) as a hard, compact olive grey till with oxidation along joint surfaces. It is the lowermost till exposed in the area. It is slightly sandier than overlying tills, with an average grain size of 40% sand and 60% silt-clay. The matrix averages 29% carbonate, similar to the younger tills. Fabrics along Gods River suggest a southwestward ice flow.

Gods River sediments and Echoing River sediments

A sequence of nonglacial sediments similar to the Nelson River sediments in composition and stratigraphic position overlies the Amery till and is well exposed along a 120 m stretch of Gods River near Wigwam Creek (Fig. 1, sections K1, K5), and along Echoing River (Fig. 4) (Klassen, 1986; Dredge et al., 1990). Less complete exposures of mainly silt were found on the Stupart and Fox rivers. The sediments have a composite thickness of about 12 m. On Gods River, a lower unit of sand with peat lenses is overlain by sand and gravel, which is in places crossbedded to the west or north. Upper units include a layer of terrestrial peat that contains beaver-chewed logs, and about 4 m of silt and sand with organic detritus. The organic beds contain pollen, wood, mosses, seeds, beetle fragments, and freshwater molluscs. The wood has a nonfinite radiocarbon age greater than 41 ka (GSC-1736, Dredge et al., 1990). Pollen samples from throughout the exposure indicate an early lower zone of sphagnum-cyperaceae representing tundra or tundra conditions with scattered birch and alder. An intermediate zone shows an increase in spruce, larch, and birch, and indicates a forest-tundra environment similar to that in the area today, although older sediments contain less pine pollen than is present in today's forest-tundra. The upper part of the deposit, organic-bearing silt, indicates a return to tundra conditions, with abundant moss and sedge. The beetles in upper strata are indicative of tundra environments, but beetles, seeds, and molluscs in detrital peat below indicate conditions closer to boreal or forest-tundra.

At the Echoing River section, the interglacial sediments are 5 m thick (Fig.12), and are composed of a lower black clay unit that is possibly of marine origin in that it has elevated quantities of boron and vanadium, and contains some foraminifera. The foraminifers indicate relatively warm (boreal) water temperatures. The sediments above represent terrestrial or shallow freshwater environments and consist of silty rhythmites, marl containing boreal freshwater gastropods and ostracodes, peat containing spruce twigs dated at over 37 ka (GSC-892) and over 51 ka (GSC-444HP, Dredge et al., 1990), and laminated to massive silt, contorted in places near the contact with overlying tills.

Pollen profiles are similar to those along Gods River, but suggest slightly warmer conditions. The samples lower in the interglacial sequence indicate forest-tundra; the middle unit contains more pine than the correlative sediments along Gods River, and indicates the proximity of coniferous spruce-pine forest. The top unit contains spruce, less pine, and more herbaceous pollen, indicating an open coniferous forest similar to present. The beetles and other insects collected from the peat suggest boreal conditions close to tree line.

Figure 12. Gods River Sangamon Interglacial sediments at Echoing River (Fig. 1, box 2): **a)** stony clay diamicton, **b)** clay, **c)** varved silt, **d)** marl, **e)** peat and wood, **f)** brown laminated silt, **g)** clay-silt, and **h**) till. Photograph by L.A. Dredge. 2010-210

The Gods River and Echoing River sediments are thought to represent an interglaciation, presumably the Sangamonian, and are correlated with the Nelson River sediments on the basis of their stratigraphic position and character.

The Wigwam Creek Formation (Long Spruce till and Sky Pilot till)

The Wigwam Creek Formation (Klassen, 1986) consists of up to three till sheets, in places separated by sand beds, that lie above the Gods River sediments (Fig. 13). Distinction of the tills relies mainly on their stratigraphic positions. The lowest till is olive grey or grey-brown, compact, and has stained joints. Typically, its matrix is 44% sand and 56% silt-clay, and matrix carbonate content is 29%. This till is about 8 m thick. Fabrics in the till indicate southward ice flow along Gods and Hayes rivers (although there was also a transverse westward fabric in each till).

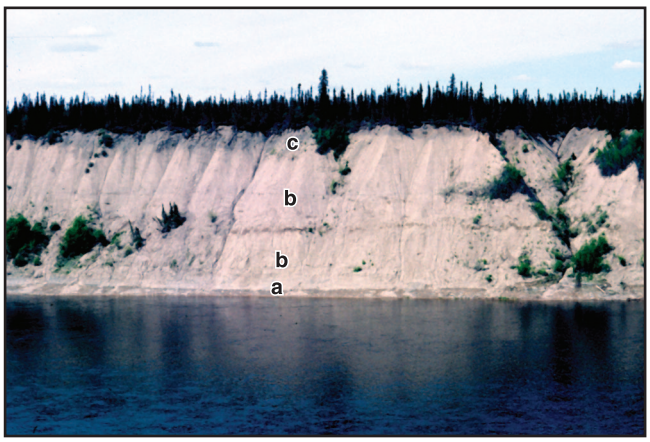


Figure 13. Wigwam Creek section along Gods River: **a)** Gods River sediments at river level, **b)** tills and sand beds of the Wigwam Creek Formation, capped by **c)** Tyrrell Sea sediments. Photograph by L.A. Dredge. 2010-211

The middle till is about 6 m thick, grey-brown, and is compact, with stained joints. Fabrics are oriented S15°W (Klassen, 1986, p. 19; Fig. 1, section K1).

The upper till is brown, looser, and less distinctly jointed. It tends to be about 4 m thick. Matrix carbonate content averages 26%. About 30% of the clasts are Shield derived, and 70% are Paleozoic carbonate. The fabric is oriented southwest on the Gods River, and west along the Nelson River. These fabrics correspond with late glacial southwesterly and deglacial westerly surface ice-flow features in the lowlands.

Almost horizontal beds of barren sand with some gravel, generally less than 30 cm thick, separate the tills in some exposures. In other sections, the tills are separated by boulder lags or unconformities. Netterville (1974) considered the lower sand unit to be an interstadial deposit because it displays evidence of oxidation. Klassen (1986) thought that the three tills represented different glacial stades, and that the sand units were part of the glacial sequence. Dredge and Nielsen (1985) also thought that the sand units were probably subglacial deposits relating to different ice regimes, or shifts in ice flow during continuous ice cover.

The Wigwam Creek tills are correlated with the Long Spruce and Sky Pilot tills along Nelson River. The lowest till is considered to be the Long Spruce till, and the upper two to be the Sky Pilot till(s). The fabric in the lowest till, however, is at odds with the westward or southwestward fabric in the Long Spruce till, whereas the fabrics and their rotation in the upper Wigwam Creek tills correspond to the westward, then southwestward flows in the Sky Pilot tills.

Glacial Lake Agassiz deposits were not logged by Klassen along Gods River, but were found along the Gods, Hayes, Stupart, Fox, and Echoing rivers by Dredge and Nielsen (1985). As in the Nelson River area, they consist of sandy diamicton, overlain by laminated or massive silty

clay. Tyrrell Sea sediments cap many sections that lie below an elevation of 140 to 50 m above sea level, and consist of locally fossiliferous silty clay and sand.

EBA Engineering Consultants Ltd. (1976) borehole records (e.g. PG 64-2-3) for this area show recent peat overlying (marine and lacustrine) sand and clay, underlain by up to 6 m of compact silt-clay with sand (i.e. till).

SECTIONS ALONG CHURCHILL RIVER

Stratigraphic sections 20 to 30 m high along the Churchill, Little Churchill, and Little Beaver (Fig. 1, area 3) rivers show multiple till units and nonglacial sediments similar to those on Nelson River (Dredge and Nielsen, 1985; Dredge and Nixon, 1992 and unpublished data). Smaller sections 5 to 10 m high on other rivers reveal shorter stratigraphic sequences.

Mountain Rapids on the Churchill River (Fig. 4, 14) lies 50 km west of the Paleozoic/Precambrian contact. There, 30 m high bluffs expose a complex sequence of up to four tills and sandy gravel units overlain by 6 m of sandy diamicton and silt associated with glacial Lake Agassiz.

Three metres of dark grey, compact, blocky, fissile silt till, with deep red oxidation along joint surfaces, form the base of the section and are correlated with the Amery till. Matrix carbonate content is 37%, and the Paleozoic clast content is 81%. Till texture typically comprises 28% sand, 43% silt, and 29% clay. Cobbles from the South Channel formation (Fig. 3a) in central Keewatin are present along the river bank at river level, but most of the diagnostic clasts observed in the till are Paleozoic carbonate.

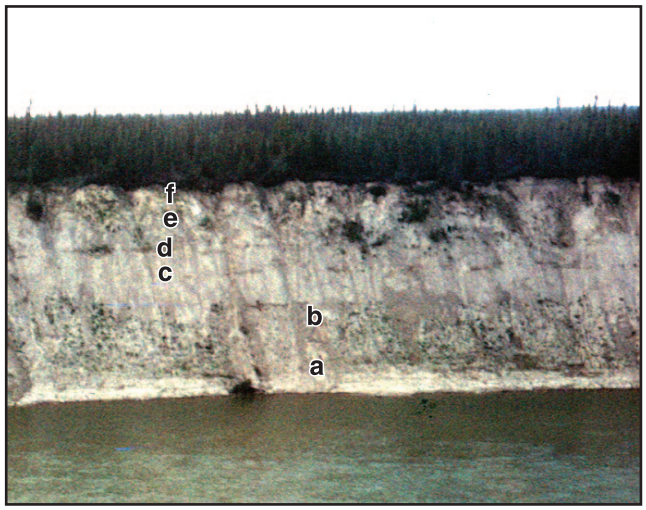


Figure 14. Churchill River section at Mountain Rapids: **a)** lower till, **b)** interglacial sand and gravel unit, **c)** middle till with sand bed, **d)** sand bed with peat balls, **e)** upper till, and **f)** postglacial sediments. Spruce trees for scale. Photograph by L.A. Dredge. 2010-212

Seven metres of stratified sand and gravel containing shell chips overlie this till. The beds dip eastward, suggesting an open Hudson Bay. These deposits are correlated with the Nelson River sediments.

Six metres of grey, oxidized silt till containing shell chips (Long Spruce till) overlie, and have been injected into, the sand beds. Carbonate makes up 36 to 49% of the matrix and 90% of the pebbles. The texture of the till is 35% sand, 46% silt, and 19% clay. The upper half of this till sheet contains sandy interbeds, considered to be subglacial deposits.

The unit above consists of 2 m of compact, olive brown, stony till with stained joints and physical characteristics similar to the Long Spruce till. Carbonate content ranges from 41 to 53% for the matrix and 91% of the Paleozoic pebble fraction. The till unit contains black Cretaceous shale clasts with fossil fish fragments. Matrix texture consists of 31% sand, 47% silt, and 27% clay, similar to the Long Spruce till. The till is overlain by 40 cm of silty sand and gravel containing flattened carbonized sticks dated at over 32 ka (GSC-3074), as well as diamictic inclusions, small, rounded organic nodules, peat fragments, and some detrital organics (Dredge et al., 1990). The diamictic inclusions contain spruce and pine, as well as birch and alder pollen, typical of a boreal-tundra transition, whereas organic nodules contain mainly grass and sedge pollen more typical of tundra biomes. The peat fragments have species characteristic of boreal-tundra environments. All organic fragments show signs of being transported and redeposited into the sands. The organics are tentatively interpreted to be Sangamonian, although the including sands are possibly much later (subglacial?) deposits containing the reworked older organics.

The uppermost till consists of 4 m of loose, unoxidized, brown, silty till (Dredge and Nielsen, 1985; Dredge et al., 1990; Dredge and Nixon, 1992, section 16). This till contains shell chips and Cretaceous clasts as well as red mudstone. Carbonate content is about 43% in the till matrix and 70% of the pebbles. The texture averages 27% sand, 43% silt, and 22% clay, but is somewhat finer grained at the top of the unit. This till is of eastern provenance and has been correlated with the Sky Pilot till along Nelson River; its upper part is gradational with glaciolacustrine deposits.

The tills at Mountain Rapids, described above, are all of eastern provenance, have the stratigraphic position and physical characteristics of the Amery, Long Spruce, and Sky Pilot tills along Nelson River, and have been correlated with them. For this interpretation, it is assumed that either the organics in the upper sand bed have been reworked from Sangamonian deposits stratigraphically below, or that an entire block of glacial and interglacial deposits has been sheared up from below and stratigraphically displaced. If, however, the organics are in correct stratigraphic position, then either a) the upper sand is Sangamonian, the lower tills are all earlier, and the lowermost stratified gravels represent

an earlier interglaciation; or b) Sangamon isotope stages 5a and 5e are both represented, and the till between represents stage 5c.

A 26 m stratigraphic sequence similar to the Mountain Rapids section, but without the problematic organics, was logged on Churchill River in Polar Gas borehole 80-1-1 (EBA Engineering Consultants Ltd., 1976) to the northeast. It consists of 7 m of basal sand overlain by clay (Nelson River sediments), 5 m of silty till, glacial Lake Agassiz silty clay, and postglacial marine gravel.

Nearby sections along the Little Churchill River have a similar stratigraphic succession consisting of three to five till units separated by beds of barren sand (Dredge and Nixon, 1992; Fig. 1, sections 18–20). However, the tills below the uppermost (Sky Pilot) till are black, and have hematite stains on the joint surfaces. The black colour is thought to be the result of incorporation of Cretaceous shale. The nearest known source is north-central Hudson Bay. However, the consistently abrupt colour change in the tills along Little Churchill River, from typically olive grey to black, suggests that there may be an unmapped Cretaceous bedrock source much closer to these sections.

SECTIONS AT LIMESTONE RAPIDS (CHURCHILL RIVER) AND SOUTH KNIFE RIVER: ICE FLOW SHIFTS

At Limestone Rapids on the northern reaches of Churchill River (Fig. 1, area 4; Dredge et al., 1990; Dredge and Nixon, 1992, section 14; Fig. 4, Fig. 15), 60 km south of Churchill and in Paleozoic terrain, postglacial sediments overlie 13 m of glacial and interglacial deposits. The basal 4 m consists of a grey, blocky, compact, silty till containing shell chips and stained joints. Carbonate content in this till sheet is 37% for the matrix and 89% for the pebble fraction. This till is separated from overlying till units by sand and gravel that contains detrital organics indicating tundra conditions with scattered trees. The overlying (middle till) unit consists of 5 m of stony, silty, grey till with oxidized joints, 29% carbonate in the matrix, and 45% carbonate in the pebble fraction. The matrix texture is 37% sand, 42% silt, and 21% clay. The till has an east-west fabric. It is unconformably overlain by 2 m of grey-brown, compact, unoxidized till that has 31% carbonate in the matrix and 58% carbonate in the pebble fraction. Texture is 34% sand, 43% silt, and 23% clay. Clast fabric in this till trends 155 to 180°.

This sequence is thought to represent the Amery, Long Spruce, and Sky Pilot tills of eastern provenance, and intervening Sangamonian Interglacial deposits. All tills are thought to be of eastern provenance originally, but the lower carbonate pebble content (compared to the lowermost till) and north-south fabric in the upper till suggests that it has been reworked by southward-flowing ice. The middle (upper Long Spruce) till also shows a northern influence in its lower pebble carbonate content. The sequence suggests that during the Wisconsinan Glaciation, there were major shifts in ice-flow direction at this location, with reworking of the upper part of the till, and that the final ice flow was to the south. This interpretation of late ice-flow shift to the south is supported by surface striation observations and eskerine landforms at Churchill, which indicate that the latest ice flow was to the south.

Figure 15. Churchill River section at Limestone Rapids: **a)** Amery till, **b)** interglacial sand and gravel, **c)** silty till, and **d)** postglacial sediments. Shovel is one metre long. Photograph by L.A. Dredge. 2010-213

Ice-flow shifts and changes in the character of the till during the late Wisconsin glacial event are also indicated in sections farther west on South Knife River (Dredge et al., 1990; Dredge and Nixon, 1992; Fig. 1, section 10), located 30 km west of the Paleozoic/Precambrian contact. Here, the lowest till is dark brown-black, compact, and silty, with black (Mn?) stained joint surfaces. The unit is overlain by 2 m of brown, silty till with oxidized joints and intercalated sand beds at its base. The carbonate content of the till matrix is 10%, and 26% of the pebbles are Paleozoic carbonate. The texture consists of 46% sand, 33% silt, and 21% clay. The till grades upward through a glaciolacustrine facies to brown silt of glacial Lake Agassiz. The tills are thought to be the Long Spruce and Sky Pilot tills, respectively, of eastern provenance, and are distinguished from the tills described along the Nelson River by the lower carbonate content in

their matrix and pebble fractions, and slightly sandier texture. This difference is thought to reflect periodic reworking by southward-flowing Keewatin ice rather than simply their position west of the Paleozoic/Precambrian contact, because the tills at Mountain Rapids (to the south), also about 30 km west of the contact, still retain the physical and chemical characteristics of the eastern provenance tills along Nelson River. The influence of ice flow from the north inferred from the properties of till on South Knife River is corroborated by nearby striae and drumlins of south-southeastward orientation, and by low ridges of east-west orientation that are thought to be subaquatic moraines related to retreating Keewatin ice (Dredge et al., 1986; Dredge and Nixon, 1986). The South Knife section suggests that there was a periodic Keewatin influence on ice flow during the last part of the Wisconsin Glaciation, and possibly during the entire Wisconsin, in this area. However, broad moraines near Mack Lake, 40 km to the south, have a north-south orientation, and suggest eastward retreat of Labradorean ice. Both the till stratigraphy and nearby surface landforms suggest that the South Knife section may lie near the most southern extent of Late Wisconsinan Keewatin ice flow in northeast Manitoba.

NORTH KNIFE RIVER SECTIONS: INTERLOBATE ZONES, SHIFTING ICE FLOWS AND READVANCES

The sections along North Knife River (Fig. 1, area 5) are key to understanding the interplay between Labradorean and Keewatin ice in northern Manitoba at the close of the Wisconsin Glaciation. West of the Paleozoic/Precambrian bedrock contact, 10 m high sections examined by boat traverse along North Knife River (Fig. 4) show areal and vertical changes in stratigraphy (Dredge et al., 1990; Dredge and Nixon, 1992; Fig. 1, sections 2, 9). Along parts of the river, yellow and blue saprolite and grus, containing large quantities of kaolinite and muscovite, were exposed near water level. These materials represent weathered equivalents of the underlying Precambrian bedrock. The saprolite is overlain unconformably by 3 to 6 m of cemented, oxidized and rubified, rounded gravel and sand. Silt and clay layers are present above and below the gravel in some sections. Above the gravel are up to four units of silty and sandy tills, separated in some places by beds of massive or stratified sand. Although characteristics vary from site to site, the sandy tills are typically olive grey and somewhat calcareous, but have low carbonate contents (5–15% matrix and <10% pebbles), and relatively high sand contents, exceeding 50%. The silty tills are olive brown to black, and have 10 to 25% carbonate and less than 50% sand in the matrix. Red mudstone clasts were seen in some of the silty till units. The silty tills have somewhat lower carbonate and higher sand matrix contents than their counterparts to the south at South Knife River and Nelson River, described previously.

The upper units of sections at elevations higher than 150 m above sea level consist of silty, grey or brown glacial Lake Agassiz sediments. Carbonate makes up 21 to 28% of the matrix; texture is 12% sand, 66% silt, and 22% clay. Below 150 m elevation, the glacial Lake Agassiz sediments are further capped by Tyrrell Sea deposits, including fossiliferous sands dating to 7760±140 ka BP (GSC-3070, Dredge et al., 1990). At Section 9, the glacial Lake Agassiz deposits consist of basal sandy turbidites with ripples and crossbeds indicating westward current flow, overlain by 6 m of silty, red-brown rhythmites. The upper 3 m of these are contorted and contain recumbent folds, indicating ice flow to the west. The beds grade upward into 3 m of stony, grey-brown, silty till with a carbonate content of 24% in the matrix, and a texture of 17% sand, 73% silt, and 11% clay. This till is considered to have been emplaced by a readvance of the eastern (Labradorean) ice margin into glacial Lake Agassiz clay. The till is unconformably capped by Tyrrell Sea sand, and ultimately, peat.

Farther west along North Knife River (Dredge and Nixon, 1992; Fig. 1, section 2), silty, olive grey till with low carbonate content (5% matrix carbonate) and sandier texture (35% sand, 65% silt-clay) occupies a stratigraphic position above glacial Lake Agassiz deposits, similar to the readvance till in section 2. However, the low carbonate content and sandier texture suggests that this till was laid down during a readvance of northern (Keewatin) ice into glacial Lake Agassiz, rather than by Labradorean ice. This till is areally associated with south-trending, elongated surface drumlins of the Quinn Lake readvance (Dredge and Nixon, 1992).

West of section 2, on the far western, north-south-oriented reach of the river, exposures up to 8 m in thickness consist of massive to stratified sand, sand with rounded gravel, and a few diamictic layers with more angular clasts. These deposits are correlated with interlobate moraine and esker sediments on the surface in the same area (Dredge and Nixon, 1985).

The different till units are thought to have been emplaced by westward- and southward-flowing ice events. Textural and compositional variations reflect the interplay between the Keewatin and Labradorean ice sheets in this area during the last glaciation, and the reworking of tills. Over much of the length of the river, the uppermost till is sandy, reflecting a late southward ice flow. This interpretation is in keeping with the orientations of striae, eskers, moraines (Dredge et al., 1986; Dredge and Nixon, 1992) and arsenic dispersal trains (Nielsen, 1987) in the surface till just north of the river, all of which also indicate southward ice flow in late-glacial times. The lower gravels could be the equivalent of the interglacial Nelson River sediments, and the saprolite is probably a pre-Quaternary bedrock weathering product.

SECTIONS NORTH OF NORTH KNIFE RIVER: KEEWATIN ICE FLOW

Polar Gas boreholes (EBA Engineering Consultants Ltd., 1976) between the North Knife River and Seal River (Fig. 1, area 6) reveal up to 8 m of silty till, sandy till, or a combination of the two (e.g. PG 87-8-1). North of North Knife River, the river sections are widely separated, have a maximum vertical exposure of 10 m, and commonly only contain one till above nonglacial gravel beds. They reflect flow southward from a Keewatin ice centre (Dredge and Nixon, 1992). Most of the sections are along the Seal River, but other stratigraphic data to a depth of 14 m are available from Polar Gas borehole records as far north as Caribou River (PG98-3-1).

Along Seal River (Dredge and Nixon, 1992; Fig. 1, section 1), grey silt outcrops at river level. The silt is overlain by 4 m of compact, olive grey sandy till (matrix carbonate of 2%, and 0% in the pebbles; texture 65% sand, 25% silt, and 5% clay) typical of Shield tills of Keewatin provenance. The matrix carbonate is thought to have been derived either from incorporation of an earlier Labradorean till, or from calcic minerals in the Shield rocks. The till grades upward into 4 m of fluvial sand and gravel with beds dipping southeast. An overlying till unit consists of 1.5 m of grey, sandy till with sand lenses. The carbonate content in this till is 3% in the matrix and 0% in the pebble fraction, and the texture of the till is 74% sand, 24% silt, and 2% clay. The lower till at section 1 is considered to be of Keewatin provenance, the overlying sand unit is thought to be a glaciolacustrine turbidite deposit, and the upper till is thought to have been emplaced by the Quinn Lake readvance into glacial Lake Agassiz (Dredge and Nixon, 1992). A similar stratigraphic sequence has been reported for the Great Island area (Trommelin and Ross, 2009).

Taylor (1961) examined an exposure at river level at Great Island (Fig 1, section 1a) which revealed oxidized gravels in a goethite matrix, containing clasts and impressions of leaves, twigs, wood, and moss. The species are typical of the present boreal environment of the area. These deposits are tentatively correlated with the Nelson River sediments.

At Seal River Polar Gas site 89-2 (EBA Engineering Consultants Ltd., 1976), the borehole log shows alluvium overlying silt, overlying sandy till to a depth of 7.2 m. Farther north, between Caribou River and the Nunavut border, borehole 98-3-1 reveals 7 m of compact sandy till (60% sand, 35% silt, and 5% clay) overlying 3 m of interstratified till and sand, overlying 2.5 m of compact sandy till (70% sand, 28% silt, and 2% clay). The two boreholes show evidence only of Keewatin ice flow. Similarly, Matile (*in* Anderson et al., 2005) reported exposures of up to 12 m of grey, sandy, noncalcareous till in south-trending drumlins in northernmost Manitoba, and deglacial sandy diamict overlying sand in hand-dug pits near Nejanilini Lake.

In summary, sections in the region between Limestone Rapids and North Knife River indicate a region of interplay between Labradorean and Keewatin ice flows, particularly during the last glaciation. Farther north, the till character, combined with striae and glacial landforms, suggest that glacial flow was southward from Keewatin during the last glaciation, although the presence of Paleozoic carbonate in both the matrix and pebble fractions of the till suggests that an earlier Labradorean ice flow extended at least as far north as the Seal River area, and extended west of the sections described here. Keewatin ice extended southward almost to Churchill River in late glacial (Late Wisconsin?) time, overrunning and reworking Labradorean tills.

SECTIONS NEAR THE SIPIWESK, SETTEE, AND ETAWNEY MORAINES

The area west of the Hudson Bay Lowlands near the Sipiwesk, Settee, and Etawney moraines (Fig. 1, area 7) is in Precambrian Shield terrain, where the till is generally thin, and commonly only one till is recognized under glaciolacustrine sediments or peat. The till typically has textures that average 40% sand in the east near the Paleozoic bedrock contact and 60% sand in the west. Correspondingly, matrix carbonate content averages 25% in the east and declines westward to 12%. At Cross Lake site K32 (Klassen, 1986) for example, there are exposures of 4 m of olive brown, silty sand till (56% sand), with a matrix carbonate content of 12%. This till is interpreted to be the Sky Pilot till, emplaced by southwest flow from Hudson Bay. The increasing sand content westward, and decreasing carbonate content, also westward, are a reflection of progressive carbonate dilution over the Shield.

Section K30 (Klassen, 1986), where the Etawney moraine crosses Churchill River, however, consists of multiple tills with higher matrix carbonate contents. The lower 15 m consists of two yellow-brown till sheets, separated by a sand bed. The till has oxidized joints, 17% matrix carbonate and 44% pebble carbonate contents, and a texture consisting of 60% sand and 40% silt-clay. This lower till is thought to be the upper part of the Labradorean Long Spruce till along Nelson River. The upper 6 m of the section is a fissile brown till that has a carbonate content of 23% in the matrix and 64% in the pebbles, and a texture of 38% sand and 62% silt-clay. This upper till is correlated with the Sky Pilot till.

AREAS BETWEEN SETTEE-ETAWNEY MORAINE AND LEAF RAPIDS MORAINE

South area

Kaszycki (*in* Kaszycki et al., 2008) studied sections in the area east of the Leaf Rapids moraine at Osik Lake and Hall Lake (Fig. 1, area 8) that revealed up to 5 m of calcareous, silty, sandy till and interstratified glaciofluvial sand beneath a surface cover of glaciolacustrine sediment. At Osik Lake (Fig.16) the lower till is a calcareous silty sand (5–23% matrix carbonate). The till fabric is oriented to the west at the base of the section, and changes to southwest (210°) near the top. The upper 50 cm of till is calcareous (36% matrix carbonate) and clay rich, and is interpreted as a readvance into glacial Lake Agassiz, based on its clay-rich texture and the presence of overlying glacial Lake Agassiz clay. At Hall Lake, a silty sand till with carbonate content varying from 8% at the base to 2.5% at the top has fabrics oriented southwest (225°). In order to account for the fabric and the presence of matrix carbonate, Kaszycki interpreted all the till units to be of Labradorean origin, with the ice following a curving trajectory that ended at the Leaf Rapids moraine. It is possible, however, that the tills with the southwest fabrics and lower carbonate contents resulted from a Keewatin ice flow that reworked the underlying, older, calcareous, Labradorean till. Support for this alternative interpretation comes from regional ice-flow patterns derived from striations and streamlined landforms (McMartin et al., 2010), in which southwestward and south-southwestward ice flows of Keewatin origin do not stop at the Leaf Rapids moraine, but rather, continue west of it.

Central area

The uppermost and surface tills exposed in hand-dug pits east of Leaf Rapids in the vicinity of Southern Indian Lake typically have textures of 56% sand and 44% silt-clay, and a matrix carbonate content varying from 8 to 13% (Klassen, 1986). Klassen interpreted these as Keewatin till. He pointed out, however, that matrix carbonate content is up to 25% in places; he attributed this to local bedrock carbonate sources of Paleozoic outliers. In contrast, Kaszycki et al. (2008) who also found that the Paleozoic carbonate pebble content in the till in the same region ranges from 0% to more than 30%, concluded that the last ice flow in this area was from a Labradorean centre. A matrix carbonate content exceeding 5% is commonly associated with Paleozoic limestone source areas, although carbonate in lesser concentrations can be derived from Shield sources (Dredge, 1988; Dredge and McMartin, 2007). What is not clear for central Manitoba is whether the calcareous upper till indicates Labradorean ice during last-glacial events, or whether this area was mainly overrun by Keewatin ice in the late Wisconsinan, and the carbonate was reworked from an earlier, westward ice flow. Streamlined features and striae in this area are oriented southward (older) and southwestward (younger) (McMartin et al., 2010). Our current interpretation is that this is Keewatin till. The ice flow producing it could be either the regional flow, or a late glacial/deglacial readvance through the area of Southern Indian Lake.

North area

Till in the South Seal River sections to the west of the Etawney moraine and north of Leaf Rapids shows a sharp drop in matrix carbonate content and is sandier than tills

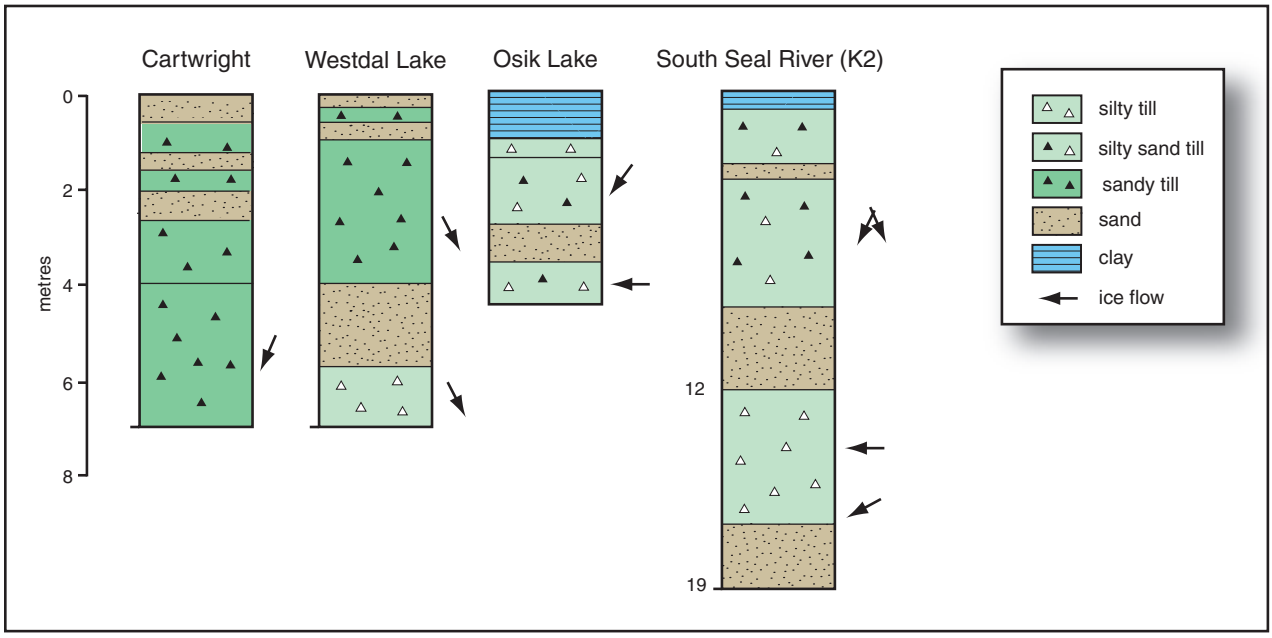


Figure 16. Stratigraphic sections east and west of the Leaf Rapids moraine in the Lynn Lake–Leaf Rapids area.

farther east. A 10 m section (Klassen, 1986; K 31) reveals two units of fissile, olive grey till, with sand content ranging from 57% to 68%, and matrix carbonate content from 4% to 5%. Klassen related these till units to south-flowing Keewatin ice on the basis of their physical characteristics, and surface landforms.

Kaszycki's et al.'s (2008) examination of the same sections along the South Seal River, and others along the Muskwesi River 40 km to the south, indicated slightly different results (Fig.16). In a 19 m exposure (K2), Kaszycki identified two distinctive tills separated by and intercalated with glaciolacustrine clay, sand, or gravel beds. The lower 4 m of till is olive brown, calcareous, and clay rich, and has fabrics ranging from southwestward near the base to westward in the upper half of the unit. The westward fabric corresponds in orientation to nearby striae at 270° and is thought to indicate a Labradorean till. The upper till at South Seal is a calcareous (6% matrix) silty sand diamicton containing a sand bed, and has fabrics oriented approximately 170° and 200°. The 170° fabric is parallel to surface fluting and striated bedrock nearby. This unit was interpreted as a Keewatin till. Kaszycki interpreted the two tills as reflecting the interplay between Labradorean and Keewatin ice in a glaciolacustrine environment in this region during deglaciation. However, both till units are fairly thick, so it is possible that they represent separate glacial events: an alternative interpretation that fits Klassen's (1986) findings is that the lower till is Labradorean, but represents a somewhat earlier ice-flow event, and that the main last-glacial flow in this area was Keewatin. Klassen's interpretation also fits better with-ice flow patterns at Chipewyan Lake and north of 58°, where south-trending, streamlined surface landforms from Keewatin ice have incorporated carbonate-rich debris from a prior Labradorean ice flow (Dredge et al., 1986; Dredge, 1988; Dredge and Cowan, 1989).

STRATIGRAPHY WEST OF THE LEAF RAPIDS MORAINE IN THE LYNN LAKE AREA

Sections examined by Kaszycki et al. (2008) indicate that commonly only one till unit, in places with multiple facies, is present and generally forms a veneer over bedrock. Sections 3 to 7 m high are exposed in roadcuts and backhoe trenches along Highway 391 between Lynn Lake and Leaf Rapids at Cartwright Lake, Westdal Lake, One Island Lake, Hughes River, and Eden Lake (Fig. 1, area 9). Till composition varies from sandy and noncalcareous in the west (Cartwright, Fig. 16) to silty and calcareous in the east.

A 7 m section at Cartwright Lake and the section at One Island Lake consist of glaciolacustrine sand underlain by olive-coloured, noncalcareous sandy ablation and basal till with interbedded sand units. Striae are oriented south-southwestward. This is interpreted as Keewatin till.

To the east at Westdal Lake (Fig. 16), a silty, calcareous till is separated from an overlying sandy, noncalcareous till by 2 m of massive sand. The fabrics in both units trend south-southeast, parallel to the youngest striae in the area. Kaszycki considered the tills to represent late glacial and deglacial events related to reorientation of Keewatin ice flow toward the Leaf Rapids moraine. Farther east at Hughes River (Fig. 1), a backhoe trench revealed a two-till stratigraphy consisting of 3 m of grey, sandy, but calcareous till at the base and brown, clay-rich, calcareous till at the top, separated by a thin layer of glacial Lake Agassiz clay. The upper till is considered to be a readvance deposit into glacial Lake Agassiz. Although the bottom till fabric at Hughes River trends south-southwestward, parallel to regional Late Wisconsin ice-flow trends and striae (190–210°), the fabrics above all indicate south-southeastward ice flow, parallel to the youngest striae, which are oriented toward the Leaf Rapids moraine. Kaszycki interpreted the tills in both the Westdal and Hughes sections to be of late glacial Keewatin provenance. The calcareous nature of the lower tills and silty texture of the lower till at Westdal Lake implies, however, that there was an earlier flow of Labradorean ice that extended west of the Leaf Rapids moraine.

At Wheatcroft Lake, south of Granville Lake (Fig. 1), there is an arsenic dispersal train in the surface till that trends south-southwest, parallel to the basal fabrics at Eden Lake and Hughes River. The dispersal train is considered to have been emplaced by Late Wisconsinan Keewatin ice flow. The Cree Lake moraine crosses, and postdates, the Wheatcroft Lake arsenic train.

Summary of events in the Lynn Lake–Leaf Rapids area

The stratigraphic record in the Lynn Lake–Leaf Rapids area relates primarily to late glacial and deglacial events, although matrix carbonate present in some basal tills west of the Leaf Rapids moraine (e.g. Westdal Lake and Hughes River) possibly relates to an earlier, extensive, westward, Labradorean ice flow. There is evidence for a main south-southwestward flow of Keewatin ice across the area, as shown by till fabrics at Cartwright, South Seal River, and Wheatcroft Lake, and an older flow of Labadorean ice that produced calcareous and silty till characteristics. The upper part of the till stack shows by its composition and fabric that there was a late, minor convergence of Keewatin ice flow toward the Leaf Rapids moraine, with reorientation of till fabrics southeasterly in areas west of the moraine (e.g. Westdal Lake and Hughes River), and southwesterly or westerly in areas east of the moraine (e.g. Osik Lake, Hall Lake). Deglacial tills that cap the sections show readvances of ice into glacial Lake Agassiz. These tills tend to be more clay rich, and are intercalated with glaciolacustrine sediments.

FLIN FLON AREA

North of Flin Flon and south of the Cree Lake moraine, the till cover is generally thin over the Shield, but borrow pits at Sherridon and Puffy Lake reveal sequences of up to 4 m of noncalcareous, sandy till units interstratified with sand and gravel (Fig. 1, area 10). At Puffy Lake, a lower, silty, calcareous till is present between the sandy till and bedrock. Fabrics in the calcareous till are oriented south-southeastward at the base, and rotate to south-southwestward at the top, corresponding with local striation sequences. The upper till is considered to be of Keewatin origin; the lower unit at Puffy Lake is possibly an earlier till of Labradorean origin, but more likely, it is Keewatin, and the carbonate comes from a local source to the north.

At Mosher Lake (Saskatchewan) near Flin Flon, three sandy, compact till units, separated by sharp erosional contacts, were observed in a roadcut (Fig.17; Campbell, 1988; Henderson, 1995; McMartin, 2000). The lowest unit is a compact, sandy silt till with a westward (276°) fabric, indicating deposition by Labradorean ice. The middle till has a silty sand texture, whereas the upper unit is a compact, fissile, sandy till with a bimodal fabric (304° and 207°). The upper two units are thought to be of Keewatin provenance (Henderson, 1995), with the upper unit being an ablation facies of the underlying till.

At Millwater near Cranberry Portage, a hand-dug hole 1.2 m deep revealed multiple till units separated by sharp contacts (McMartin, 2000). At the base of the pit is a sandy, noncalcareous, greenish grey till enriched in greenstone clasts. This till is overlain by grey, fissile, calcareous (matrix carbonate varies from 36 to 44%), silty till with a fabric of 259°. The upper unit is a brown, noncalcareous, bouldery, sandy, clay-rich till. Based on its texture and clast composition, the lower unit is likely a basal till of Keewatin provenance, whereas the middle till was deposited from a westward Labradorean ice flow that carried carbonate debris over the Shield. Surface landforms suggest that the upper till was deposited by a southwestward advance of Keewatin provenance, and that it incorporated some material from glacial Lake Agassiz.

South of Flin Flon, tills are thin, but sections with multiple till units have been observed in backhoe exposures and hand-dug pits (Fig. 17). At Wanless, which is located in Phanerozoic terrain west of The Pas moraine, a 1.7 m backhoe excavation exposed three thin tills separated by glaciolacustrine sediments (McMartin, 1994, 2000). A thin, compact, orange-brown, strongly calcareous, silty, sandy till with a matrix carbonate content of 42% rests on Paleozoic bedrock that has been striated by a westward ice flow (267°). It is considered to be associated with Labradorean ice flow. The middle till, which is pinkish brown, compact, and highly calcareous (matrix carbonate of 53%), has a sandy, silty

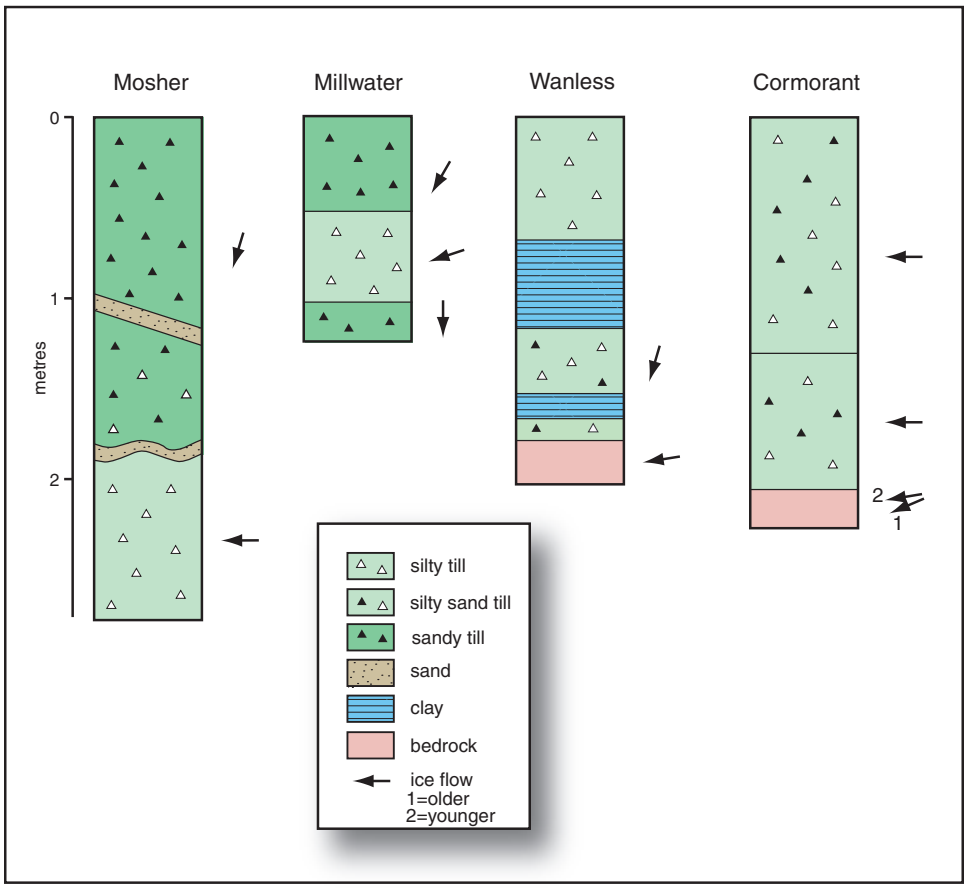


Figure 17. Stratigraphic sections near Flin Flon.

texture and a strong southward fabric (199°); it is considered to be of Keewatin provenance. A layer of brown, massive clay and laminated silt separates the middle till from an upper unit of greyish brown, calcareous (matrix carbonate of 17%), sandy, clay-rich, substratified till. The composition and texture of the upper till suggests that it was deposited by a southwestward glacial readvance into glacial Lake Agassiz.

At Cormorant Lake, east of The Pas moraine, two till units separated by a sharp contact rest on bedrock that is cross-striated nearby at 248° and 266° (McMartin, 1994; 2000). The lower unit is a greyish, calcareous (matrix carbonate 37–57%), silty sand till with 21% Precambrian clasts. The upper unit is a greyish, calcareous (matrix carbonate 53–63%), sandy silt till with 11% Precambrian clasts. Both tills are considered to be of Labradorean provenance, with the upper till reflecting a late shift in westward ice flow prior to deglaciation.

In summary, sections in the southern part of the study area consist of Labradorean tills of eastern provenance east of The Pas moraine, and Labradorean till that has been overrun by southward-flowing Keewatin ice west of the moraine.

DISCUSSION AND GENERAL CONCLUSIONS

This is the first regional systhesis of the stratigraphy of northern and central Manitoba. The stratigraphic record and its interpretation presented here indicate that the Laurentide Ice Sheet and its precursors have had a long and complicated history, with both minor and major shifts in ice flow occurring not only at the southerly limits of glaciation, or during deglaciation, but also at the heart of the Laurentide Ice Sheet and throughout the course of at least the last several glaciations.

The stratigraphic record across central and northern Manitoba consists of a sequence of tills and intertill sediments representing a series of ice-flow events spanning a number of glaciations and interglaciations. The exposures containing the longest records are found along the large rivers in the Hudson Bay Lowlands, where two interglacial periods are recorded. Most sections farther north and west contain sediments related to the last glacial, and mainly to deglacial events, although striation sequences in that area preserve a longer record.

Based on the stratigraphic records presented above, we have interpreted the sequence of glacial and nonglacial events to be as follows:

1. An early major ice flow from the east, inferred by Omarolluk erratics in the lowermost tills along Nelson River.
2. A major flow of Keewatin ice across northern and central Manitoba, emplacing the Sundance till on Nelson River, and Keewatin erratics regionally.
3. A pre-Sangamon interglacial event consisting of both warm and cold climate phases, indicated by soil horizons at the top of the Sundance till, and correlative clay-rich sediments.
4. A major flow of Labradorean ice westward, emplacing the Amery till on Nelson River and areas south in the Hudson Bay Lowlands, and accounting for westward striae in the Lynn Lake and Flin Flon areas, and in Saskatchewan farther west (e.g. Campbell and McMartin, 2008). This ice flow is tentatively assigned to the Illinoian Glaciation.
5. An interglaciation with climates and biomes similar to present, as evidenced by interglacial peat, alluvium, and glaciolacustrine deposits along rivers in the Hudson Bay Lowlands and as far north as Seal River in eastern Manitoba. These deposits are considered to represent the Sangamon Interglaciation. Radiocarbon dates are nonfinite and greater than 59 ka, and optical dates are about 121 ka.
6. Early to main Wisconsinan flow of Keewatin ice southeast, inferred by crosscutting striae in the Lynn Lake area (Kaszycki et al., 2008), The Pas (McMartin, 1994, 2000) and eastern Saskatchewan (Henderson, 1995; McMartin et al., 1996; Campbell and McMartin, 2008), and by numerous Proterozoic Dubawnt clasts in the base of the Long Spruce till in the Hudson Bay Lowlands. There is no actual corresponding till unit in the lowlands.
7. There were shifts in ice flow within both the Keewatin and Labradorean sectors of the Laurentide Ice Sheet during the main to late Wisconsin Glaciation. Also, there was a westward shift in the confluence of Keewatin and Labradorean ice during this glacial period. A major Labradorean ice flow westward emplaced the Long Spruce till/Wigwam Creek till in the Hudson Bay Lowlands. Kaszycki (*in* Kaszycki et al., 2008) thought that Labradorean ice of this age followed an arcing flow path, creating striae at about 210°, and stopped in the Leaf Rapids area. We conclude, however, that it extended westward somewhat farther, into the Lynn Lake area and west of The Pas moraine near Flin Flon, as evidenced by silty and/or calcareous tills. Also, more recent compilations of ice-flow datasets (McMartin et al., 2010) suggest that the 210° ice flow that Kaszycki attributed to a Labradorean source is just as likely, or more likely, to be of Keewatin provenance. The northern extent of Labradorean ice at this time was probably somewhat north of Seal River, as inferred from the presence of reworked Paleozoic carbonate clasts in later Keewatin tills.
8. Eastward migration of the Keewatin Ice Divide caused shifting ice-flow patterns during the late Wisconsin Glaciation and during deglaciation. In northeastern Manitoba, both striation records and till stratigraphy indicate that the northern limit of the Keewatin/Labradorean convergence shifted between Churchill River and North Knife River. Areas north of this zone lay in the Keewatin

ice domain. South of this zone of interplay, Labradorean ice deposited the Sky Pilot till. South of the Flin Flon area, Keewatin flow dominated in areas west of the The Pas moraine, which marks the westerly limit of Labradorean ice during deglaciation.

North of the Cree Lake moraine, Kaszycki (*in* Kaszycki et al., 2008) interpreted the Leaf Rapids moraine area to mark the westward limit of convergence of Labradorean and Keewatin ice, with converging flow recorded in till fabrics and local striae. She interpreted the Setee-Etawney moraines to be recessional moraines that developed after retreat of Labradorean ice from the Leaf Rapids moraine.

Klassen (1986), however, interpreted the Etawney moraine to be the deglacial interlobate zone between the Keewatin and Labradorean ice masses. Streamlined landforms, esker patterns, and the composition of surface till sheets (Dredge and Nixon, 1992; McMartin et al., 2010), suggest confluent flow of Keewatin and Labradorean ice during deglaciation in the area east of North Knife Lake. Thus, it is likely that the Etawney and contiguous North Knife kame moraines mark a major zone of convergence. Either these moraines mark a major convergence after the confluent ice margins had retreated north and east of Leaf Rapids, or they were the major convergence, and the Leaf Rapids moraine is essentially an esker that was large enough to pull ice toward it, thus accounting for the till fabric and striation rotations along its flanks. At present, we conclude that the latter scenario is more likely, in which case the Labradorean ice flow that reached as far as, or beyond Leaf Rapids, was an earlier ice flow mentioned above (event 7 or 4), and the late Labradorean ice did not extend west of the Etawney moraine. The sandy Limestone moraine, oriented east-west, is considered to be a radial kame moraine feature within the Labradorean ice sheet that is parallel to the regional ice flow.

During deglaciation, stacked tills in the Lynn Lake–Leaf Rapids area, intercalated with glacial lake sediments, indicate small glacial readvances into glacial Lake Agassiz. Similar intercalated till and glaciolacustrine sediment sequences are also present in the lowlands. A major regional fanning pattern of sandy, noncalcareous till with drumlinoidal surface landforms, representing the Quinn Lake readvance, marks a major surge of Keewatin ice into the northern margin of glacial Lake Agassiz. Similar readvances into glacial Lake Agassiz from the receding Keewatin ice margin may account for south-southwestward striation patterns along Southern Indian Lake.

9. Accompanying deglaciation, the Keewatin ice margin retreated northward, while the Labradorean ice margin retreated eastward. Diamictic and substratified till-like deposits, as well as distal-facies, clay-rich, varved sediments were deposited into glacial Lake Agassiz. Following breakup of Hudsonian ice, marine waters inundated lowland areas surrounding Hudson Bay, depositing a coarsening-upward sequence of postglacial marine deposits.

Several factors limit a more precise interpretation and correlation of the stratigraphic sections. The first is the lack of absolute dates on the till units: most of the interpretation has been based on sequence stratigraphy and till characteristics. The second revolves around the interpretation of Paleozoic carbonate clasts and matrix carbonate content in the tills. High carbonate content is generally a strong indicator of Labradorean (or Hudsonian) ice flow westward across the Paleozoic carbonate platform underlying Hudson Bay. However, its presence in low amounts is not always a clear indication of Labradorean ice flow. Carbonate may also be found in Keewatin tills for the following reasons: 1) The presence of carbonate clasts and matrix carbonate in any till sheet can derive from materials that have been reincorporated from underlying till sheets and previous ice flows. 2) Both Keewatin and Labradorean tills that have resulted from readvances into glacial Lake Agassiz are calcareous to some degree, because of the incorporation of fine-grained glaciolacustrine sediments that contain distal debris, transported in suspension, from the Labradorean ice sheet. 3) It is possible that some limestone clasts found in anomalously high quantities in the western part of the study area may have originated from Paleozoic outliers within the Keewatin ice domain that were eroded away during successive glaciations. 4) Regional geochemical studies of till in this area have shown that up to about 5% of the calculated matrix carbonate could have been derived from Shield marbles, and other calcium-bearing, or easily leached, minerals (Dredge, 1988; Dredge and McMartin, 2007; McMartin et al., in press). A final complicating factor in assigning provenance to till based on carbonate content is that some carbonate has been leached from the upper part of the surface till during the postglacial period (Dredge, 1981; Kaszycki et al., 2008), and presumably during other warm intervals for other till units. Thus, the limits of Labradorean ice may have extended beyond the northern and western limits defined by the presence of small quantities of carbonate in the till.

Some of the uncertainties and interpretation problems associated with the stratigraphic record in northern and central Manitoba, particularly Wisconsin-age ice flows, may be resolved by an examination of the striations and landforms in the area. Striation and landform datasets have been compiled recently (Dredge et al., 2007; McMartin et al., 2010; McMartin et al., in press), and will form a solid basis for further refinement of the glacial record.

ACKNOWLEDGMENTS

We thank Janet Campbell and Beth McClenaghan for substantive reviews of the original manuscript, and their helpful suggestions.

REFERENCES

Anderson, S.D., Bohm, C.O., and Matile, G.L.D., 2005. Bedrock and surficial geological field investigations in the Nejanilini Lake area; Manitoba Geological Survey, Paper GS-10, p. 92–103.

Bell, R., 1879. Report on the country between Lake Winnipeg and Hudson's Bay, 1878; Geological Survey of Canada, Report of Progress for 1877–1878, part 6, 31 p.

Bell, R., 1880. Report of explorations on the Churchill and Nelson Rivers; Geological Survey of Canada, Report of Progress for 1878–1879, part C, 51 p.

Bostock, H.H., 1971. Geological notes on Aquatuk River map area, Ontario, with emphasis on the Precambrian rocks; Geological Survey of Canada, Paper 70-42, 57 p.

Campbell, J.E., 1988. Quaternary geology and till geochemistry – East Amisk Lake area, Saskatchewan; Saskatchewan Research Council, Report R-842-59-E-88, 31 p.

Campbell, J.E. and McMartin, I., 2008. The Flin Flon Targeted Geoscience Initiative 3: Update on the Quaternary sub-project activities; Saskatchewan Geological Survey, Miscellaneous Report 2008-4.2, Paper A-6, 11 p.

DiLabio, R.N.W. and Kaszycki, C.A., 1988. An ultramafic dispersal train and associated gold anomaly in till near Osik Lake, Manitoba; *in* Current Research, Part C; Geological Survey of Canada, Paper 88-1C, p. 67–71.

Dredge, L.A., 1981. The leaching of carbonates in discontinuous permafrost, boreal Manitoba; *in* Current Research, Part C; Geological Survey of Canada, Paper 81-1C, p. 23–25.

Dredge, L.A., 1988. Drift carbonate on the Canadian shield II: carbonate dispersal and ice-flow patterns in northern Manitoba; Canadian Journal of Earth Sciences, v. 25, p. 783–787.

Dredge, L.A. and Cowan, W.R., 1989. Quaternary geology of the southwestern Canadian Shield; *in* Chapter 3 of Quaternary Geology of Canada and Greenland, (ed.) R.J. Fulton; Geological Survey of Canada, Geology of Canada, no 1, p. 214–235 (also Geological Society of America, The Geology of North America, v. K-1, p. 214–235).

Dredge, L.A. and McMartin, I.M., 2007. Geochemical reanalysis of archived till samples from northernmost Manitoba; Geological Survey of Canada, Open File 5546, 1 CD-ROM.

Dredge, L.A. and Nielsen, E., 1985. Glacial and interglacial deposits in the Hudson Bay Lowlands: a summary of sites in Manitoba; *in* Current Research, Part A; Geological Survey of Canada, Paper 85-1A, p. 247–257.

Dredge, L.A. and Nielsen, E., 1986. Gold concentrations in till, Great Island, northern Manitoba; *in* Current Research, Part A; Geological Survey of Canada, Paper 86-1A, p. 779–782.

Dredge, L.A. and Nielsen, E., 1987. Glacial and interglacial stratigraphy, Hudson Bay Lowlands, Manitoba; Geological Society of America, Centennial Field Guide – north-central section, p. 43–46.

Dredge, L.A. and Nixon, F.M., 1992. Glacial and environmental geology of northeastern Manitoba; Geological Survey of Canada, Memoir 432, 80 p.

Dredge, L. A. and Nixon, F.M., 1985. Surficial geology, northwestern Manitoba; Geological Survey of Canada, Map 1608A, scale 1:500 000.

Dredge, L. A. and Nixon, F.M., 1986. Surficial geology, northeastern Manitoba; Geological Survey of Canada, Map 1617A, scale 1:500 000.

Dredge, L.A. and Pehrsson, S.J., 2006. Geochemistry and physical properties of till in northernmost Manitoba; Geological Survey of Canada, Open File 5320, 130 p.

Dredge, L.A., McMartin, I., and Pyne, M., 2007. Surface materials and landforms, northernmost Manitoba; Geological Survey of Canada, Open File 5435, 22 p. (1 sheet), CD-ROM.

Dredge, L.A., Morgan, A.V., and Nielsen, E., 1990. Sangamon and pre-Sangamon interglaciations in the Hudson Bay Lowlands of Manitoba; Géographie physique et Quaternaire, v. 44, p. 319–336.

Dredge, L.A., Nixon, F.M., and Richardson, R.J., 1986. Quaternary geology and geomorphology of northwestern Manitoba; Geological Survey of Canada, Memoir 418, 38 p.

EBA Engineering Consultants Ltd., 1976. Polar Gas compilation of field data, summer 1976, v. 5: Seal River to Longlac, and v. 4: Thelon River to Seal River.

Henderson, P.J., 1995. Surficial geology and drift composition of the Annabel Lake–Amisk Lake area, Saskatchewan; Geological Survey of Canada, Open File 3026, 201 p.

Kaszycki, C.A., Dredge, L.A., and Groom, H., 2008. Surficial geology and glacial history of the Lynn Lake–Leaf Rapids area, Manitoba; Geological Survey of Canada, Open File 5873, 105 p.

Kaszycki, C.A., Suttner, W.C., and DiLabio, R.N.W., 1988. Gold and arsenic in till, Wheatcroft Lake dispersal train, Manitoba; *in* Current Research, Part C; Geological Survey of Canada, Paper 88-1C, p. 341–351.

Klassen, R.W., 1986. Surficial geology of north-central Manitoba; Geological Survey of Canada, Memoir 419, 57 p.

Matile, G.L.D. and Keller, G.R., 2006. Surficial geology compilation map series of Manitoba. Manitoba Geological Survey compilation map series SG-CMS, scale 1:250 000 and 1:500 000.

McMartin, I., 1994. Ice flow events in the Cormorant Lake–Wekusko Lake area, northern Manitoba; *in* Current Research, Part C; Geological Survey of Canada, Paper 1994-C, p. 175–182.

McMartin, I., 2000. Quaternary geology and environmental geochemistry of the Flin Flon region, Manitoba and Saskatchewan; Ph.D. thesis, Carleton University, Ottawa, Ontario, 289 p.

McMartin, I., Campbell, J.E., Dredge, L.A. and Robertson, L., 2010. A digital compilation of ice flow indicators for central Manitoba and Saskatchewan: datasets, digital scalable maps and 1:500 000 scale generalized map; Geological Survey of Canada, Open File 6405, 1 DVD.

McMartin, I., Dredge, L.A., Grunsky, E., and Pehrsson, S., in press. Till geochemistry in west-central Manitoba: interpretation of provenance and mineralization based on glacial history knowledge and principal component analysis; Economic Geology.

McMartin, I., Henderson, P J., Nielsen, E., and Campbell, J E., 1996. Surficial geology, till and humus composition across the Shield margin, north-central Manitoba and Saskatchewan: geospatial analysis of a glaciated environment; Geological Survey of Canada, Open File 3277, 1 CD-ROM / 2 diskettes.

Netterville, J.A., 1974. Quaternary stratigraphy of the lower Gods River region, Hudson Bay Lowlands, Manitoba; M.Sc. thesis, Department of Geology, University of Calgary, Calgary, Alberta, 79 p.

Nielsen, E., 1987. Till geochemistry of the Seal River area east of Great Island, Manitoba; Manitoba Energy and Mines, Open File Report OF87-1, 28 p.

Nielsen, E. and Dredge, L.A., 1982. Quaternary stratigraphy and geomorphology of a part of the lower Nelson River; Geological Association of Canada, Field Trip Guide 5, Winnipeg, 56 p.

Nielsen, E., Morgan, A.V., Morgan, A., Mott, R.J., Rutter, N.W., and Causse, C., 1986. Stratigraphy, paleoecology, and glacial history of the Gillam area, Manitoba; Canadian Journal of Earth Sciences, v. 23, p. 1641–1661.

Norris, A.W., 1993. Hudson platform geology; *in* Chapter 8 of Sedimentary Cover of the Craton in Canada, (ed.) D.F. Stott and J.D. Aitken; Geological Survey of Canada, Geology of Canada, no. 5, p. 655–700 (also Geological Society of America, v. D-1, p. 655–700).

Prest, V.K., Donaldson, J.A., and Mooers, H.D., 2000. The Omar story: the role of Omars in assessing glacial history of west-central North America; Géographie physique et Quaternaire, v. 54, p. 257–270.

Rainbird, R.H., Hadlari, T., Aspler, L.B., Donaldson, J.A., LeCheminant, A.N., and Peterson, T.D., 2003. Sequence stratigraphy and evolution of the Paleoproterozic intracontinental Baker Lake and Thelon basins, western Churchill Province, Nunavut, Canada; Precambrian Research, v. 125, p. 21–53.

Roy, M., 1998. Stratigraphie Pléistocene du cours inférieur de la rivière Nelson – implications pour l'évolution des basses-terres de la Baie d'Hudson du Manitoba, Canada; M.Sc. thesis, Université du Québec à Montréal, Montréal, Québec, 220 p.

Taylor, F.C., 1961. Interglacial conglomerate in northern Manitoba; Geological Society of America, Bulletin, v. 72, p. 167–168.

Trommelen, M.T. and Ross, M., 2009. Manitoba far north geomapping initiative: field reconnaissance of surficial sediments, glacial landforms and ice-flow indicators, Great Island and Kellas Lake areas, Manitoba (NTS 54L, 64I, P); Manitoba Geological Survey, GS14, p. 148–153.

Tyrrell, J.B., 1898. Report on the Doobawnt, Kazan, and Ferguson rivers, and the northwest coast of Hudson Bay; and on two overland routes from Hudson Bay to Lake Winnipeg; Geological Survey of Canada, Annual Report (new series), v. 9, part F, p. 1–218.

Contents
This CD-ROM contains the full contents of Bulletin 600 in .pdf format, including any maps or oversized figures.

System requirements
PC with 486 or greater processor, or Mac® with OS® X v. 10.2.2 or later; Adobe® Reader® v. 6.0 (included for both PC and Mac) or later; video resolution of 1280 x 1024.

Quick start
This is a Windows®-based autoplay disk. Should the autoplay fail, navigate to the root of your CD-ROM drive and double-click on the autoplay.exe file. Mac® users must use this method to begin.

****

Contenu
Ce CD-ROM renferme le contenu intégral du Bulletin 600 en format .pdf, y compris les figures surdimensionnées ou les cartes, s'il y a lieu.

Configuration requise
PC avec processeur 486 ou plus rapide, ou Mac® avec OS® X v. 10.2.2 ou ultérieure; Reader® v. 6 d'Adobe® (fourni pour PC et Mac) ou version ultérieure; résolution vidéo de 1280 x 1024.

Démarrage rapide
Ceci est un disque à lancement automatique pour les systèmes d'exploitation Windows®. Si le lancement automatique ne fonctionne pas, allez au répertoire principal du CD-ROM et faites un double clic sur le fichier autoplay.exe. Les utilisateurs de systèmes Mac® doivent procéder de cette façon pour débuter la consultation.