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QUATERNARY GEOLOGY AND GEOMORPHOLOGY OF NORTHWESTERN MANITOBA

L.A. DREDGE
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R.J. RICHARDSON

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Preface

The landscape of northwestern Manitoba is typical of much of the Canadian mid-north. The area includes an extensive tract of muskeg in the south, which passes through boreal forest to tundra barrens. Some parts of the region lie within the zone of continuous permafrost; others lie in the discontinuous permafrost zone. Major landscape elements were shaped in pre-Quaternary times, but most surface deposits and landforms are the result of the last continental glaciation and the subsequent inundation of glacial lakes and the sea.

This report was written in response to a need for information on terrain conditions related to engineering construction, and on glacial transport patterns as they relate to drift prospecting and mineral exploration. An understanding of the Quaternary evolution of northwestern Manitoba is especially interesting because the region lies within the heart of the former Laurentide ice sheet, but along the zone of convergence of two distinct ice masses (Keewatin and Hudsonian) which had different centres of inception and styles of flow. The interpretation of features and the glacial history of the region is therefore crucial to understanding the dynamics and structure of the North American ice sheet.

OTTAWA

R.A. Price
Director General
Geological Survey of Canada

Préface

Le paysage du nord-ouest du Manitoba est typique des régions du Moyen nord au Canada. Une zone prolongée de muskeg qui se trouve dans le sud de cette région traverse une forêt boréale et aboutit à la toundra du bas-arctique. Certaines parties de cette région se situent dans la zone de pergélisol continue tandis que d'autres se situent dans la zone de pergélisol discontinue. Les éléments importants du paysage ont été façonnés antérieurement au Quaternaire; cependant, la plupart des dépôts et formes de relief superficiels résultent de la dernière glaciation et de l'inondation ultérieure des lacs glaciaires et de la mer.

Ce rapport vise à combler le besoin de renseignements de nature géotechnique sur les conditions de terrain et d'information sur les modes de transport glaciaire qui peuvent influer sur la prospection et l'exploration minérale à partir des dépôts quaternaires. Il est particulièrement intéressant de comprendre l'évolution du nord-ouest du Manitoba au Quaternaire étant donné que cette région s'étend à la fois au coeur de l'ancienne calotte glaciaire laurentidienne et le long de la zone de convergence de deux masses de glace distinctes (Keewatin et Hudsonien) dont les centres d'origine et les styles d'écoulement étaient différents. Il est, par conséquent, crucial de faire l'interprétation des formes de relief et de l'histoire glaciaire de la région pour comprendre la dynamique et la structure de la calotte glaciaire de l'Amérique du Nord.

OTTAWA

Le directeur général de la
Commission géologique du Canada
R.A. Price

CONTENTS

1 Abstract/Résumé
2 Introduction
2 General
2 Field work
3 Scope of the report
3 Acknowledgments
3 Previous work
3 Physiography
3 Bedrock topography and landforms
4 Glacial topography and landforms
5 Drainage
5 Physiographic units
5 Climate
6 Surficial geology
6 Glaciated bedrock outcrop
6 Lithology
6 Abrasion and weathering
6 Striae
6 Residuum
6 Felsenmeer
7 Saprolite and reworked saprolite
7 Till
8 Tills emplaced by Keewatin Ice
8 Sandy till
10 Bouldery till
11 Till veneer
11 Tills emplaced by Hudsonian Ice
11 Silty till
12 Glaciofluvial deposits
12 Crevasse fillings
12 Kames and eskers
12 Interlobate kame moraine
13 Radial and lateral kame moraines, and eskers
14 Outwash
14 Glaciolacustrine and lacustrine deposits
15 Glaciolacustrine deposits
15 Lacustrine pelite
17 Littoral sand
18 Glaciomarine and marine deposits
18 Stony marine and glaciomarine pelite
18 Littoral and sublittoral sands
18 Undifferentiated marine deposits
18 Fluvial deposits
18 Modern alluvium
18 Older alluvium
19 Organic deposits (peat)
19 Forested bog peat
19 Fen peat
19 Tundra peat
20 Stratigraphy
20 Morand Lake and Gimby Lake exposures
20 Seal River sections
20 North Knife River sections
20 Sediment sequence and interpretation of events
21 Chronology and regional correlations
21 Summary
21 Glacial and postglacial history
23 Ice flow indicators
23 Continental context
23 Early glaciations and nonglacial intervals
23 Late Wisconsinan glaciation
23 Limits of Keewatin and Hudsonian ice
23 Changes in flow direction
25 Regime of Hudsonian and Keewatin ice masses during late phases of glaciation
26 Deglaciation
26 Overview: extent and deposits of Lake Agassiz
26 Overview: style and pattern of ice retreat
28 Rupture of the suture between Keewatin and Hudsonian ice
29 Early high-level lake
30 Money Lake phase
30 The 377 m lake level and eastward extension of the interlobate moraine
30 Sandy Lake phase: deepening of Lake Agassiz

30 Maximum expansion of Lake Agassiz
30 Shifting ice divide and the Quinn Lake readvance
31 Gradually falling lake levels
31 Abrupt drops in lake level
31 A possible late, low-level phase: Lake Netterville
31 Readvance and catastrophic demise of Hudsonian ice: the end of Lake Agassiz
31 Shift in the Keewatin ice divide and development of isolated glacial lakes
31 Radial recession of Keewatin ice to a final centre near Hudson Bay
31 Tyrrell Sea episode
32 Postglacial climate changes
32 Correlation of northern and southern Lake Agassiz levels
33 Economic and engineering geology
33 Introduction
33 Land use concerns
33 Sand and gravel
33 Foundering of equipment in loose till
34 Permafrost and ground ice
36 Peatlands
36 Construction problems related to permafrost conditions
36 Introduction
36 Base metal concentrations
36 Location of anomalies
36 References

Tables

17 1. Diatoms in Lake Agassiz deposits, northwestern Manitoba
22 2. Stratigraphic table showing the sedimentary succession along North Knife River, with several possible interpretations of events and chronologies
26 3. Contrasting deposits and landforms associated with Keewatin and Hudsonian ice retreating against Lake Agassiz
29 4. Sea, ice, and lake relationships

Illustrations

Map 1608A. Surficial geology, northwestern Manitoba

2 1. Location map
4 2. Topography, drainage, and physiographic regions
6 3. Rock blister
7 4. Boulder patch
7 5. Felsenmeer
8 6. Till texture
9 7. Sedimentary structures in sandy Keewatin till
9 8. Sandy till plain, aerial view
10 9. Sandy till, ground view
10 10. Active mudboil in sandy till
11 11. Bouldery till, aerial view
11 12. Bouldery till, ground view
11 13. Ribbed moraine
13 14. Crevasse fillings
14 15. Radial and ice front marginal kame moraine
15 16. Sandy, gently convex surface of esker ridge
15 17. Esker with delta pad
15 18. Cross-section of esker ridge
16 19. Outwash channels
17 20. De Geer moraine
17 21. Ice laminae in lacustrine silt
17 22. Landscape in the Lake Agassiz basin near South Knife River
18 23. Beach ridges in sandy till; beach ridges in littoral sand
19 24. Forested bog and fen landscape
19 25. Forested bog
20 26. Palsa in fen
20 27. Tundra peat with frost polygons, and sandy till
24 28. Gathering grounds and migrating ice divides of the Late Wisconsinan glaciation
25 29. Ice flow patterns
27 30. Sedimentation pattern in the Lake Agassiz Basin
28 31. Pattern of ice retreat in northern Manitoba
in pocket 32. Deglaciation of northern Manitoba
32 33. Areas inundated by Lake Agassiz, isolated glacial lakes, and the Tyrrell Sea
33 34. Late phases of Lake Agassiz in Manitoba
34 35. Lake level summary for the northern part of Lake Agassiz
34 36. Uranium and base metal concentrations in till
35 37. Location of uranium and base metal anomalies

QUATERNARY GEOLOGY AND GEOMORPHOLOGY OF NORTHWESTERN MANITOBA

Abstract

Northwestern Manitoba constitutes a gently rolling pre-Quaternary peneplain which was subsequently modified by Quaternary processes. The surface deposits and landforms are a product of two confluent ice masses that occupied the region during the last glaciation, and of the glacial lakes which succeeded the receding glaciers.

Keewatin ice flowed southwards across the region and deposited a sandy to bouldery till sheet whose surface is divided into belts of transverse and longitudinal bedforms. The radial moraines and long, massive, regularly spaced eskers which interrupt the till blanket attest to the importance of meltwater within the Keewatin ice domain. The orientation of glacial features systematically changed as the Keewatin ice divide migrated eastwards; one limb of this divide stagnated near Caribou Lake. A second major ice mass, from an ice divide over Hudson Bay, flowed westwards across the southern part of the area and deposited several calcareous, silty till sheets, the uppermost of which is gently ridged with grounding line moraines. The zone of convergence of Keewatin and Hudsonian ice shifted over time, but the location of final convergence is marked by the Knife River Interlobate Moraine.

During deglaciation, Lake Agassiz covered the area vacated by the receding ice sheets and persisted as long as glacier ice blocked natural drainage into Hudson Bay. Blanket sands, esker deltas, and De Geer moraines formed where debris from the Keewatin glacier entered the lake. More extensive deposits of substratified diamicton or massive and varved clay were left by Hudsonian ice. Beach ridges and wave cut notches mark lake levels, which fell from 442 m to less than 155 m as new outlets opened in eastern Manitoba and Ontario. Between 8000 BP and 7800 BP the ice mass occupying Hudson Bay disintegrated, and Tyrrell Sea flooded areas below 180 m elevation.

Thick deposits of peat with large amounts of ground ice accumulated over the silty substrates during postglacial time. Frost riving of bedrock, frost churning of soils, and aggradation or degradation of ground ice are current periglacial processes.

The surface till sheet has anomalously high uranium concentrations over some of the pelitic gneisses, and high arsenic or iron-zinc-chromium concentrations south of the Great Island volcanic and metasedimentary rocks.

Résumé

Le nord-ouest du Manitoba est formé d'une pénéplaine pré-quaternaire doucement ondulée qui a été modifiée au cours du Quaternaire. Les formations superficielles et la topographie sont le résultats de deux masses de glace confluentes qui ont occupé la région au cours de la dernière glaciation et de lacs glaciaires formés lors du recul des glaciers.

Le glacier du Keewatin s'est déplacée vers le sud en travers de la région, laissant une nappe de till sableux ou blocailleux dont la surface est divisée en zones de formes transversales et longitudinales. Des moraines radiales et des eskers longs et massifs à espacement régulier coupent la nappe de till, attestant l'importance des eaux de fonte dans la zone recouverte par le glaciel du Keewatin. L'orientation des formes produites par la glace a été modifiée à mesure que la ligne de partage des glaces du Keewatin se déplacait vers l'est; un des versants de cette ligne de partage a stagné près du lac Caribou. Une deuxième masse importante de glace, provenant d'une ligne de partage des glaces qui recouvrait la baie d'Hudson, s'est écoulée vers l'ouest en travers de la partie sud de la région et a déposé plusieurs nappes de till calcaire silteux, dont la plus élevée comporte des crêtes douces formées par des moraines frontales. La zone de convergence des glaciers du Keewatin et d'Hudson s'est déplacée avec le temps, mais la moraine interlobaire de Knife River marque le lieu de convergence définitive.

Au cours de la déglaciation, le lac Agassiz a inondé la région délaissée par les nappes de glace en recul; ce lac a persisté aussi longtemps que le glacier empêchait le drainage naturel des eaux dans la baie d'Hudson. Des couvertures de sable, des deltas d'eskers et des moraines de De Geer se sont accumulés là ou les débris du glacier du Keewatin ont débouché dans le lac. La glace hudsonnienne a laissé des dépôts plus étendus de diamicton substratifié ou d'argile massive et varvée. Des plages et des entailles de sapement marquent les niveaux des lacs, qui sont passés de 442 m à moins de 155 m durant l'ouverture de nouveaux exutoirs dans l'est du Manitoba et en Ontario. La masse de glace occupant la baie d'Hudson s'est désintégrée il y a entre 7 800 et 8 000 BP, et la mer de Tyrrell a envahi les zones situées à moins de 180 m d'élévation.

Des dépôts épais de tourbe riche en glace se sont accumulés au-dessus des substrats silteux au cours du postglaciaire. La gélifraction du socle rocheux, la géliturbation des sols et la croissance et la décroissance de la glace dans le sol sont tous des processus périglaciaires actuels.

La nappe de till superficielle contient des teneurs anormalement élevées en uranium là où elle repose sur certains gneiss pélitiques, et des teneurs élevées en arsenic ou en fer-zinc-chrome au sud des roches volcaniques et métasédimentaires de Great Island.

INTRODUCTION

Over the years, scientists have held a number of varying views about the structure of the North American ice sheet. As early as the last century, on the basis of striae measurements and intuitive insight, Tyrrell (1898, 1913) proposed that the Laurentide ice sheet had three centres of growth: one in Keewatin, one in Labrador-Quebec, and one in northern Ontario. He proposed that not all ice centres were equally active simultaneously, but that their dominance varied over the course of glaciation. Later Flint (1943) proposed a different theory, in which all ice flowed radially from a single ice dome centred over Hudson Bay. His concept, based on inferred climatic and topographic parameters, was strenuously supported until recently, in part because the observed pattern of postglacial rebound seemed to coincide with that model (e.g., Andrews, 1970). The single dome model is still held today by some scientists. Extensive field operations by the Geological Survey of Canada in recent years have allowed geologists the opportunity to re-examine the field evidence bearing on these two main concepts. As a result, a number of different ideas concerning the structure of the North American continental ice sheet have been proposed, but each of these involves the idea that there were multiple centres of glacial outflow. Prest (1970) first divided the Laurentide ice sheet into a number of distinctive sectors. On the basis of drift dispersal patterns Shilts et al. (1979) showed that Laurentide flow originated, and was maintained from, two ice centres, one in District of Keewatin and one over central Quebec. Shilts suggested that not only was there no ice divide centred over Hudson Bay, but that Quebec ice reached westwards into the prairie region. Recent analysis of drift composition patterns, examination of new stratigraphic sections over broad areas, the reinterpretation of major landforms in the central part of the country, and new maps of geophysical parameters led Dyke et al. (1982) to propose a Laurentide ice sheet that had five continental centres of outflow and a number of satellite ice sheets. One of these centres of outflow, which developed relatively late in the glacial cycle, was centred in the southern part of Hudson Bay. Each of the ice domains was semi-independent, had a distinctive glaciological signature, and interacted with adjacent ice masses. Some of the concepts and supporting field evidence published for the multi-dome model of Dyke et al. arose from fieldwork on till types and glacial landforms from northern Manitoba, a region which lies in the heart of the area of contention. Consequently, the report is written from the viewpoint that two ice masses converged, over northern Manitoba: one ice sheet flowed southwards from a centre in the districts of Keewatin and Mackenzie; the other flowed westwards from a centre in Hudson Bay. Although the Hudson ice divide was active during the last glacial maximum, glacier ice from centres in central Quebec and the District of Patricia may have reached this area during the earlier part of the last glaciation. The landforms in the region, the composition of glacial drift, the behavioural characteristics of unconsolidated materials, and the glacial history of northwestern Manitoba are explained in this report in the light of this model.

General

This report and Map 1608A complete an investigation of the Quaternary geology and geomorphology of northwestern Manitoba, an area of 77 000 km^2 lying between 58° and 60°N (the Northwest Territories boundary) and 96° and 102°W (the Saskatchewan boundary) (Fig. 1). The landscape of northwestern Manitoba was shaped by the last continental glaciation and by the subsequent glacial lakes and seas which inundated parts of the region. The area includes an extensive tract of forested muskeg in the south, which passes northwards through open spruce woodlands to tundra barrens.

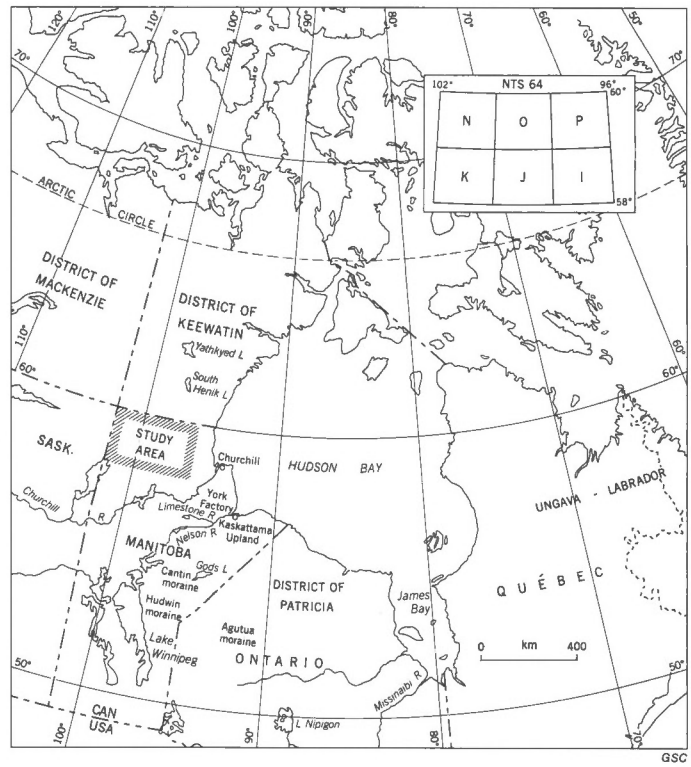


Figure 1. Location map of the study area and place names mentioned in the report.

The need for information on terrain conditions related to engineering construction and for general land use planning prompted the present study. An understanding of glacial transport of debris was also required for drift prospecting in this area where bedrock outcrop is scarce. The region is also important because its suites of deposits and landforms, its glacial and deglacial history, and its permafrost conditions are representative of conditions over much of boreal Canada – a region largely unstudied because of its difficult terrain; the results of this study can be applied to a much broader area. An understanding of the geomorphology and glacial history of this particular region is especially interesting because it lies in the heart of the former Laurentide ice sheet, but was glaciated by two confluent ice domains, which had different centres and styles of flow, within the larger ice sheet complex. The interpretation of features and the glacial history of the region is thus crucial for understanding the dynamics and structure of the North American ice sheet complex.

Fieldwork

Fieldwork was carried out in 1977 and 1980. Areal mapping was accomplished by airphoto interpretation, which was subsequently checked and refined by ground surveys. Ground investigations were made by helicopter traverses, supplemented by short foot traverses at landing sites and a boat trip down North Knife River. About 600 ground sites were examined. Mapping in the northern half and southwestern part of the field area was well controlled by airphoto interpretation, by helicopter traversing, by the examination of materials and sedimentary structures in hand-dug pits, and by laboratory analyses of samples. Mapping in the southeastern part of the area was much less well controlled because the relatively thick organic cover made both airphoto interpretation and ground mapping difficult.

Helicopter landings were restricted to small openings in the bogs, and extensive swamps limited traversing on foot. In organic terrain with permafrost, observations were restricted to samples taken by hand-boring through the peat into the mineral soil. Map unit boundaries in the muskeg-covered terrain of the map area are thus only approximate. Most river cuts in northwestern Manitoba do not penetrate the surface organic cover, but natural exposures along North and South Knife rivers yield information about both the surface deposits and the stratigraphy.

Scope of the report

Surficial geology maps at a scale of 1:250 000 have been released (Dredge and Nixon, 1981f; Nixon and Dredge, 1981; Dredge et al., 1982a, b; Nixon et al., 1982; Richardson et al., 1982). Topical reports have also been published as part of this project; they deal with till geochemistry (Dredge, 1981a, b, 1983 a, b), ice flow sequences (Dredge and Nixon, 1982), and ice recession against Lake Agassiz (Dredge and Dufour, 1977; Dredge, 1982a, 1983c; Dredge and Grant, 1982). Some aspects of glacial history and permafrost conditions pertaining to this area are covered in an unpublished report by L.A. Dredge and F.M. Nixon for northeastern Manitoba, entitled "Quaternary geology and geomorphology of northeastern Manitoba". In addition, manuscript maps from this project were used to produce parts of the surficial geology map of Manitoba (Manitoba Mineral Resources Division, 1981).

This report integrates earlier reports and provides a more comprehensive synthesis of the geomorphology and glacial geology. Map 1608A portrays nine genetic classes of surficial materials and forms the basis for the text. The report describes the physical nature and distribution of the surface materials and offers an interpretation of conditions of formation. First is a description of the physical character of the surface materials and landforms, along with laboratory data on texture and composition. The following section is an interpretation of the late Quaternary history of the region – of ice flow centres, glacial events, ice recession, and inundation of the region by postglacial lakes. The final section deals with topics of particular interest to drift prospecting, construction, and resource development.

Acknowledgments

The three authors each mapped substantial parts of northwestern Manitoba. L.A. Dredge compiled the final map and wrote this report. Field assistants were Maryann Mihychuk and Serge Paradis. We would also like to thank R.N.W. DiLabio for helpful comments resulting from critical review of this manuscript, and Erik Nielsen for interesting discussions during the course of the work.

Previous work

A number of geologists and adventurers have commented on the terrain of northwestern Manitoba, but there has been no systematic study of the geomorphology or glacial geology of the region prior to this study. Hearne (1796) explored Wolverine and Seal rivers but did not describe the landscape. In 1880 A.S. Cochrane track-surveyed what is now Cochrane River. Tyrrell (1897) and Tyrrell and Dowling (1896) canoed along Cochrane and Thlewiaza rivers in the western part of the area, and were the first and principal observers of the geomorphology of the region. Tyrrell (1897) identified the main elements of the landscape; he mentioned the swampy character of the terrain, the ice-moulded drift forms, abundant eskers, two moraines – one directly north of Reindeer Lake, the other at Blue Lake (near Fort Hall Lake), and areas of frost shattered rock. Tyrrell also found that striae trend southwest and south-southwest and concluded that they were formed by the westward extension of the Keewatin glacier. Alcock (1921) described the large hummocky sandy ridges which extend from Southern Indian Lake northward to Chipewyan Lake (58°N, 98°30'W; Fig. 2), near the southern margin of the map area. He considered them to be part of a massive terminal moraine, formed along the front of a lobed ice sheet. During the course of bedrock mapping along Seal River, Taylor (1961) encountered a subtill conglomerate bearing plant remains and suggested that these were interglacial in age. Ritchie (1962) conducted a geobotanical survey of northern Manitoba and mapped landforms and vegetation types within this study area. His landform map differs substantially from map 1608A, which accompanies this report. Klassen (in press) mapped parts of north-central Manitoba adjacent to this study area, and described the glacial history for that region; his interpretation of glacial conditions and sequence of deglacial events differ somewhat from the picture presented in this report.

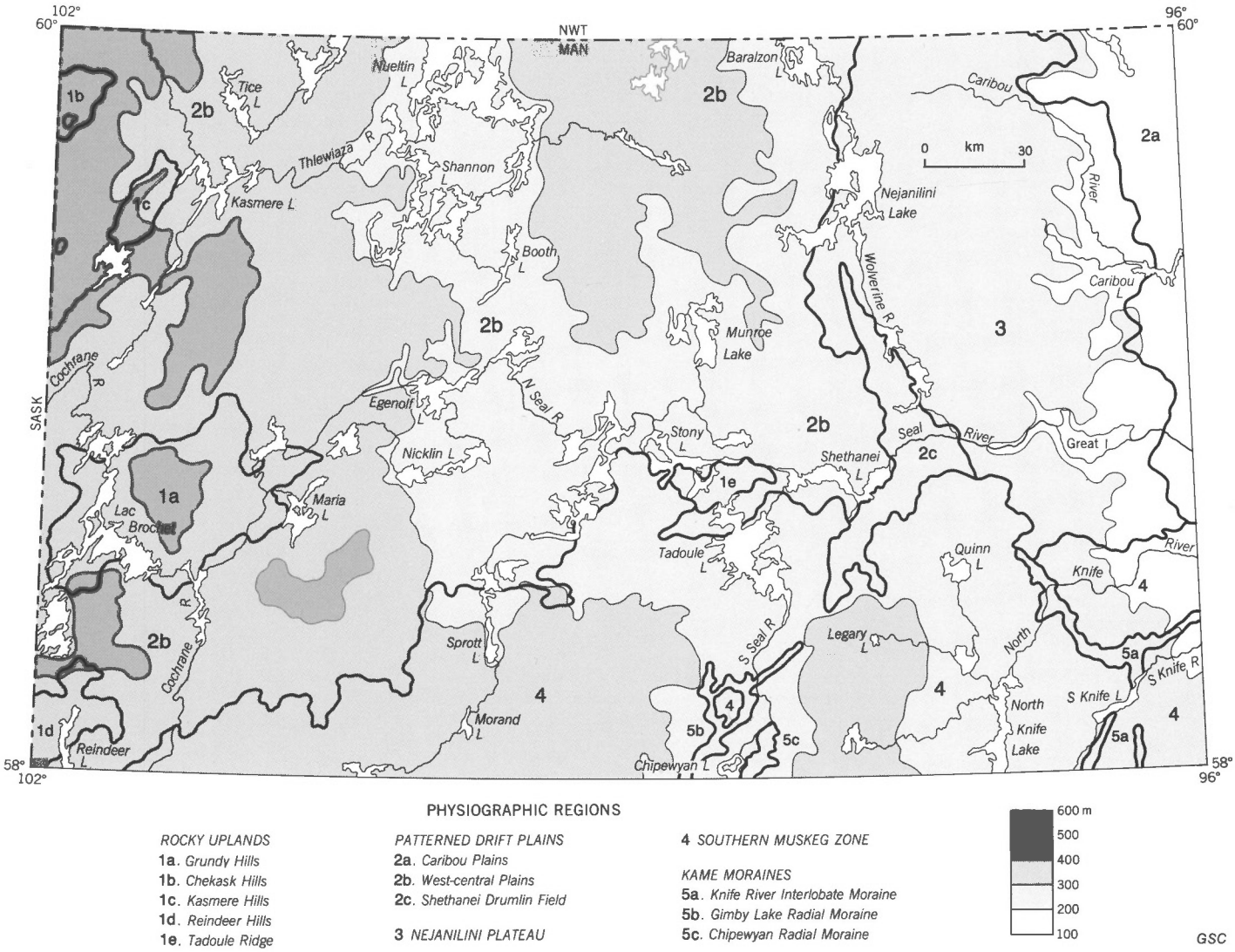
Reconnaissance bedrock geology along Seal River was conducted by Johnston (1935). Since then, the bedrock geology has been systematically mapped by Russell (1953), Taylor (1958), Currie (1961), Davison (1962, 1963, 1968) and Fraser (1962). Each geologist measured striae and made at least passing reference to Quaternary deposits. More detailed geological work and remapping of the bedrock has been undertaken by Manitoba Department of Mines (Weber et al., 1975; D.C.P. Schledewitz, personal communication, 1982).

Physiography

The entire study area consists of a broad, gently rolling lake-spattered country which Bostock (1970) has placed into the Kazan region of the Canadian Shield. The land rises steadily from 150 m above sea level in the east to about 500 m at the western extremity. Most areas are below 400 m elevation. Many of the surface features are the product of Quaternary glaciations, but these are superposed onto broad landscape elements with pre-Quaternary origins.

Bedrock topography and landforms

The study area lies within the Churchill province of the Canadian Shield. Although the region consists of geologically distinct units, the overall aspect of the landscape is that of a gently undulating plain formed of two bevelled surfaces of slightly different slope. The older surface, which dips eastwards at about 2.5 m/km is well exposed east of Nejanilini Lake. Alcock (1920) examined the character of the contact between Precambrian rocks and Paleozoic cover rocks farther south, and observed that the Precambrian surface has the same rolling relief as is shown by the present landscape. He concluded that the Precambrian surface is an ancient erosion surface, formed in pre-Paleozoic times, buried by Paleozoic sediments, and subsequently exhumed as the Paleozoic rocks were stripped away. Alcock and others have concluded that the Precambrian surface is an ancient peneplain, formed by subaerial denudation. If so, some of the rock basins, so typical of glacial erosion, may have developed during an ancient glaciation. The second surface, which has more irregularities than the older one, consists of the hills and plains west of Nejanilini Lake. Its regional slope is about 0.6 m/km. Since the surface truncates Paleozoic beds in Hudson Bay, it is probably post-Devonian in age and may have developed during the Tertiary. This surface has remnants of deep weathering exposed below drift along North Knife River.



1 ROCKY UPLANDS – (a) Grundy Hills; (b) Chekask Hills; (c) Kasmere Hills; (d) Reindeer Hills; (e) Tadoule Ridge

2 PATTERNED DRIFT PLAINS – (a) Caribou Plains; (b) West-central Plains; (c) Shethanei Drumlin Field

3 NEJANILINI PLATEAU

4 SOUTHERN MUSKEG ZONE

5 Kame Moraines – (a) Knife River Interlobate Moraine; (b) Gimby Lake Radial Moraine; (c) Chipewyan Radial Moraine

Figure 2. Topography, drainage, and physiographic regions of northwestern Manitoba.

Within the region there is a close harmony between local topography and bedrock type. The western part of the map area has a variety of rock types and local relief of 100 m. Granitic and arkosic rocks form rolling upland plains and rocky hills; volcanic and pelitic metasedimentary rocks, more easily eroded, form valleys. Extensive plains have developed over areas of uniform lithology, as in the area around Nejanilini Lake, where local bedrock relief of the granitoid gneiss seldom exceeds 5 m.

Glacial topography and landforms

Although the regional aspects of the landscape were shaped in pre-Quaternary times the details of the terrain are a product of the Quaternary glaciations.

The scouring action of ice has freshened the ancient landscape, gouging out small lake basins, smoothing some rocks and quarrying others. Rock surfaces are grooved and chipped, or striated. Most areas are drift covered – less than 2 per cent of the region is rock outcrop – and this mantle gives the landscape its surficial character. There are some areas of featureless drift blanket, spattered with a myriad of shallow lakes, where relief is commonly less than 5 m. More extensive areas consist of patterned landscapes. Belts of streamlined, fluted drift features with relief up to 10 m give the land a predominantly north-south fabric; these zones lie adjacent to contrasting areas of ribbed moraine, with similar relief, where the till ridges and intervening lake-filled depressions create an east-west fabric. The till forms are transected by numerous enormous eskers, radial kame moraines, and an interlobate kame moraine. These distinctive, sinuous features are up to 30 m high and some are continuous for over 100 km. Glacial lakes inundated the southern part of the region, infilling the underlying topography with finegrained sediment. The glacial lake basin now consists of extensive areas of muskeg, interspersed with

small De Geer moraines and cobbly to sandy beach ridges. Recent freezing and thawing has produced fields of frost-heaved blocks in bedrock areas and thermokarst depressions in areas of muskeg; these are the principal microrelief features in the region.

Drainage

Six major river systems flow through, or originate within, the region and all eventually empty into Hudson Bay. South Seal River flows northwards into Tadoule Lake and thence eastwards across the centre of the area. Generalized topographic contours for northern Manitoba show that the river flows in a major valley. This river probably has ancient origins and once drained those areas farther west which now form the headwaters of Churchill River. Cochrane River flows southwards into Reindeer Lake. Its ancestor flowed northwards into the Thlewiaza whose headwaters flow in an oversized river valley, but glacial debris has since altered the preglacial river course and created a low drainage divide. The present Thlewiaza flows north into District of Keewatin. Caribou, North Knife, and South Knife rivers flow eastwards directly into Hudson Bay. The remaining rivers flow either north or south into the Seal system.

Numerous small streams flow across the drift plains from one lake to another in a very immature drainage network or flow through muskeg areas in poorly defined channels. The landscape is riddled with lakes. The larger lakes are controlled by bedrock structure; smaller lakes occupy shallow basins in drift or lie between ridges in ribbed moraine terrain. Other minor lakes lie in small rock basins or in thermokarst depressions in muskeg.

The soils in the northern part of the area are well drained because of the sandy nature of the drift cover. Those in the southern half are poorly drained because glacial lakes have caused sediment to infill natural depressions and because fine grained tills and lacustrine sediment have created a substrate less permeable than the sandy till. The southern area is covered with muskeg.

Physiographic units

The map area can be divided into a number of physiographic units according to suites of landforms and drainage conditions. The units named herein are shown in Figure 2.

The *Grundy Hills* (1a), *Chekask Hills* (1b), *Kasmere Hills* (1c), *Reindeer Hills* (1d), and *Tadoule Ridge* (1e) are rocky uplands composed of Archean granitic gneiss. They form the highest terrain in the region (up to 540 m) and have a relief up to 100 m. Substantial areas are bare outcrop or are veneered by a thin cover of till. Areas of broken, frost-shattered rock are common. Rivers flow in rocky channels with rapids and small waterfalls. The uplands are well drained because of the topographic relief and the surface cover of sandy till.

Caribou Plains (2a) and *West-central plains* (2b) are extensive areas of patterned drift. They consist of belts of bouldery ribbed moraine having an east-west fabric, alternating with belts of sandy, drumlinized or fluted terrain with a north-south fabric. Local relief imparted by these features is about 10 m. Long sinuous eskers and radial moraines 30 m high wind through the region. Many small lakes lie within this physiographic unit, particularly between morainic ridges. The soil consists of sandy till and is well drained. The *Shethanei Drumlin Field* (2c) is a third area of patterned drift, consisting of closely spaced flutes and drumlins made of sandy till, and wedged between the Nejanilini Plateau and Southern Muskeg zone.

Nejanilini Plateau (3) is a drift-covered bedrock plain of extremely low local relief, which rises from 150 m elevation to about 280 m. The area, which lies above treeline, is part of the barren lands. It consists of a featureless till blanket covered by mudboils, a myriad of small shallow lakes with irregular outlines, an area of till plateaus, with miscellaneous small esker segments, and rock outcrop.

The *Southern Muskeg Zone* (4) is a tract of wetland with little local relief. It consists of forested bog or wet fenland underlain by either silty till or finegrained lacustrine sediment. The main relief features are the eskers and radial moraines which transect the swamps, sandy to cobbly beaches above elevations of 380 m, small De Geer moraines, and thermokarst depressions. Ground ice is abundant, and the region is poorly drained because of the low relief and impermeable substrate.

Knife River Interlobate Moraine (5a) is a prominent sandy, in a few places gravelly, arcuate ridge with several laterals, standing as much as 60 m above the surrounding swamps. It is about 1 km broad along its narrowest portion and widens in several bulbous masses to 6 km. The surface is hummocky and in places is cut by glacial ice-marginal drainage channels. The feature formed in glacial Lake Agassiz at the confluence of the Keewatin and Hudsonian ice sheets. The *Gimby* (5b) and *Chipewyan (5c) Radial Moraines* are slightly smaller features which formed in much the same manner along the edges of ice streams within the Keewatin glacier.

Climate (and its significance to surficial deposits)

The northeastern quadrant of the region lies within the subarctic climatic region, the remainder of the area in the boreal. Climate is continental in the western part of the area and becomes less extreme eastwards. The mean annual air temperature at Brochet (Reindeer Lake, directly south of the map area) is -5.2°C; daily means range from 15°C in July to -29°C in January. There are 234 days with frost. Precipitation averages 426 mm annually, of which 168 mm falls as snow. The northern part of the area is colder and drier. Records at Ennadai, about 50 km north of the Manitoba border, show the mean annual temperature there to be about 4.5 degrees lower than at Brochet; the mean annual precipitation is 140 mm less.

Many of the geomorphic features, the presence of permafrost, and the thick organic deposits which are extensive in the southern half of the region are directly related to climatic conditions:

1. The summers are sufficiently warm and humid to produce large organic accumulations, and the climate is cold enough to prevent rapid decay. The southern half of the region is extensively mantled by peat 2 to 6 m thick.
2. Low annual temperatures promote deep freezing. Permafrost is prevalent.
3. Frost cracks, ice wedges, and palsas are common features related to repeated melting and freezing of water in soils and to the development of massive ice bodies. Thermokarst depressions develop when these ice bodies melt.
4. Seasonal or diurnal freezing also promotes frost churning of soils – manifested as mudboils; and frost shattering of bedrock – manifested as rock blisters and felsenmeer.

SURFICIAL GEOLOGY

Glaciated bedrock outcrop

Lithology

Bare rock outcrop covers less than 2% of the region whereas rock, mantled by a thin veneer of till, is much more prevalent. The most extensive areas of outcrop are the hilly uplands, but smaller areas (symbolized on map 1608A) are scattered over all the region beyond the muskeg zone.

Precambrian intrusive, metasedimentary, and volcanic rocks belonging to the Churchill Structural Province of the Canadian Shield (Stockwell et al., 1970) form the basement rocks of northwestern Manitoba. (Their distribution is shown in the section on *Till geochemistry*).

The bold rounded hills of the uplands consist primarily of Archean granites and granitoid gneisses. Relief exceeds 100 m on some of these hills, although there are very few steep rock faces. More subdued hills and clusters of smaller rock knobs 2 to 3 m high, such as those west of Caribou Lake, are made of similar granitoid rocks as well as Proterozoic granites and tonalites. Rocks outcropping along river valleys and lakes in lowlands are commonly the less resistant Proterozoic pelitic gneisses and schists, metagreywackes, meta-arkoses, and metavolcanics.

A special form of isolated outcrop, and incipient form of felsenmeer (unit 1b, Map 1608A), is the rock blister (Fig. 3). These domed structures, roughly 4 m across and up to 2.5 m high, consist of bedrock sheets raised to form low mounds. They are limited to areas where bedrock exhibits horizontal fracturing and to sites where the water table is high. The development of rock blisters is associated with excessive pore pressures created during annual freeze-back (Dyke, 1979) and with ice riving. The features were observed only in the granitoid rocks of the Nejanilini plateau and nearby areas of northeastern Manitoba (L.A. Dredge and F.M. Nixon, unpublished report), although DiLabio (1978) described similar features in other rock types near Bathurst Inlet, Northwest Territories.

Abrasion and weathering

The surfaces of all outcrops are glacially scoured but small grooves are poorly defined – they are manifested as chip lines – and striae are rare. Such conditions are common in glacially abraded, medium textured, relatively hard rocks. Striae are preserved in a few places, and numerous small glacial scratches were observed on quartz grains. Rock surfaces have been roughened or pocked to several millimetres by the weathering out of ferromagnesian minerals. Spalls, flakes, and weathered rinds up to 1 cm thick are also common. Schledewitz (1977) observed deeper weathering and noted that some outcrop surfaces were "rusty orange grading to a brown inner zone extending 5 to 10 cm into the rock". The majority of the rocks are buff to pink in their unweathered state.

Striae

Although striae are not abundant, there are sufficient to determine the basic pattern and sequence of ice flow. Those west of 98°W are oriented south, south-southwest, and southwest. Crosscutting relationships, as well as the regional pattern of glacial landforms, show that the more southwesterly trending striae postdate the southerly trending ones. Most of the area east of 98°W shows striae oriented southwards and south-southeastwards. In the northeast corner of the map area, striae are oriented south, southwest, and southeast.

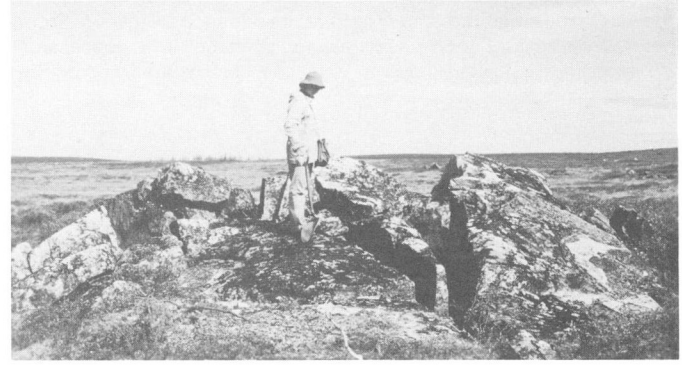


Figure 3. Rock blister. Dome with central cavity, consisting of frost-heaved slabs of jointed bedrock. Doming is caused by seasonal ice riving and build-up of excessive pore water pressures during annual freeze-back. 203121-V

The pattern suggests a principal ice flow southwards across the area, from a broad dispersal centre in the District of Mackenzie and west-central District of Keewatin. This southward flow was later replaced by a radial flow pattern; projection of striae up-ice suggests that subsequent ice flow emanated from a more restricted ice divide in central Keewatin. Final flow, affecting only the northeast corner of the study area was from a very late ice divide in southeastern Keewatin near Hudson Bay and its subsidiary limb in northern Manitoba.

In addition to this regionally consistent pattern of ice flow, there are multiple west-east trending striae and crescentic grooves on the Chekask hills. Crosscutting relationships indicate that these predate the south trending striae. They may relate to early ice flow eastwards from a divide in the south-central part of the District of Mackenzie.

Residuum

Felsenmeer

Felsenmeer occurs in small but mappable areas in the eastern part of the region (Fig. 4). These areas form the western margin of the extensive blockfield covering northeastern Manitoba. Broken rock is also prevalent throughout northwestern Manitoba (Fig. 5), north of the muskeg area, but occurs as sporadic patches too small to portray at the scale of mapping; the location of these areas of broken rock is shown more precisely by symbols on the 1:250 000 scale maps of this area (Dredge and Nixon, 1981f; Nixon and Dredge, 1981; Dredge et al., 1982a,b; Nixon et al., 1982; Richardson et al., 1982). Broken rock develops preferentially where there are homogeneous rock types (e.g. monzonites) that split along near-vertical and horizontal fractures, where bedrock lies near the surface, and where drainage is impeded. Near the northern limit of trees, broken rock thus forms irregular patches in low or swampy areas; within the boreal forest it is more commonly seen as narrow linear bands occupying slope breaks at the base of drumlins and ribbed moraines.

Individual blocks are commonly subcubic in shape, measure 0.5 to 2 m on a side, and have angular edges. Blocks are stacked about three-deep. Large interstices occur in the uppermost layer of blocks, but the blocks are more closely spaced at depth and ultimately merge into ruptured, jointed bedrock. Ground ice occupies the lowermost interstices and subjacent bedrock joints in some places. The uppermost blocks are commonly lichen covered but rarely have weathered rinds or glacial markings. Although some glacially

Figure 4. Ground view of a boulder patch or small area of frost-shattered rock near Shethanei Lake. These features lie in low wet areas, particularly along the base of drumlins. 203121-S

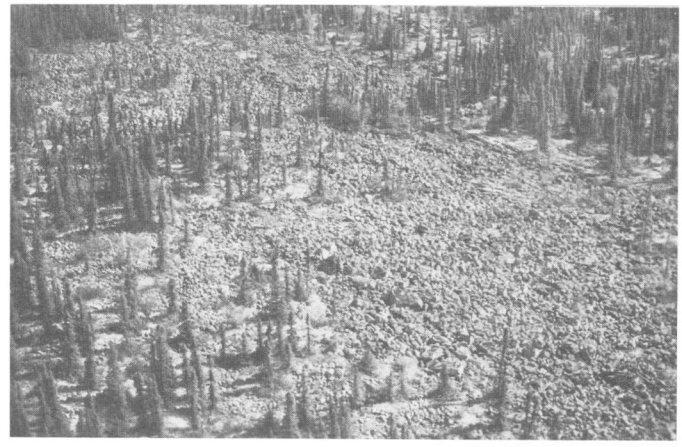


Figure 5. Felsenmeer. Fields of frost-shattered rock interspersed with till patches near Kasmere Lake. 204035-F

transported erratic blocks are present in each rock patch, the majority of blocks are of one rock type and are clearly derived directly from the underlying bedrock.

The lithic and structural nature of the block assemblages and their geographic situation suggest that they are the product of frost shattering of bedrock and are not lag concentrates of glacially transported boulders. The main processes producing fracturing of the rock are (1) the expansion caused by the transformation of water to ice, which may occur many times during a season in this area, and (2) the build up of excessive pore pressure of unfrozen water trapped in joints during annual freezeback (Dyke, 1979). Once frost shattering begins, cobbles from drift and small bedrock fragments fall down the widened joints, wedging them open so that water penetrates progressively deeper during each freezing cycle.

Frost shattering is an active process in the present environment, as indicated by climatic data and the presence of ground ice in interstices. However, the multitude of similar, only slightly abraded blocks in bouldery till suggests that subaerial frost shattering, and possibly subglacial shattering, has also occurred before or during the last glaciation, and that the rubble was subsequently incorporated into a till. The larger fields may therefore be part relict, part active features.

Saprolite and reworked saprolite

Saprolite, derived from weathering and chemical alteration of quartzose granitic metasedimentary rocks, phyllites, and diorite, appears in section along a 15 km stretch of North Knife River and in isolated patches along Seal River directly east of Great Island. The unit is about 7 m thick and is overlain by one to three tills. In a few places the rock has been altered to gruss, mainly irregular, hackly, friable pebble sized fragments of rotted diorite; more commonly it occurs as saprolite, which is softer and more cohesive. Strong hues are characteristic, mainly white, yellow-buff, orange, and blue-green. Feldspars are highly kaolinized and large crystals of muscovite are abundant. Palimpsest beds, faults, and grussified dyke rocks, remnants of the original rock structure, are still visible in the lower 3 to 4 m of sections, but in the upper part, the original saprolite has been reworked and redeposited by flowing water. Crossbeds in this uppermost unit indicate a current flowing eastwards.

Till

In northwestern Manitoba unsorted or poorly sorted glacial debris has been deposited terrestrially from ice at the front of, or beneath, moving glaciers and subaqueously beneath ice shelves. The resulting tills are widely distributed. They form the bulk of the surficial materials in the western and northeastern parts of the area and underlie muskeg, sand, and clay in the southeastern quadrant. The till varies from a patchy veneer less than 2 m in thickness to blanket deposits more than 15 m thick.

The physical character of tills in this area is controlled by the rock types over which the glacier has passed and by ice dynamics (the ice condition at the time of till incorporation or deposition): the first factor controls texture and composition; the second affects texture, compaction, sedimentary structures, and landforms of the till deposits. One ice mass in this area flowed southwards over predominantly medium textured rocks of the Precambrian Shield and produced a till with a sandy textured matrix consisting of granitic components. A second ice mass flowed westwards into the southeastern part of the map area and crossed Paleozoic limestones and dolomites in the Hudson Bay Lowland before reaching the Shield rocks which underlie the study area. The tills emplaced by this ice are finer textured and are slightly to moderately calcareous.

The surface tills mapped in this report were all deposited during the same glaciation. They have been subdivided here according to texture as sandy, bouldery, and silty tills. The textural parameter was used as the basis for subclassification because differences could be readily recognized in the field. Distinctive landforms are also associated with the bouldery and sandy tills, but morphologic expression was not used as a primary mapping criterion because the surface form of the distinctive till of eastern provenance is obscured by postglacial lacustrine deposits and thick peat accumulations. Textural differences also account for behavioural differences in tills across the region and explain differences in background trace metal levels.

Thin or patchy till deposits, mostly either sandy or bouldery till, are grouped as undifferentiated till veneer. Unmapped till units may lie within the area shown as lacustrine deposits, where peat and swamplands prevent the accurate determination of geological boundaries in the field and make photo interpretation difficult.

Tills emplaced by Keewatin Ice

Sandy till

Sandy till covers or underlies about 70% of the study area. It extensively blankets the north-central part, occurs as elongated belts within areas of predominantly bouldery till in the northwest, and underlies relatively thin lacustrine deposits in the southern half of the region.

Texture and lithology. Sandy till consists of a very sandy, olive grey matrix, with numerous abraded clasts. The till surface is also sandy, having only scattered boulders. The amount of cobble and boulder clasts in the subsurface is also small, and although there are numerous subangular pebbles, between 70 and 90% of the till mass is matrix. The average matrix texture of unreworked till is 5% granules, 67% sand, 25% silt, and 3% clay (Fig. 6). Most of the clay and some of the silt have been plastered onto the surfaces of pebbles and larger clasts. There is a wide variation in texture from one area to another, depending on what rock types were incorporated, what older Quaternary deposits were overrun, the manner of deposition of the till, and the extent of reworking by postglacial processes. Textures range between 2 and 11% granules, 40 and 76% sand, 19 and 34% silt, and 1 and 8% clay.

Tills south of Seal River lying between 370 m and 442 m elevation have had their upper parts altered by waves and currents in the postglacial lake that inundated the area. The main effects of the lake have been to remobilize some of the silts and redeposit them in topographic lows, to create a lag concentration of pebbles and boulders, and to redeposit some of the till as subhorizontally stratified sediment. The reworking does not extend below a depth of about 2 m.

The till consists of the glacial comminution products of the granitic, metasedimentary, and metavolcanic rocks which are prevalent in the region. Because the majority of the rocks are medium textured, they comminute into a sandy textured till by breaking first along joints and structural weaknesses, and then along mineral grains. The silt fraction is supplied in part by the pelitic gneisses and schists which break down into finer sizes than granites and monzonites; additional fines are derived from the abrasion of individual mineral grains from all rock types into rock flour, and from the overriding of older silty tills (e.g., at Gimby Lake) and glaciolacustrine silts (e.g., Shethanei Lake).

The granitic character of the parent rocks produces a till rich in quartz, feldspar, and amphibole, with lesser amounts of other minerals, and traces of base metal sulphides. Because considerable mixing of near and far-travelled debris occurred during transport, it is difficult to determine the source rocks of any given till sample. The tracing of garnets to their parent outcrops, however, has shown that much of the till in fluted terrain, at least in the area of Burnie Lake, has not been transported more than 8 km from its rock source (Dredge, 1981a).

Density and compaction. The till density ranges from loose to compact, but loose (basal ablation) till is more common. No density measurements were made but the ease with which these tills were dug by hand indicates that there is a high volume of voids in the till. The till may thus have a substantially lower normal strength under saturated conditions (e.g., in wet depressions or during snowmelt) than would otherwise be expected from a granular deposit.

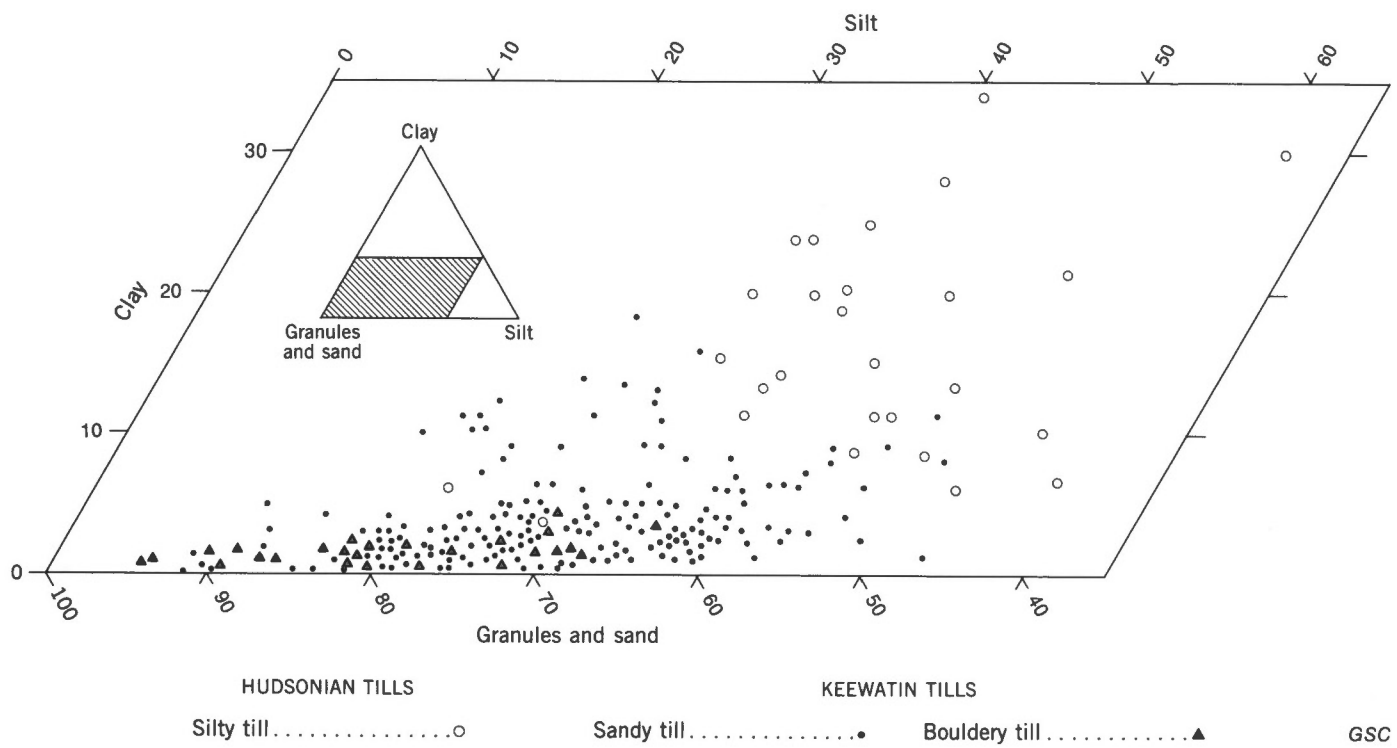


Figure 6. Till texture. Ternary diagram shows matrix textures for till of Keewatin and Hudsonian provenance.

Sedimentary structures. Although some truly diamictic material was encountered, most of the till is laced with sedimentary structures which indicate deposition in the presence of abundant (mostly nonchannelled) meltwater (Fig. 7). Small discontinuous sorted beds, stringers of silt, and sandy crossbeds continuous for distances of 10 to 20 cm are common structures. These, combined with the relatively loose density, suggest that much of the till is ablation till, emplaced by basal meltout. There may also be substantial amounts of supraglacial ablation till, although large-scale slough structures typical of flow tills were not observed.

In addition to the structural variations created by the reworking of till by waves and currents, discussed under texture, the sandy till is one component of De Geer moraines (see *Glaciolacustrine deposits*). These consist of beds and laminae of sandy till, partly current bedded, intercalated with lacustrine deposits.

Landforms. Although some areas of sandy till have been grouped into the undifferentiated till veneer unit, sandy till usually totally masks the underlying bedrock. It is commonly at least 2 m thick, and the thickness in some places may exceed 20 m. A gently rolling till plain, interrupted by small shallow lakes, covers an extensive area of barrens east and southeast of Nejanilini Lake (64 P) and south of Blevins Lake (64 O) (Fig. 8, 9). Solifluction lobes and terracettes drape the hillslopes and active mudboils, each 0.5 to 1 m across, are ubiquitous. The mudboils and corresponding stony earth circles which lie in the shallow margins of lakes attest to the activeness of frost churning. Active mudboils are also common on till plains below treeline (Fig. 10) but are obscured by the surrounding vegetative cover.

Most sandy till is fluted, although true drumlin shapes are scarce; many fluted features are extremely elongated forms 1 to 2 km in length, with slopes gently inclined both up- and down-ice. An average height is 12 to 15 m. In places, fluted features are gradational with ribbed moraine, and some are horned or lunate, rather than linear. Although fluted features are distributed more or less evenly in the west, there are swarms of flutings directly west and east of Nejanilini Lake and an offset series from Nejanilini Lake to the southern border of the map area. If streamlined forms are indicative of energetic, mobile ice, then these swarms denote zones of very active late glacial ice flow within a generally less active ice mass. The relatively energetic flow may be a response to (1) the southerly and easterly migration of the Keewatin ice divide (Dredge, 1982; Map 1608A) or to (2) instability associated either with marginal surges into glacial lakes or with build up of basal pore pressures behind the ice margin.

A cluster of till plateaus lies on the height of land (275 m) 10 to 15 km southeast of Nejanilini Lake (64 P). These roughly circular mounds, each 100 to 200 m across, have peripheral rims standing about 5 to 8 m above the surrounding till plain, and concave upward centres. The origin of the forms in this area is unclear but similar features in Alberta described by Stalker (1960) are attributed to the squeezing of saturated till into subglacial cavities in a disintegrating ice sheet. If that genesis is applicable to the plateaus in northwestern Manitoba, the area east of Nejanilini may have supported a late, remnant stagnating ice mass.

End moraines, particularly those characterized by distinct ridges, are rare in this area. A few classic moraines, such as that forming the southern margin of Munroe Lake, are present but for the most part the end moraines shown on the maps are very broad swells in the landscape and have poorly defined limits. These ridges rise 10 to 20 m over several kilometres. The moraine south of Munroe Lake and the multicrested moraine due east of Shethanei Lake may mark short readvances during recession. The short morainic segments scattered elsewhere over the region and the set of broad-crested ridges between Tadoule Lake and Lac Brochet probably reflect simple recessional slow-downs. The diffuse nature of these moraines may be indicative of their

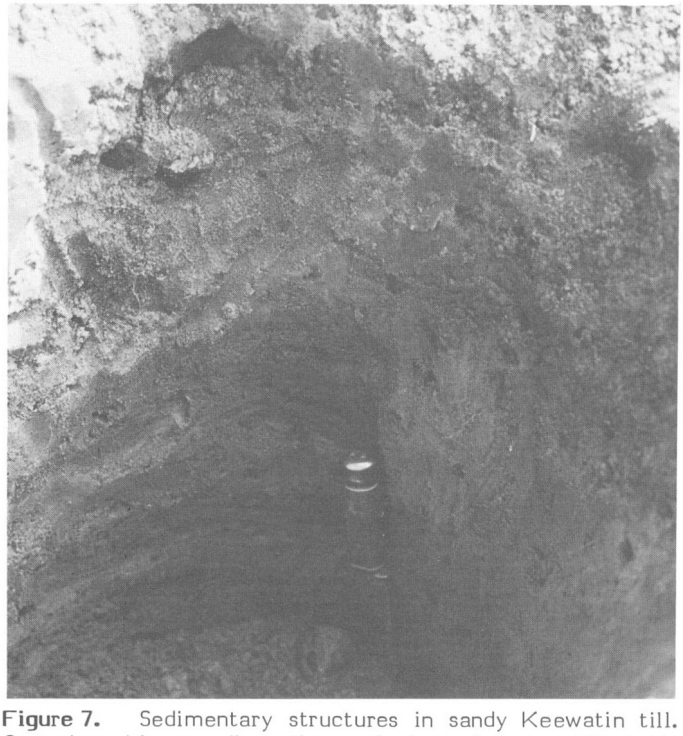


Figure 7. Sedimentary structures in sandy Keewatin till. Sorted sand lenses, discontinuous beds, and zones with ripple drift laminae characterize this basal meltout till. 204034-H

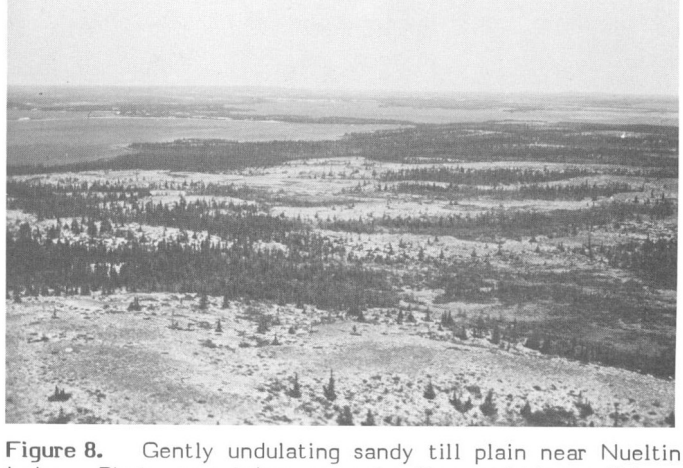


Figure 8. Gently undulating sandy till plain near Nueltin Lake. Photo was taken near treeline and shows lichen-covered till barrens, open woodlands, and patches of thin tundra peat in depressions. 204035-A

formation in Lake Agassiz or of the inability of the late Keewatin glacier to bulldoze material or to transport material in shear planes to the snout of the glacier.

De Geer moraines are also made of sandy till and are discussed under *Glaciolacustrine deposits*.

Bouldery till

Composition and texture. The bouldery till unit, which is a coarse lateral equivalent of the sandy till unit, covers about 13 000 km^2 or 17% or the map area. It occupies the northeastern corner of the region and much of the northwestern quadrant. In the east the unit is interrupted by belts of conjugate ridges (crevasse fillings); in the west it is interrupted by belts of fluted sandy till. Like the sandy till, bouldery till is derived from Precambrian granites and gneissic rocks entrained by southward flowing Keewatin ice. However, there is a close spatial relationship between bouldery till and broken rock (unit 1b, Map 1608A). The till consists of cobbles and boulders in a stony, olive grey gritty sand matrix (Fig. 11, 12), and it is the abundance of large clasts in the till that distinguishes it from its sandy till counterpart, which is relatively boulder poor. In general the boulder-sized clasts appear to be abraded, slightly rounded joint block fragments which may have existed as shattered bedrock prior to incorporation into the till mass. Smaller clasts in the till and the till matrix are derived from the direct abrasion of bedrock and from further comminution of the rock rubble. There is a substantial silt component but extremely low clay content; most of the silt is stuck onto the larger clasts.

Typical textures for the till matrix are 13% granules, 65% sand, 20% silt, and 2% clay. The range in texture is shown in Figure 6. The matrix is essentially that of sandy till except for a higher percentage of granules. The boulder content is much higher than for sandy till although there is a substantial variation. In some places the till has only a moderate amount of boulders (and approaches a sandy till), whereas in others it is composed almost entirely of bouldery rock blocks. In addition, where ribbed moraine lies below the limit of postglacial marine submergence, the surface of the till is boulder-amoured.

The texture gives some clue to the origin of the bouldery till: either (and in some cases, definitely) it consists of previously frost-shattered broken rock, abraded and slightly rounded from glacial transport; or blocks of coherent bedrock were entrained and deposited before they could be comminuted to their terminal mineral grades in the silt and sand sizes. In either case, the bouldery texture indicates that comminution was limited and that ice flow was more restricted than in areas with sandy till. Its association with transverse landforms (described below) suggests that there may have been high basal shear stress.

Landforms associated with bouldery till and the relation to those in sandy till. Bouldery till areas form rough terrain with a pronounced east-west fabric of ribbed moraine and intervening elongated lakes (Fig. 13).

Ribbed moraines have an ENE-WSW orientation in the eastern part of the map area, and a slight WNW-ESE orientation in the northwestern part. The individual ribs are slightly sinuous and vary from 4 to 8 m in height, 200 to 250 m in width, and 500m to 1 km in length. The ends of one rib merge with adjacent ridges. The cross-sectional form is asymmetric: northern (proximal) slopes are gentle, whereas southern slopes are relatively steep. Ribs are commonly spaced 200 to 300 m apart and shallow lakes occupy the low areas between ribs. The surfaces of many ribs are fluted perpendicular to the axis of the ridge, and where fluting is prevalent, some ribs grade into "crescentic drumlins" and thence into ice-parallel fluted features.

The presence of fluting on ribs and gradation of features suggests that (1) ribbed moraine is a bed form, not an ice marginal feature and that (2) the two bed types were created contemporaneously by ice whose base had zones of varying mobility or load-carrying capabilities. In ribbed moraine areas the ice was less plastic, probably relatively slow moving, and had sufficiently high basal shear to create transverse landforms. The additional association of ribbed moraine with adjacent conjugate crevasse fillings near Caribou Lake in the northeast suggests that those ribs were formed late in the glaciation where drift had concentrated along shear planes in a relatively thin brittle ice sheet.

In some places, particularly where the bouldery till unit grades into rock rubble, well formed ribs are replaced by low knolls, irregularly shaped but generally elongate in an east-west direction. The "till" in these areas has little matrix and consists primarily of broken rock, shoved into piles by the overriding ice sheet.

Figure 9. Sandy Keewatin till has a regular, sandy surface aspect, with scattered boulders. Compare with Figure 12. 204035-Z

Figure 10. Active mudboil in sandy till near Stony Lake. These features are common in areas of continuous and discontinuous permafrost, both above and below treeline. Light spot in centre of mudboil marks the vent through which mud was recently ejected. 203992-N

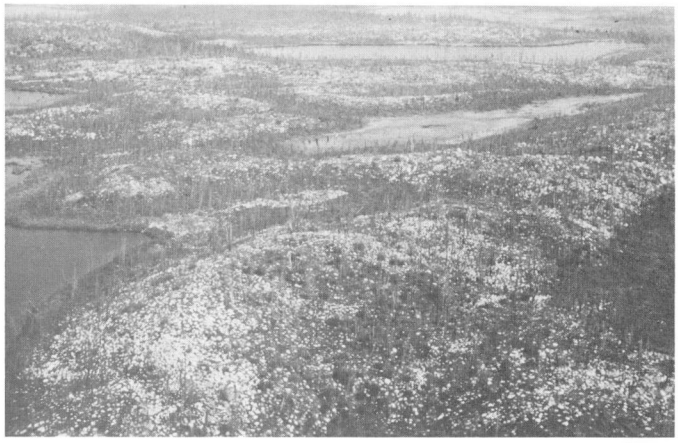


Figure 11. Aerial view of bouldery till, Tice Lake area. Note irregular, heavily boulder strewn till ridges, and intervening lakes and swamps. 204034-W

Figure 12. Ground view of surface of bouldery till. Although the matrix is sandy, the percentage of abraded boulders is much greater than for sandy till. Compare with Figure 9. 204035-B

Periglacial processes are active in the upper metre of the till in northeastern areas, and the till surface is commonly strewn with mudboils; there are fewer mudboils in the northwest.

Till veneer

Areas of till veneer are gradational with thick sandy or bouldery till units described above and with bedrock outcrop. The till veneer is thin (1 to 2 m thick) and patchy; the till veneer unit may also contain knobs of bare rock and depressions infilled with thick drift. The till surfaces in veneer areas mimic the bedrock topography, and rock structure is clearly visible on airphotos.

Figure 13. Ribbed moraine landscape, consisting of arcing, partly fluted ridges of bouldery till, and intervening lake-filled depressions. 204035-C

Tills emplaced by Hudsonian Ice

Silty till

Silty till was deposited by ice moving westwards out of, or across Hudson Bay. Since the ice crossed Paleozic carbonate terrain before reaching the Shield rocks which underlie northwestern Manitoba, the tills are finer and more calcareous than the Keewatin tills. Silty till is confined principally to the southeastern corner of the map area, east of North Knife Lake and south of North Knife River. It underlies forested bog and thin to thick glaciolacustrine deposits and is observed in sections along both North and South Knife rivers. Along North Knife River the silt till interfingers with sandy Keewatin till. Silty till is also encountered below sandy till in sections near Chipewyan Lake.

Texture and composition. The silty till consists of one to five sheets, each 2 to 6 m thick, separated by thin beds of sand and gravel. The tills are greyish, slightly to moderately calcareous, relatively stone-free, and have a silty sand matrix. The average grain size is 2% granules, 40% sand, 38% silt, and 20% clay. The relatively high percentage of fines compared with the sandy till results from the comminution of less resistant and finer textured sedimentary rocks. There is a slight systematic decrease in silt and clay from east to west but this trend is not as distinctive as for matrix carbonate contents (below).

Most clasts are in the pebble size range. These consist largely of the nearby Shield rock types, but because the ice also crossed carbonate rock, there are substantial amounts of limestone and dolomite pebbles. The silty tills are sparsely fossiliferous; they contain Paleozoic fossils and Quaternary marine shell chips. The Quaternary shell fragments were incorporated into the till at one or more times when Hudsonian ice overran nonglacial marine deposits in Hudson Bay. The average carbonate content of the <2 mm fraction of the till, determined by acid digestion, is about 12%, but values range between 5 and 46%. Carbonate content is highest along the eastern margin of the region and decreases towards the west, as the ice progressively entrained and deposited increasing amounts of local granitic rock and lost carbonate through deposition of its load. Carbonate has been subsequently leached out of the till during the postglacial period. The depth of carbonate depletion is 0.6 m for till in permafrost and up to 3 m in till in nonpermafrost terrain (Dredge, 1981b).

Colour, texture and structural differences in the various silty till sheets. The uppermost till is red-brown to buff, moderately plastic, contains granule-sized mud peds, and in places exhibits subparallel horizontal stratification. The upper part of this till sheet was probably deposited from the base of the Hudsonian ice sheet into the proglacial lake that developed as the ice sheets receded. It grades into the basal facies of the glaciolacustrine sediments (unit 5a). The origin of the red colouration is unknown; it may relate to red source rocks in central Hudson Bay, or to oxidation of iron colloids as particles settled through the water column.

The lower till units are grey to black and show little sign of water sorting. They are more compact than the upper till and have a blocky structure. The stratigraphically higher of these tills have closely spaced unoxidized joints, and the till blocks break into hackly, pebble-sized fragments. Tills lower down have wider joint spacing and are more intensely oxidized along joint planes; the lowermost till cleaves into blocks about 20 cm wide and has heavily stained, irridescent weathered joint surfaces.

Landforms. The surface form of the silty till has been muted somewhat by the glaciolacustrine deposits and muskeg which mantle most of the original relief. Auger holes and river exposures indicate, however, that the till surface forms a plain with little local relief – a marked contrast to the ribbed moraine and fluted terrain associated with the bouldery and sandy till. The generally flat surface aspect, at least of the uppermost silty till sheet and possibly lower tills as well, may be due in part to the deformability of the wet, silt-sized debris which was deposited from the glacier. But the flat topographic aspect is probably also related to (1) the highly plastic nature of the Hudsonian ice mass and (2) to relatively low shear stress at the base of this glacier. The low basal shear stress is possibly due in part to glacier flow and deposition over previous tills with little shear resistance and only moderately resistant Paleozoic sedimentary rocks. It is also related to the depositional conditions of the till during ice recession: much of the till was deposited as loose basal ablation till near the front of an ice mass which was buoyed up by a proglacial lake. Some of the till grades upwards into a waterlaid till and thence into glaciolacustrine deposits.

Within the ground moraine of the silty till are a number of low swells with broad, even crests. A few of these lie at the southeastern corner of the map area, and others are found outside the study area in northeastern Manitoba between Little Churchill River and Hudson Bay. These features are most likely grounding line moraines.

Glaciofluvial deposits

Glaciofluvial deposits cover only a small part of the map area but are significant because they contain large volumes of sand and gravel, because they form prominent landforms, and because they provide passageways across the muskeg which is so prevalent in the region. The principal glaciofluvial deposits are crevasse fillings; interlobate, radial and lateral kame moraines; eskers; and outwash. These deposits belong to a facies continuum reflecting progressively increasing effects of running water. Alluvium, an end member, is discussed as a separate unit. The glaciofluvial deposits all belong to the Keewatin ice regime and are a reflection of the abundance and importance of running water within the ice during the late stages of glaciation.

The location of major kame and esker deposits bears little relation to the modern drainage pattern, and they commonly cut across the path of present day streams. Outwash, in contrast, lies below and along the flanks of modern streams and commonly forms their antecedents.

Permafrost is not generally associated with these deposits; however, differential surface water levels of lakes lying on opposite sides of some eskers suggest that these ridges may have a permafrost core and ground ice which inhibits drainage through otherwise permeable materials.

Crevasse fillings

Crevasse fillings occur as: (1) infrequent but areally extensive belts of conjugate ridges between till units in the northeastern part of the region (Map 1608A) and as (2) smaller but more common units spaced at intervals along eskers over the rest of the area.

The conjugate ridges occur in several belts about 15-20 km long and 1 to 2 km wide. These trend south-southeast in the Caribou River area, but those farther west are oriented north-south. Unit boundaries are abrupt and form an areal pattern consisting of linear segments which intersect at acute angles.

Hummocky topography is created by sets of reticulated ridges, the largest of which are about 5 m high. They consist of a combination of sandy to bouldery till, and poorly stratified or discontinuously stratified water sorted sand and gravel. Between the larger ridges are reticulated sets of smaller ridges, which are composed of finer and better sorted sediment.

The sediment was deposited as the till flowed or was dumped into crevasses or fractures in brittle, thin, decaying ice. Stagnation occurred over an extensive area, not solely at the ice margin. The presence of large ridges with inset smaller features indicates that in situ downwasting occurred, the smaller ridges being formed by lowering and progressive fracturing of the ice, accompanied by the availability of increasing amounts of meltwater. The proximity of these belts to fluted ribbed moraine and sandy till suggests that adjacent parts of the ice were still plastic when these features formed.

Crevasse fillings are more common as nodes along eskers. At these locations the main esker ridge separates into a honeycomb of ridges, again consisting of a primary set of large reticulated ridges, with second order and third order sets of smaller features. In this setting the crevasse fillings consist principally of sand, although some gravel may be present, and they mirror the pattern of fractures at the ice margin (Fig. 14) or at isolated locations behind the margin where the ice forming the roof of the esker was thin.

Kames and eskers

Kames and eskers are the most prominent features in the landscape, forming continuous ridges up to 100 km long. Both features formed in a similar manner in channels on, or tunnels in, the ice. In the southern half of the map area large quantities of sediment were deposited from these conduits into proglacial Lake Agassiz. North of the lake, sedimentation was subaerial or subglacial. The features consist primarily of sand. Their presence and sedimentary character indicate the abundance of meltwater flowing within the Late Wisconsinan Keewatin ice sheet.

Isolated kames occur as hummocky mounts of poorly stratified sand and sandy till, generally 4 to 5 m high. They occur primarily in the north-central part of the region in association with eskers and outwash deposits.

Interlobate kame moraine

The most massive feature of the landscape is the Knife River Interlobate Moraine, composed of a series of discontinuous, broad ridge segments of partly stratified sand,

Figure 14. Network of crevasse fillings, composed mainly of stratified sand, reflects pattern of glacial fracture near the ice margin. Apron of proglacial outwash in background. 203121

gravelly sand, or washed till. Each segment varies in length (3 to 12 km), height (10 to 60 m) and width (1 to 4 km). The moraine, an extension of the Burntwood-Etawney Moraine in central Manitoba (Klassen, 1983; in press) continues northwards about 40 km from South Knife Lake. It then swings eastwards, and is traceable almost to Churchill. Where it is largest it forms a massive elongated arcuate mound approaching 60 m in height and 5 km in width; the surface here is hummocky and has been incised in places by meltwater channels. Scattered sections show that the internal composition of the moraine consists primarily of tabular beds and crossbeds of sand, with small amounts of fine gravel; no consistent current direction could be determined. Some segments of this moraine may also be composed of till.

Ice flow patterns indicate that the feature marks the position of confluence of the Keewatin and Hudsonian ice masses. The moraine formed in segments along a major line of weakness, slower flow, and thin ice within the North American ice sheet complex. Although the bulk of the feature was created during deglaciation, some segments, especially those with a till core, may have formed along the zone of flow convergence over a longer period of time.

Radial and lateral (ice-marginal) kame moraines, and eskers

Other kame moraines and eskers form prominent broad-crested hummocky ridges which snake across both till plains and lake basins. They are commonly 20 to 30 m in height, 50 to 200 m in breadth, and from 10 to over 100 km in length. They consist primarily of sand, with some zones of gravel or sandy till. The features formed towards the close of glaciation along lines of weakness in the deactivating Keewatin glacier where meltwater flowed in an organized network englacially or in open channels within the ice. The radial moraines and some of the eskers were deposited where sediment-laden meltwater debouched into the glacial lake which spread progressively northwards as the ice front receded.

The two largest radial moraines lie in the south central-part of the field area east and west of the South Seal River. They are massive hummocky deposits (Fig. 15) each about 40 km long. Alcock (1921) described these features and assumed that they were ice front terminal moraines. However, we consider them to be radial moraines, formed at right angles to the ice margin. They consist primarily of sand, in places with gently sloping planar beds of deltaic sand having ripple drift crossbeds. They developed along the edges of ice streams within the Keewatin glacier, where 1) the ice was relatively thin or slower flowing than in the central parts of the ice streams, which had more vigorous flow and 2) where there was a hydraulic drawdown. The features are extremely sandy, and in section are composed of overlapping, gently sloping tabular beds of medium to fine sand having internal ripple drift crossbeds which indicate current flow southwards. The occurrence of deltaic beds indicates that parts of these large features were deposited where sediment-laden meltwater debouched into Lake Agassiz.

Associated with these radial kame moraines (and also with some eskers) are ice marginal kame moraines, which extend as stubby wings outwards from the main radial ridges. These features, identical in composition to radial moraines, lie parallel to former ice margins and mark short halts in the recession of the ice sheet.

Thirteen regularly spaced esker systems, most with tributaries, fan out across the map area. In the western half of the region the eskers trend towards the southwest. In the southeastern part they are oriented south or southeast, but change direction abruptly north of 59°15'N. These features are similar in size to the radial moraines, but are much longer. Some eskers consist of multiple intertwining ridges. Their crests are broad in some places (Fig. 16), sharp in others; sideslopes are commonly steep. They are composed primarily of massive or crossbedded sand and are thus much finer textured than typical eskers. Where the surface has been reworked by waves in Lake Agassiz, beach ridges and lacustrine blanket deposits mantle the unmodified core. The esker ridges are interrupted by crevasse fillings, hummocky beads, and delta pads (Fig. 17). The delta pads are aprons of fine to medium, well stratified sand which extend outwards from the main ridge (Fig. 16, 17). The pad is generally flat-topped, but foreslopes are steep and 10 to 20 m high. The form and internal sedimentary structures of these pads suggest that they are subaqueous deposits, formed where sediment emptied into the glacial lake (Fig. 18). Strings of closely spaced deltas, separated by esker segments, developed as the ice front receded. The locations of these pads along eskers mark successive (summer?) periods of rapid sedimentation, but because the roof of the esker conduit lay below the lake surface, the elevations of the delta pads do not relate to lake levels.

The regular spacing and length of the eskers suggest that there was a well formed hydraulic geometry and gradient within the ice mass, and that the drainage network persisted for a substantial period of time (decades or centuries?). The esker tunnels may have been maintained well behind the ice margin, where transverse and longitudinal bedforms indicate that the ice mass was actively flowing.

The change in orientation of eskers from south to north suggests that there was a corresponding change in orientation of the ice marign, and thus the hydraulic gradient. At the beginning of deglaciation the ice margin arced across the southern part of the area, with an overall east-west trend. When the major doglegs developed, however, the ice margin must have receded to the northeastern quadrant of the map area and trended northwest-southeast. The increased number of tributary eskers in the northern part of the region reflects decreased plasticity of the ice and increasing amounts of englacial or supraglacial meltwater; they are preserved because the receding ice mass was becoming stagnant.

Figure 15

Hummocky, multi-ridged Gimby Lake radial moraine, composed of stratified sand, marks the line of convergence between two ice streams in the Keewatin glacier. It bifurcates into two esker systems (top). Much of the feature was deposited from conduits as the ice receded against Lake Agassiz. Also shown are small subglacial meltwater channels, and peat-mantled lacustrine pelite which covers most of this area. (NAPL A14990-9)

Outwash

Outwash is of limited extent in this region and is of variable character. Most outwash occurs as gravelly terrace or channel bottom deposits flanking eskers or linking esker segments. In a few cases, such as north of Ducharme Lake, the deposits are subaqueous, being deposited from eskerine systems into a proglacial lake. Such deposits are extensive, sandy, and stratified into low angle planar beds. Outwash was deposited subaerially into two deeply incised meltwater channels at 58°15'N, 100°W (Fig. 19). These channels carried water and sediment from a glacier on the uplands at about 420 m elevation and dumped it into Lake Agassiz, which at the time stood at 377 m. Most of the outwash is coarse grained and the bottom of the channel is boulder armoured, but where the sediment entered the lake the outwash grades into finer deltaic sand.

Five subaerial outwash fans were identified within the region. These typically have a steep bouldery ice contact slope standing 8 to 10 m high. The distal margin of the fan is commonly less than 1 m thick and grades to gravelly sand. Apron surfaces are pitted with kettle holes and incised with shallow braided channels.

Outwash predating the last glaciation was identified at several riverbank exposures. Outcrops of muddy cobbly gravel, generally well rounded and crossbedded with sands, appear beneath one or more tills in sections along North Knife River. In some places the uppermost part of the gravel is oxidized and rubified (i.e. reddened profoundly by iron accumulation and oxidation). The degree of oxidation indicates that a soil formed on this material after its deposition, during a warm period predating the last glaciation.

Glaciolacustrine and lacustrine deposits

A substantial part of northwestern Manitoba, especially areas south of Seal River, was inundated by glacial lakes which expanded against the receding ice fronts as long as natural drainage to the north and east was blocked by the Keewatin and Hudsonian ice masses. The deposits left on the bottom of the lakes range from waterlaid till and the glaciofluvial sediments described earlier, to massive pelite and blanket sands. Lacustrine deposits associated with Lake Agassiz form an almost continuous cover over the southern 30% of the region, and deposits associated with

Figure 16. Sandy, gently convex surface of typical 20 m-high esker ridge. Texture of the deposits and broad form are typical of eskers deposited from conduits which emptied into glacial Lake Agassiz. 204034-J

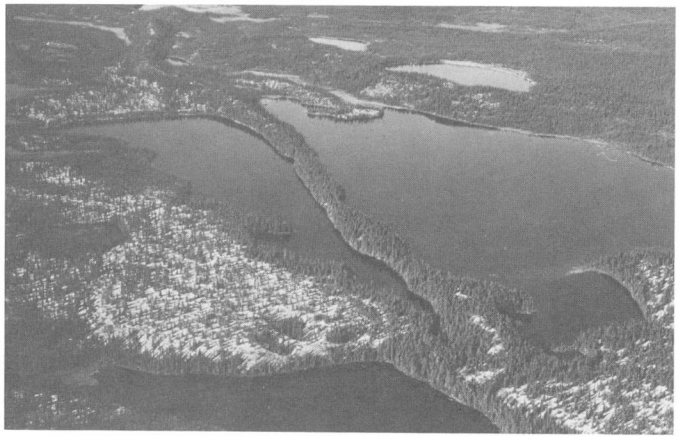


Figure 17. Esker ridge and lateral delta pad. Ice proximal side of the pad is kettled. Slightly older delta pad occurs in the background. 203797-I

smaller isolated glacial lakes north of the Agassiz limit cover an additional 5%. Although Lake Agassiz covered the southern half of the region, true lacustrine deposits are restricted to elevations below about 400 m. Above this elevation, the main effect of the lake was to winnow and slightly rework the upper metre of the sandy till and to construct isolated strandlines. It should be pointed out that some segments of eskers, delta pads, and radial and interlobate moraines were also deposited in the lake basin and are glaciolacustrine deposits in the broad sense.

The deposits of Lake Agassiz are sparsely fossiliferous. Diatoms were found in fine grained sediment at a number of localities in the central part of the lake basin, and gastropods were found at Mountain Rapids, several kilometres east of the eastern limit of the map area. Table 1 lists the diatom species found in northwestern Manitoba.

Glaciolacustrine deposits

Underlying the littoral sands and silty pelite, and occurring at the surface in isolated areas, are mixed glaciolacustrine deposits consisting of interstratified till and lacustrine sediment.

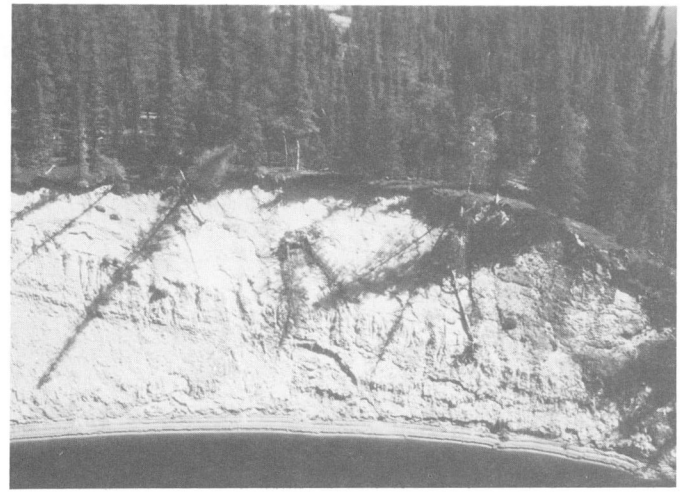


Figure 18. Cross-section of esker ridge, showing foreset beds of medium to fine sand; bluff is 25 m high. 204034-F

The glaciolacustrine deposits laid down by Hudsonian ice are calcareous, silty diamictons that differ markedly from the underlying silty till because of their characteristic brown colour and their sedimentary structures. The glaciolacustrine deposits are truly diamictic in some places but grade into poorly stratified or discontinuously stratified beds over short distances. The diamicton is slightly compact, has horizontal fissility and crumbles easily into pea-sized fragments. These deposits are waterlaid till, deposited beneath or near the floating edge of the Hudsonian ice mass, slugs of flow till deposited where slurries of watery sediment sloughed off the surface of the ice into the lake, and turbidites. This unit is only recognizable in section.

Glaciolacustrine material associated with Keewatin ice is found in section below lacustrine pelite and at the surface in the south-central and southeastern part of the region. It consists of sandy till, interfingering with, and grading both vertically and laterally into, sand and silt. The sand in this situation commonly displays current bedding. The distinctive morphological features of this unit are De Geer moraines (Fig. 20); typical moraines are about 5 m high and 1 to 2 km long. They consist of the interstratified till and lacustrine sediment and are capped by a sand or clay veneer. Along a 100 km-long north-south profile across the Lake Agassiz basin there are 132 moraines. These ridges were produced by seasonal advances during glacier recession. Their distribution in the area marks the pattern and rate of retreat in areas where the Keewatin ice front terminated in deep water.

Mudboils are prevalent on areas of fine grained sediment between De Geer ridges.

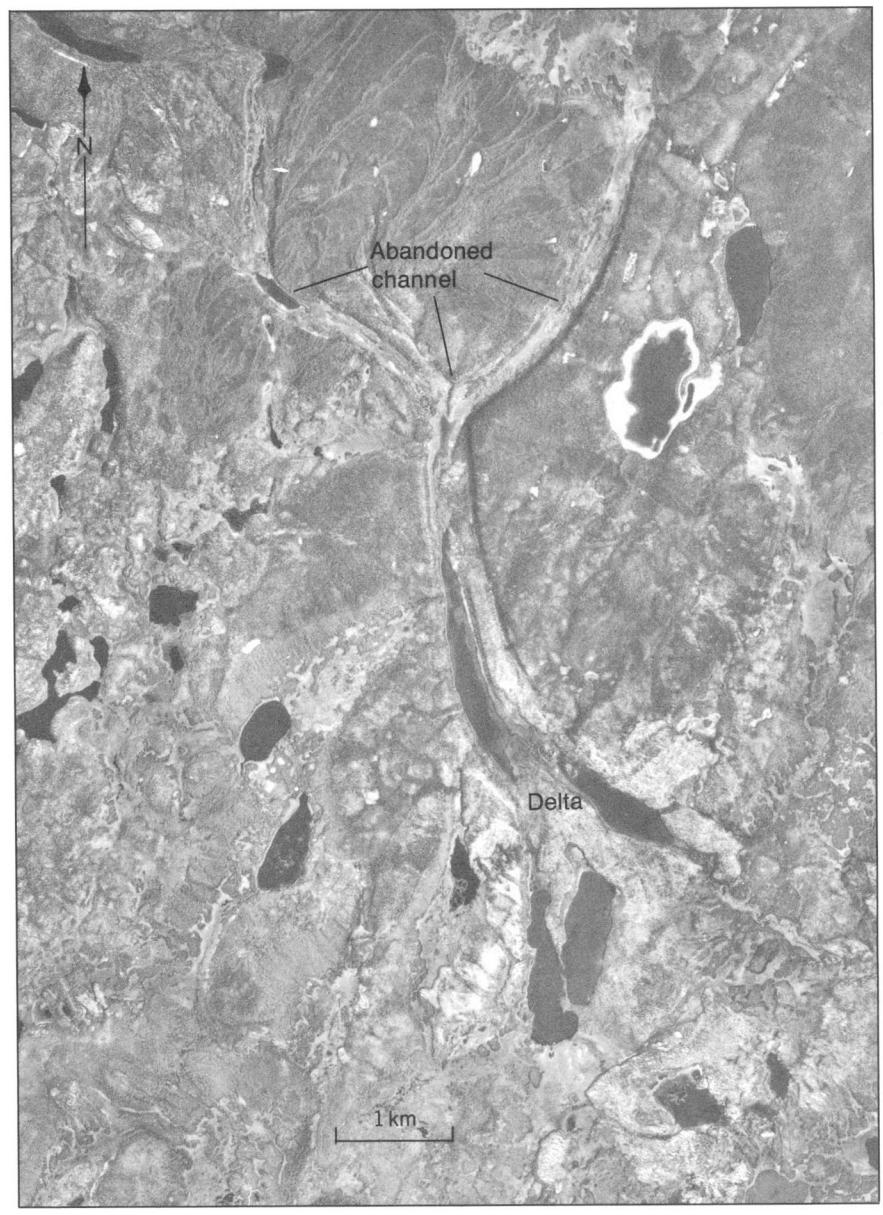
Lacustrine pelite

The term *pelite*, as used in this report, is a textural term referring to materials consisting of silt- and clay-sized particles, and having minor amounts of sand. Lacustrine pelite is the principal lacustrine material below 335 m elevation, and forms an extensive blanket east of Kinsman Lake. The blanket exceeds 3 m in thickness and mantles till, glaciolacustrine sediment, and some glaciofluvial deposits; it is overlain in turn by forested bog and fen peat.

Fine grained sediments were deposited into the lake basin as suspended sediment beyond the direct influence of glacial ice. They consist of stiff clay-silt or silty clay, with granules of rock and mud pellets. The average texture of the

Figure 19

Incised meltwater channels (arrows) and delta created where sediment-laden meltwater emptied into Lake Agassiz during the Money Lake phase. The channel bottom is armoured with boulders. NAPL A14977-51



pelite in this region is 30% sand, 40% silt, and 30% clay but there is a substantial range of texture from site to site: (sand 11-68%, silt 25-80%, clay 3-60%). The texture commonly coarsens towards the northern and western limits of this map unit. There is no systematic texture change vertically at any specific site.

The pelite is a characteristic chocolate brown in the Shethanei Lake map area (64 I), where much of the sediment is derived from Hudsonian ice, and is grey in the Tadoule Lake area (64 J), where Keewatin ice was the principal sediment source.

The silts are slightly to moderately calcareous, and the average carbonate content is 16%. Carbonate is most abundant (up to 23%) in areas formerly occupied by Hudsonian ice, but it is also significant (at least 5%) in areas that overlie the noncalcareous tills of Keewatin provenance. The presence of carbonate in these latter areas indicates that Hudsonian rock flour was carried in suspension into the lake basin well beyond the limit of Hudsonian ice.

Over much of their extent the lake silts are massive. In some areas, however, the massive unit is underlain by rhythmites. Sections along North and South Knife rivers in the east and at Morand Lake in the west show thinning upwards sequences of rhythmites. The couplets consist of clayey red brown to mauve beds, alternating with silty grey beds. The rhythmites were deposited near the ice margin, under the influence of gravity currents. The thinning sequence is indicative of a steadily retreating ice margin.

The glaciolacustrine silts are moderately plastic. The average liquid limit is 30%, and the plastic limit is 20%. Water contents lie between the liquid and plastic limits in unfrozen soils, but may greatly exceed the liquid limit where ground ice is present. The pelite unit is generally perennially frozen because of the insulating peat cover. The seasonal active layer is 30 to 90 cm. Below this depth the sediment is moderately to slightly icy (Fig. 21). Ground ice is present as random crystals, several millimetres across, and as segregated laminae several centimetres thick. Ice generally accounts for less than 30% of the volume of the sediment.

Table 1. Diatoms in Lake Agassiz deposits, northwestern Manitoba. Identification are by S. Lichti-Federovich, unpublished GSC Diatom Report No DT-77-104, 1977.

Caloneia silicula (Ehr.) Cleve
Caloneis silicula var. **trunculata** (Grun.) Meist.
Cymbella aequalis W. Smith
Cymbella Ag. spec.
Diploneis ovalis (Hilse) Cleve
Diploneis ovalis var. **oblongella** (Naeg.) Cleve
Eunotia pectinalis (Kutz) Rabh.
Eunotia praerupta Ehr.
Gomphonema angustatum (Kutz) Rabh. var. **producta** Grun.
Neidium iridis (Ehr.) Cleve
Neidium dubium (Ehr.) Cleve
Neidium incurvum (Greg.) Ostrup
Neidium productum (W. Sm.) Cleve
Neidium affine (Ehr.) Pfitz. var. **longipes** (Greg.) Cleve
Neidium iridis var. **amphigomphus** (Ehr.) V. Heurck
Neidium temperei Reimer var. **temperei**
Pinnularia mesolepta (Ehr.) W. Smith var. **angusta**
Pinnularia mesongyla (Ehr.) Hust.
Pinnularia Ehr. fragment
Pinnularia viridis (Nitzsch.) Ehr.
Stauroneis phoenicenteron (Nitzsch.) Ehr.
Stauroneis phoenicenteron fo. **gracilis** (Ehr.) Hust.
Stauroneis phoenicenteron var. **brunii** (Perag. & Héribe)
Stauroneis fluminea Patr. & Freese var. **fluminea**

Figure 20. De Geer moraine. Small straight ridge about 1 km long and 5 m high composed of till and lacustrine sediment; these ridges protrude above the surrounding muskeg. 204036-Q

Figure 21. Massive lacustrine silt with numerous laminae of black ice. The frozen pelite is mantled by an insulating layer of peat. 204034

Figure 22. Landscape near South Knife River. Forested bog with thermokarst depressions filled with peat characterizes areas underlain by fine grained lacustrine deposits. 204035-J

The pelite is susceptible to frost churning, and active mudboils protrude through the organic cover where the peat is thin.

Soil drainage is poor because of the fine grained nature of the sediments. This condition has contributed to the development of peatlands.

The lacustrine pelite forms a blanket mantling the underlying till plain, and smooths or subdues its topography (Fig. 22). Local relief is 2 to 3 m. Ornamenting this subdued landscape are patches of criss-crossing linear and arcuate grooves about 1 m deep. These are most commonly found on the crests of till ridges in areas covered by, or adjacent to, Hudsonian ice (Dredge, 1982a). The features are relict iceberg scour marks (furrows) produced where the keels of icebergs scraped against rises on the lake floor. The grooves are cratered where grounded icebergs melted out.

Littoral sand

Littoral sand is common in the western and northern parts of the Lake Agassiz basin and is the main lacustrine deposit in small isolated glacial lake basins north of the Lake Agassiz limit. Like the fine grained lacustrine pelite, it is commonly mantled by peat. The sand blanket, commonly less than 2 m thick, consists of medium grained, planar, subhorizontally stratified sand derived from drift from the Keewatin ice sheet. Part of the sand was deposited directly along the ice front as a lakeward-thinning wedge which, as the ice receded, resulted in a blanket of roughly uniform thickness. The rest of the sand blanket is reworked, resedimented sandy till. Silt and clay seldom make up more than 15% of the deposit. Blanket deposits, which cover extensive areas, have infilled small depressions in the underlying till surface, creating a landscape of low relief.

Beach ridges, both isolated strands and flights of beaches, lie within the littoral unit and in adjacent areas which are mapped as (slightly washed) till (Fig. 23). At the margins of the lake basin, beaches developed in sandy till; in central parts of the basin they formed against kames and eskers. Most beaches are sandy, although some consist of highly rounded cobbles or boulders that attest to a high energy environment during their formation. Above 400 m elevation, beach ridges are poorly developed and scattered, and relate to high, generally short-lived lake levels where there was little exposed area for beach construction. Between 400 and 370 m flights of longer, better developed beaches, tilted upwards towards the northeast, are common; they formed when the lake had reached its most northerly extent and during recessional phases. Beaches are scarce below 370 m, which suggests that lake levels dropped rapidly and uniformly after reaching this level.

Glaciomarine and marine deposits

The eastern margin of the map area was inundated by the postglacial Tyrrell Sea. As this sea receded it reworked, transported, and redeposited the underlying glacial sediment. Marine deposits associated with the inundation have been recognized along North Knife and Seal river valleys, the Meades Lake area, and along the Caribou River system. Most of the deposits are thin, nonfossiliferous, and lie beneath a thin cover of peat.

The exact limit of marine inundation is difficult to determine, but washing limits on till and eskers, and the upper limit of blanket marine deposits and beach ridges suggest that the marine limit rises from about 160 m at South Knife River to 180 m at Seal River.

Stony marine and glaciomarine pelite

Stony marine pelite, varying in thickness from 1 to 3 m, occupies low areas between belts of ribbed moraine. The material is grey, poorly sorted to diamictic, gritty silt. The matrix texture is 4 to 12% granules, 30 to 55% sand, 25 to 50% silt, and 8 to 16% clay. The material is nonplastic and nonfossiliferous. These deposits form a blanket of very low relief, littered with mudboils. The subsurface contains ice below the active layer, which has a vesicular structure. The sediment is a mixture of glaciomarine material, dropped from the receding Keewatin glacier, and fine grained marine sediment, frost churned and admixed with the underlying till.

Littoral and sublittoral sands

Littoral and sublittoral sands are found up to 160 m elevation near South Knife River, and up to 180 m farther north. They form thin blankets, less than 2 m thick, interrupted by scattered beach ridges. Both ridges and blankets consist of well sorted, subhorizontally stratified sand.

Undifferentiated marine deposits

Caribou River and North Knife River valleys have surficial sediments of variable character and problematic origin. These sediments have been mapped as undifferentiated marine deposits. They consist of 1 to 4 m of massive to horizontally stratified, well sorted sand, grey silty sand, massive grey silt, or interbeds of all three. Most exposures are nonfossiliferous but marine pelecypods were found in similar deposits at the eastern margin of the map area, and for this reason the sands and silts are all presumed to be of marine origin. It is possible however, that some of the deposits exposed along North Knife River are lacustrine in origin, although they do not have the reddish coloration typical of lacustrine silts in this general area.

Fluvial deposits

Modern alluvium

Minor quantities of modern alluvium are shown on Map 1608A; alluvial units, too small to show on the 1:500 000 scale map, also occur as low flood terraces, channel bars, and channel bottom deposits along the major rivers of the area, and as delta islands where these rivers broaden or flow into lakes. The alluvium consists of cross-stratified sand, silty sand, and rounded gravel.

Most small rivers and streams in this region are peat-flanked and appear to contain little inorganic or detrital organic sediment.

Older alluvium

Older alluvium was exposed in section along Seal River 20 km east of the outlet of Shethanei Lake. The massive, planar bedded, and crossbedded sediments consist of more than 4 m of sand and gravel. They underlie a sandy till, but the age of the unit remains unknown. Subtill alluvium is also exposed in sections along North Knife River. It consists of medium grained sands, oxidized sand and gravel, and resedimented saprolite.

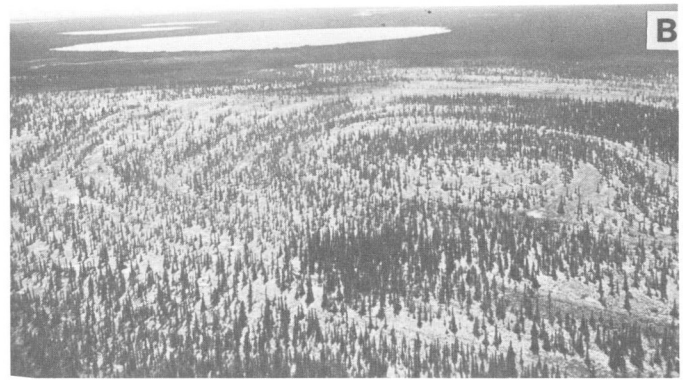


Figure 23. A. Bouldery beach ridges, small rock knobs, and washed till near Nicklin Lake. B. Major flight of beach ridges and surrounding littoral sands 20 km southwest of Legary Lake in the main part of the Agassiz basin. 204034 R. 204036-P

Organic deposits (peat)

Peat covers about 40% of the map area. It forms a nearly continuous blanket in the southern half of the area, and smaller, more confined units over the rest of the region. The blanket deposits mantle relatively flat-surfaced, fine grained materials, chiefly silty till and glaciolacustrine sediments, both of which are poorly drained. Basin deposits lie in isolated topographic depressions. Three peat types have been recognized on the basis of their appearance on airphotos – tundra peat, fen peat, and forested bog peat. Each type has distinctive composition and surface forms. Peat units have been mapped in considerable detail at 1:250 000 scale (Dredge and Nixon, 1981a, b, c, d, e; Dredge et al., 1982a, b; Nixon and Dredge, 1981, 1982; Richardson et al., 1982) but only the more generalized regional patterns are shown on Map 1608A.

Forested bog peat

Forested bog peat is composed of spongy, forest-covered raised bogs and intervening narrow fens, interspersed with thermokarst depressions which give the terrain a pitted appearance on aerial photographs (Fig. 24, 25). The bog surface is covered with closed spruce forest, ericaceous shrubs, and an understory of hummock-forming mosses. Forested bog stretches uninterrupted over about 7000 km^2 and is part of the largest tract of muskeg in North America. It has developed on the fine grained deposits that comprise the smoothed bottom of Lake Agassiz. The peat ranges in thickness from about 25 cm at its northern and western extremities to more than 4 m in the east. It is commonly about 1 m thick in the Tadoule Lake map area (64 J) and 2 to 3 m thick in the Shethanei Lake map area (64 I). The peat is yellow to brown and consists of a stratified mixture of amorphous to fibrous moss peat and woody peat, minor amounts of sedge peat, with some layers of charcoal. Deposits are derived from the accumulation and partial preservation of a spruce forest vegetation cover, with some additional components from adjacent grassy fens. Forest fires produced the charcoal.

The peat is moist to wet above the frost table, which lies at between 30 and 60 cm depth. Permafrost lies below this depth. Random ice crystals, coatings on woody fragments, and layers of segregated ice were observed in all cores, and there is commonly also a thick ice layer between the peat and the mineral substrate. The water content of frozen peat is on average 600% of the dry weight, and up to 1200% where there is visible segregated ice.

On a regional basis the terrain is almost flat. Water-filled thermokarst depressions 2 to 3 m deep and 30 to 100 m across account for most of the local relief and give this peat type its distinctive pocked appearance on airphotos.

There are few age determinations on peat from this area, but one ^{14}C date on basal peat from a bog in the Kasmere Lake area gives an age of 5990 ± 80 BP (GSC-2759; Coker and DiLabio, 1979).

Fen peat

Fens occupy modern drainageways, abandoned channels, and low areas between raised bog. They have flat grassy surfaces; the peat below is dark brown, wet, dense, amorphous sedge peat, with some moss peat, which grew in environments with slow-flowing water. The unit is extremely poorly drained and slow-flowing water is present at the fen surface. Permafrost is absent beneath some fens but in others, frost occurs at depths between 30 and 70 cm, and segregated ice is present within the frozen peat.

Palsas are common features in the fenlands of this region (Fig. 26). These features form domes and irregular plateaus which protrude 1 to 2 m above the surrounding fen. Active young palsas have dark surfaces composed of sedges which died when they were heaved upwards above the water table. Mature palsas are covered with live herbaceous plants. Inactive palsas are recognized by their collapsed centres.

Palsa mounds typically consist of a layer of unfrozen peat about 50 cm thick, underlain by frozen peat and silt or silty sand. The peat and silt contain lenses and crystals of segregated ice.

Tundra peat

Small patches of tundra peat (Fig. 27) overlie both glaciolacustrine deposits and sandy till in relatively flat areas beyond treeline. The peat is vegetated by, and is derived from lichen heath vegetation. Tundra peat is only 20 to 70 cm thick, and thus is the thinnest peat type in the area. Its surface is inscribed with frost polygons 5 to 10 m in diameter; in some areas second order polygons are inset into

Figure 24. Typical muskeg landscape, near Tadoule Lake, in an area of discontinuous permafrost. The main elements are hummocky forested bog and intervening fen (light toned areas). The lake in the foreground is gradually filling in with organic sediment. 204034-Q

Figure 25. Ground view of forested bog showing hummocks, ground cover of moss and shrubs, and spruce forest. 204035-P

Figure 26. Fenlands, consisting of grassy wetlands and palsa. Forested raised bog in background. 203121-N

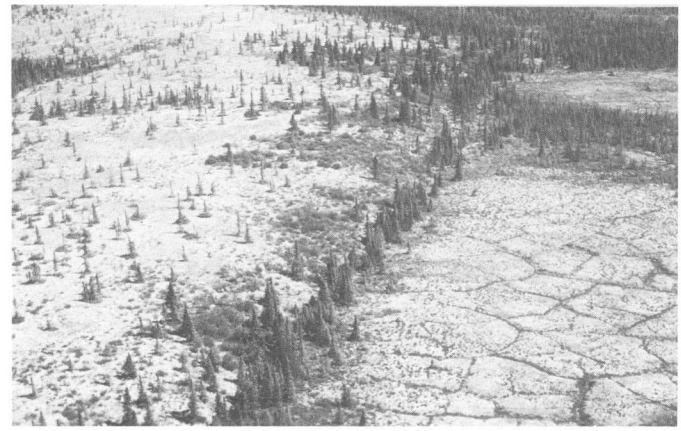


Figure 27. Tundra peat with fossil ice-wedge polygons (right), and moraine of sandy till (left). 204034-B

the larger features. At least some of the frost cracks in areas of continuous permafrost contain ice wedges. The active layer is about 65 cm thick near the southern limit of the study area and decreases to about 40 cm in the northern part. Where the peat is thin, the active layer may extend into the underlying substrate.

STRATIGRAPHY

Exposures are rare in northwestern Manitoba, but sections around Morand Lake, along Seal River, and particularly North Knife River record a number of glacial events in the Late Quaternary record. The composite sedimentary succession, as determined in northwestern Manitoba, can be interpreted in several ways because of the absence of a complete record at any one place and because materials for absolute dating have not been discovered.

Morand Lake and Gimby Lake exposures

Sections along two rivers near Morand and Gimby lakes reveal Late Wisconsinan basal till, grading upwards either to stratified waterlaid till and thence to massive lacustrine clay with dropstones, or to current bedded sand, thinning upwards sequences of rhythmites and thence to massive clay. These sections show facies changes from glaciolacustrine conditions to lacustrine conditions associated with progressive recession of the Late Wisconsinan ice margin.

Seal River sections

The sections along Seal River represent a longer time period than those at Morand and Gimby lakes.

One section 20 km east of Shethanei Lake reveals a basal oxidized silt unit, overlain successively by 3 m of sandy till, 0.5 m of silt, a second sandy till, 4 m of crossbedded sand presumed to be of fluvial origin, capped by a third till unit about 1 m thick. The fluvial beds and overlying till could be related to the draining of Lake Agassiz and to a slight glacial readvance succeeding that event. The lower tills and intervening silt units may then represent older (pre-Late Wisconsinan) glacial advances and ice free periods when the area was covered by ice-dammed lakes. Because neither the tills nor the fluvial and lacustrine deposits are deeply weathered, they may not represent a long period of time.

During the course of bedrock mapping Taylor (1961) found and described a plant-bearing conglomerate at Great Island. The river gravels were rusty and heavily cemented with goethite and contained impressions of leaves whose species were identified by J. Terasmae (Brock University) as representing an assemblage similar to the vegetation presently growing in the region. Because of the degree of weathering of the gravel, the climate implied by the plant assemblage, and the occurrence of till overlying the bed, Taylor assigned these materials to the last interglaciation.

North Knife River sections

Sediment sequence and interpretation of events

Sections primarily along North Knife River, but also along South Knife River, reveal the most complete record of glacial and the intervening nonglacial sediments in northwestern Manitoba. River cuts expose weathered rock, buried soils or otherwise oxidized zones, subtill outwash and alluvium, multiple till beds separated in places by beds of sand and gravel, and finally lacustrine and marine silts. A composite section, constructed by cross-correlating common beds from one place to another is shown in Table 2. Because only about half the beds are present at any given section some of the lower units could be incorrectly assigned, for example, units B and E may be equivalent.

The lowest unit (A) is the saprolite, described previously, which may represent a preglacial period of deep and intense weathering, or which could be low temperature rock alteration. This material is overlain by a sequence of fresher deposits relating to Quaternary glaciations. The lowest Quaternary unit of up to 3 m of rubified, indurated crossbedded sand and gravel (B) and reworked saprolite is a fluvial deposit, emplaced by eastward flowing rivers. The current direction suggests that drainage was towards Hudson Bay, which was therefore likely ice free at the time these beds were deposited.

A black silty compact till unit (C) up to 3 m thick, observed only near the eastern border of the map area, overlies the indurated gravel and represents a glacial advance from the east. The till is overlain by plane beds of fine sand, graded beds of sand and silt, and massive silt (unit D), which are interpreted as standing water deposits. The total thickness of the stratified unit is about 2 m. This sequence could relate to downslope drainage obstruction caused by the retreating ice mass in Hudson Bay that previously emplaced the black till. The yellow and reddish oxidation of the sand, though not of strong chroma suggests that the deposits had subaerial exposure at some time. The overlying unit of sand with rounded gravel (unit E) represents a return to free-running fluvial conditions following disappearance of Hudson ice. The extent of red and yellow oxidation and partial

cementation, particularly near their top, suggests that they have been subaerially weathered. Beds of brown, unoxidized sand and subrounded cobbles (unit F) overlie the weathered gravels. They are commonly massive but southward-dipping beds were observed in some places. These gravels grade upwards into the till of unit G and they represent the proglacial outwash related to glacial readvances.

A sequence of one to three sandy or silty till units (G,I,K), either stacked directly above each other or separated from one another by sand and gravel beds, overlies the outwash. The till sheets are each 2 to 6 m thick, and all contain shell chips. Along the western part of the river, sandy till generally lies at the base of the sequence; along the eastern part silty till more commonly forms the basal unit. Silty till generally forms the upper till in the sequence along North Knife River, although across most of northwestern Manitoba the uppermost unit is the sandy surface till. The tills mark successive advances of Keewatin ice (sandy till) and Hudsonian (or Labradorean) ice (silty till). Units G and I indicate that Keewatin and Hudsonian ice fluctuated across the North Knife River area; unit K indicates that the last ice movement was from the east.

The units separating the till sheets are either poorly sorted, massive sand and gravel layers or beds of stratified sand. They are slightly oxidized to fresh in appearance. The beds could be nonglacial steam deposits, in which case they represent interstadial or interglacial conditions. Alternatively, the sand and gravel units could be subglacial meltwater deposits that may have formed along the shifting convergence of Keewatin and Hudsonian ice. In this case, the region could have been continuously ice covered. The second alternative is preferred because the sedimentary structures are not indicative of subaerial stream deposits, and because the areal distribution of the silty calcareous till and sandy till, converging striae, and a large interlobate moraine independently indicates that two distinct ice masses contemporaneously occupied the North Knife River area.

The uppermost regional till (K) is overlain by, or grades into, a sequence of current-bedded sands (M), thinning upwards rhythmites (N), and massive silts (P). These deposits are associated with Lake Agassiz, the proglacial lake which expanded northwards against the receding ice fronts. The cross-bedded sands and varves were deposited under the influence of tractive bottom currents near the ice front. The overlying silt was deposited from suspension some distance from the ice margin. In some places the uppermost lake deposits are contorted and overlain by a silty till (O) emplaced when part of the Hudsonian ice margin readvanced into the lake. In others, lacustrine deposits are directly overlain by fossiliferous massive marine silts (R) and stratified sand (S). These last units represent the incursion of the postglacial Tyrrell Sea. Deposits of this unit are not found above 160 m. In some places the uppermost unit is alluvium (T) which was deposited by the postglacial river that subsequently downcut to its present level.

Chronology and regional correlations

The absence of datable pre-Holocene material in these sections, and problems with the interpretation of the intertill beds make the absolute age, and even the climatic rank of the deposits, indeterminate.

Long chronology: If we equate one till sheet with one glaciation, then we arrive at a "long chronology", shown in column B of Table 2, where the record covers many glaciations and interglaciations, and a long period of time. Such a chronology would account for the main sedimentary sequence and the presence of shell chips in the tills, since Hudson Bay would expectedly be open between glaciations; but the long chronology does not explain the variable amounts of weathering or nonweathering in the sands and gravels.

Short chronology: The authors prefer a "short chronology" wherein the record probably spans the last glaciation, or at most two glaciations if the lower till and gravel belong to separate, earlier events.

The strong oxidation, cementation of the matrix and rubefaction of some of the lower sand and gravel deposits suggest that a soil developed at one or more times. Both soils on units B and E (Table 2) are much more developed than are the postglacial podzols presently forming in the region. It would thus appear that the soils developed during two warm intervals. The simplest age assignment for unit E is therefore the last (Sangamon) interglaciation. The gravels are then tentatively correlated with the Great Island conglomerate within northwestern Manitoba, with the interglacial organic beds along Nelson River (Nielsen and Dredge, 1982), with the Gods River sediments (Klassen, in press) of central Manitoba, and with the Missinaibi beds in the James Bay area of the Hudson Bay Lowlands (Hughes, 1964; Skinner, 1973). In this interpretation the black till represents a cold period event occurring during either the middle part of the Sangamon Interglaciation or a pre-Sangamonian glaciation.

As outlined above, the sandy and calcareous silty tills (i.e. those above unit F) either could be separate glacial events or could represent provenance shifts in one glaciation. It is simpler and more conventional to assume that each till represents a separate glacial event; if this is so, and the rubified gravels are Sangamonian, then there were two major periods of ice recession since the last interglaciation. The presence of shell chips in the silty tills further suggests that Hudson Bay may have been ice free, that is, that there were "interglacial" periods during the Wisconsin Glaciation. However, because both the character of the sand and gravel beds and independent ice flow evidence (converging striae, interlobate moraine, and areal till sheet character) suggest that this area lay along the zone of convergence of Keewatin and Hudsonian ice, we propose that both the tills and intertill sediments were deposited during a period of continuous ice cover; in this case, the various till sheets and gravel beds were produced by the interplay of Keewatin and Hudsonian ice, and by basal meltwater in the convergence zone. In this interpretation, the shell chips in the upper silty tills are considered to be recycled from older tills and marine deposits. Andrews et al. (1983) have claimed that amino acid determinations on shell chips in other parts of the Hudson Bay Lowlands indicate two separate mid-Wisconsinan openings of Hudson Bay. We dispute their claims; the data they presented seem rather to indicate that (1) there is a continuum of amino acid "ages" ranging from the time of the Bell Sea to present and (2) that the variation, even within a single shell, is considerable.

Summary

There are a number of ways of interpreting and assigning ages to the deposits observed in the stratigraphic record of northwestern Manitoba. The interpretation preferred by the authors is the record that begins with a Sangamon (or pre-Sangamon) Interglaciation, during which soils formed. This interglaciation was interrupted by a cold period during which glacier ice advanced into the region from the east in the North Knife River area. There was a succeeding return to warm conditions, followed by a single Wisconsin Laurentide glaciation.

GLACIAL AND POSTGLACIAL HISTORY

This section deals with those glacial events that shaped the landscape, for which there is a record as sediments exposed in river cuts, as surface deposits on Map 1608A, or as landforms. Introductory sections discuss ice flow indicators and how the ice sheets in northwestern Manitoba fit into the

Table 2. Stratigraphic table showing the sedimentary succession along North Knife River, with several possible interpretations of events and chronologies

SEDIMENTARY SUCCESSION UNIT	MATERIAL	ICE FLOW DIRECTION	INTERPRETATION	A. SHORT CHRONOLOGY One main glacial event	A. SHORT CHRONOLOGY Multiple glacial and nonglacial intervals	B. LONG CHRONOLOGY Separate glaciations
T	Current-bedded sand		Alluvium	Postglacial	Postglacial	Postglacial alluvium
S	Stratified sand	South	Tyrrell Sea and late Keewatin ice in northern areas			Tyrrell Sea episode
R	Fossiliferous grey silt (Q) Sandy till	1			Wisconsin Glaciation with two partial or total deglaciations	
P	Massive brown silt (O) Silty till	West	Lake Agassiz, with local Hudsonian readvance during recession			Lake Agassiz episode with Hudsonian surge
N	Silty varves					
M	Current-bedded sand					
L	Waterlaid till					
K	Silty till	West 2	Hudsonian advance on N Knife R Keewatin ice dominant to north and west	Wisconsin Glaciation: continuous ice cover over central part of the Laurentide ice sheet. Different tills emplaced by shifting Keewatin and Hudsonian ice masses across the region. Unoxidized sands deposited subglacially		Wisconsin Glaciation. Hudsonian ice occupied N Knife R area with Keewatin ice in north and west
J	Sand and gravel	South, West	Subglacial or stream deposition			Sangamon Interglaciation*
I	Sandy till/silty till		Glacial advance with shifting Keewatin and Hudsonian ice			Three pre-Sangamonian glaciations and interglaciations *
H	Slightly oxidized sand with gravel		Subglacial or stream deposition			
G	Sandy till/silty till		Shifting Keewatin and Hudsonian ice			
F	Brown sandy gravel	South, West	Advance outwash			
E	Rubified sand and gravel		Nonglacial interval with soil development *	Sangamon Interglaciation	Sangamon Interglaciation	
D	Crossbedded sand; Massive silt; Graded beds of sand and silt; Plane-bedded sand, oxidized gravel		Proglacial lake deposits; ice mass blocking drainage into Hudson Bay	Mid-Sangamonian or pre-Sangamonian glaciation	Mid-Sangamonian or pre-Sangamonian glaciation	
C	Black silty till	West	Hudsonian ice advance			
3 B	Rubified, strongly cemented gravel		Interglaciation with soil development *	Early Sangamonian or Illinoian Interglaciation	Early Sangamonian or Illinoian Interglaciation	
A	Saprolite		Intense subaerial weathering *	Tertiary ?	Tertiary ?	
	Rock					

GSC

1. Area north of Seal River only
2. Sandy till and southerly ice flow in areas north and west of North Knife River
3. Unit B may be equivalent with unit E; units never exposed together.

* Ice free Hudson Bay

continental pattern of glaciation. Succeeding sections deal with older glaciations, the style and pattern of ice flow during the last glaciation, the incursion of Lake Agassiz – the glacial lake which expanded as the ice fronts receded, final inundation of the area by the Tyrrell Sea, and postglacial climate changes.

The stratigraphic interpretation, proposed centres of outflow, limits of Lake Agassiz, relative vigour of the two ice domains, and regional correlation of lake levels differ somewhat from the reconstruction of Klassen (1983) for north-central Manitoba.

Ice flow indicators

A wide variety of features and landforms indicates the direction of successive glacial advances and final retreat of the last ice sheet. For northwestern Manitoba, however, the best ice flow indicator is the till itself. Till texture, clast composition, and matrix carbonate content serve to identify major regional ice flow patterns and to indicate ice streams within the regional pattern. The main erosional markings are striae, grooves, and roches moutonnées. These markings give the direction, and in places the sense, of ice flow. The sequence of flow is recorded in crosscutting relationships. Ice moulded bedforms, such as fluting and drumlins, also show directions of ice flow, although these features may represent flow only near the ice margins. Features that yielded information about the position and orientation of successive recessional ice margins, such as moraines and eskers, provide indirect information about ice flow directions, particularly during retreatal phases of glaciation.

The studies of landforms, and internal sedimentary structures associated with them, reveal the style of ice flow during the ice recession.

Continental context

On the basis of many striation measurements, and by intuitive insight Tyrrell (1898, 1913) proposed that the Laurentide ice sheet had three "gathering grounds" or centres of growth (Fig. 28): (1) the Keewatin ice centre, spanning the area now covered by the districts of Mackenzie and Keewatin (then Keewatin); (2) the Patrician, in northwestern Ontario in the District of Patricia; and (3) the Labradorean, in central Quebec (then Labrador). Data from northwestern Manitoba, together with new findings relating to the broader structure of the North American continental glaciers (Dyke et al., 1982), in essence confirm Tyrrell's concept that the North American ice sheet was composed of a number of interacting but semi-independent ice masses. Two of these ice masses affected northern Manitoba during the last glaciation. Keewatin ice, centred in the mainland part of Northwest Territories (not just District of Keewatin), flowed southwards, and at some time reached as far south as Iowa. In the latter part of the last glaciation Hudsonian ice spread from a centre in Hudson Bay slightly north of Tyrrell's centre in the District of Patricia, and reached as far west as Lake Winnipeg and southwest Minnesota. Hudsonian or Labradorean ice stretched even farther west at some earlier time.

Northwestern Manitoba lies along the edge of the convergence between the Keewatin and Hudsonian ice sheets. The stacking of different till types and variations in the surface till sheet show that at some times Keewatin ice inundated the area, while at others, such as the last glacial episode, both ice sheets were co-active and confluent in the region. The centres of outflow migrated and the relative vigour of the two ice masses changed during each glaciation, and with these changes the zone of confluence shifted.

Early glaciations and nonglacial intervals

Although many details of the stratigraphic succession remain problematical' we are able to sketch in some of the events that preceeded the last glacial stade. Following a long or intense weathering interval, during which Hudson Bay was open, there was an early ice advance from Labrador or Hudson Bay, which emplaced a black silty till seen only in river cuts along North Knife River. A proglacial lake developed as the ice receded. A second nonglacial weathering interval, somewhat less intense than the previous one, succeeded these events. During the next (Wisconsin) glaciation both Hudsonian and Keewatin ice were active in the region. During the initial pulse of this glaciation Keewatin ice was more vigorous and deposited a sandy till in the North Knife River area. This ice may have been the same flow that created the eastward trending striae on Chekask Hills, in which case the early Wisconsin Keewatin ice divide lay somewhere in eastern District of Mackenzie. The occurrence of Paleozoic fossils, limestone pebbles, and abnormally high carbonate contents in the subsurface till at Chipewyan Lake (Fig. 2) indicates that Hudsonian ice reached that far west some time later. The northern limit of the Hudsonian ice margin is uncertain but lies somewhere between North Knife and Seal rivers. Keewatin ice later overrode the Hudsonian tills at Chipewyan Lake during this same glacial stade; both Hudsonian and Keewatin ice occupied the North Knife River area. During the Late Wisconsinan, Hudsonian ice deposited the silty calcareous grey surface till in the North Knife area, although Keewatin ice occupied areas farther north and west.

Late Wisconsinan glaciation

Limits of Keewatin and Hudsonian ice

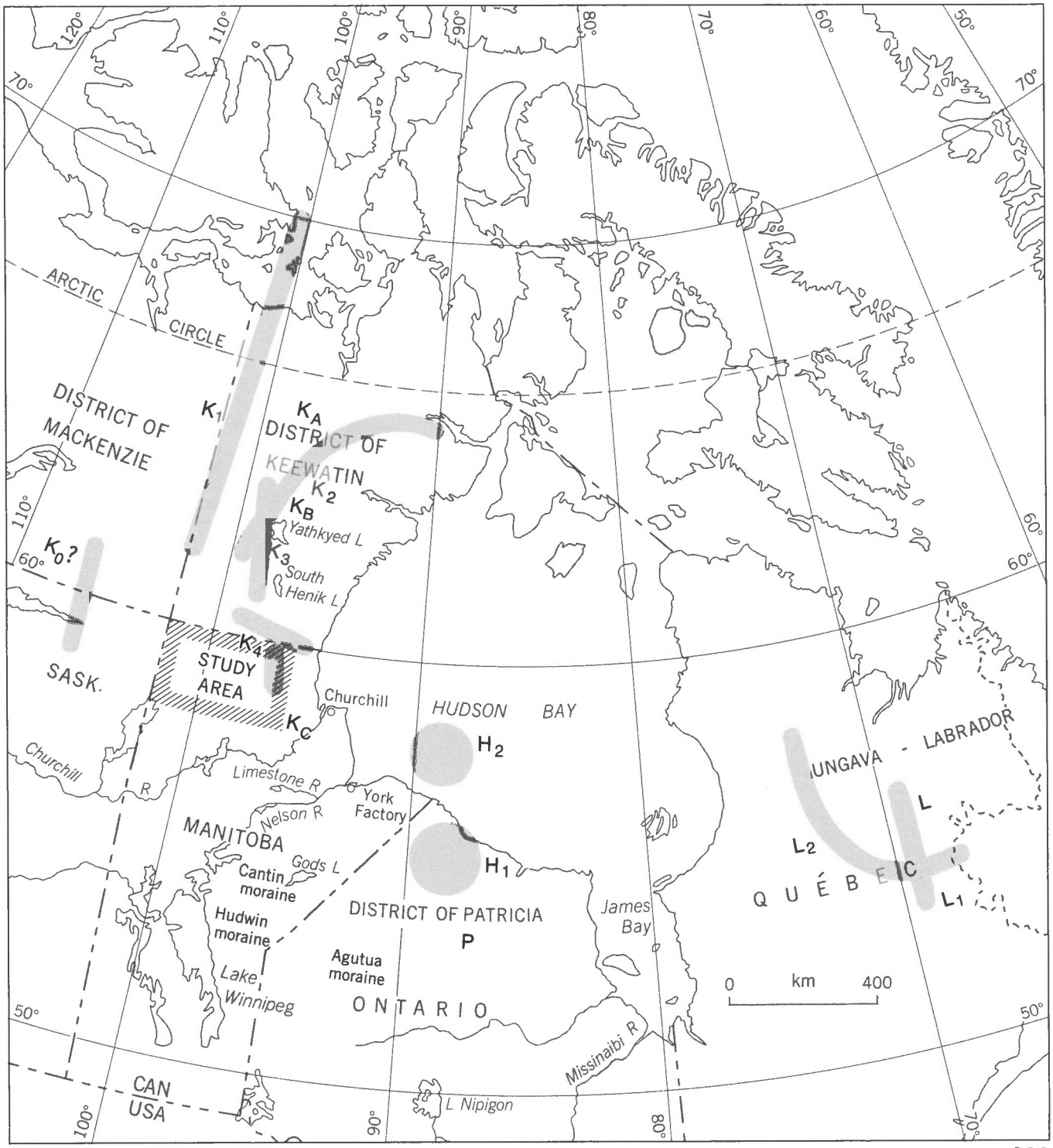
Most of the surficial glacial deposits and features shown on Map 1608A relate to the last glacial event, which spanned at least the Late Wisconsinan, but may have been longer. The advance phase is associated with two major ice masses of differing provenance.

Keewatin ice flowed over resistant Precambrian terrane, and generated a till blanket which is sandy textured and consists of granitic components. The till blanket is ornamented by transverse and longitudinal bedforms. Hudsonian ice flowed westwards from a centre in Hudson Bay basin and deposited a thick featureless blanket of silty calcareous till. The extent and vigour of these two ice masses varied considerably over the course of time.

The stratigraphic record and landforms indicate that Hudsonian ice was once more extensive than is indicated by the surface till sheet; the ice extended westwards as far as Chipewyan Lake and northwards slightly beyond North Knife River. Similarly, at some time during the last glaciation, Keewatin ice advanced farther south than is indicated by the surface sandy till sheet. East-west trending end moraines in northeastern Manitoba suggest that Keewatin ice extended as far south as Churchill River before being finally overridden by Hudsonian ice. The area of convergence of the two ice masses thus shifted across a zone about 100 km wide during the last glaciation. The southern quadrant of the map area lies within the convergence zone. The last (deglacial) position of the confluence between Hudsonian and Keewatin ice is marked by the Knife River Interlobate Moraine.

Changes in flow direction: (Figure 29: ice flow sequences)

The regional pattern of striae and streamlined landforms indicates that Keewatin ice initially flowed southwards from the M'Clintock (Dyke et al., 1982) centre in western District of Keewatin and eastern District of



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K_A, P, L — The Keewatin (K_A), Patrician (P), and Labradorean (L) "gathering grounds" as proposed by Tyrrell (1896, 1898, 1912).

K_A, K_B, K_C — Late glacial shifts in the Keewatin ice divide as proposed by Tyrrell (1896, 1898).

K_0, K_1, K_2, K_3, K_4 — Successive positions of an elongated Keewatin ice divide (after Tyrrell 1896, 1898; Lee, 1959; Dredge and Nixon 1982; Dyke et al., 1982; Dredge, 1983c; this report).

H_1, H_2 — Successive positions of the migrating Hudsonian ice centre (Dyke et al., 1982; Dredge, 1983c; this report).

L_1, L_2 — Successive positions of the migrating Labradorean ice divide (Henderson, 1959; Hughes, 1964).

Figure 28. Gathering grounds and migrating ice divides of the Late Wisconsinan glaciation.

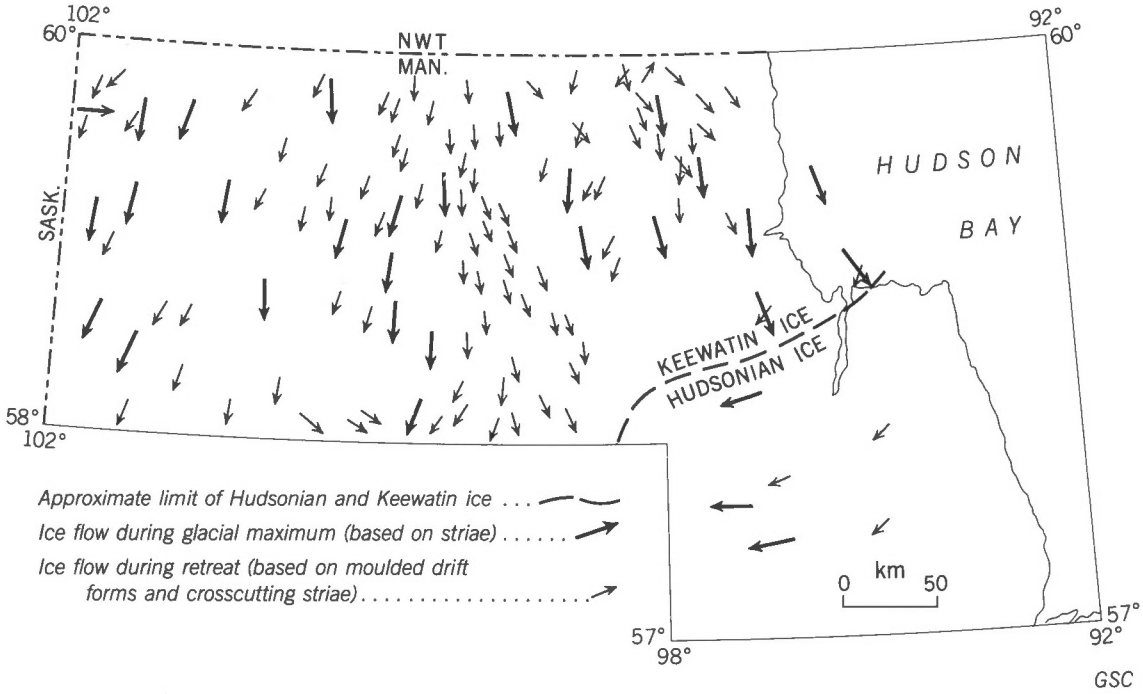

Figure 29. Ice flow patterns as indicated by striae and moulded bedforms.

Mackenzie whereas Hudsonian ice flowed westwards from a centre in Hudson Bay just north of District of Patricia (Fig. 1). Superposed striae and the correspondence between striae trends and the orientation of recessional landforms indicate that towards the close of glaciation there were major directional shifts within the Keewatin glacier and minor shifts in Hudsonian ice flow. One limb of the Keewatin ice divide migrated to west-central District of Keewatin (Lee, 1959) and thence southwards and eastwards towards Hudson Bay (Fig. 28; Dredge and Nixon, 1982). Ice flow in Manitoba correspondingly shifted from south, to southwest and southeast when the centre of outflow moved from the District of Mackenzie to central Keewatin near Yathkyed Lake. Within the ice sheet were variant ice flow patterns around topographic prominences, along unstable parts of the ice margin, and along zones of convergent ice flow. For example, the central part of the ice front between Tadoule Lake and North Knife Lake bulged and surged forward into Lake Agassiz. The zones of converging flow are marked by radial moraines, which delineate the edges of ice streams. Final flow in the region was radial to an ice remnant with a divide lying just north of the Manitoba border near Hudson Bay. There is also some evidence for northward flow from a small isolated ice cap or limb of the final ice divide situated north of Caribou Lake.

Hudsonian ice flowed mainly westwards, although redrumlinized moraines in northeastern Manitoba indicate that the Hudsonian centre migrated northwards during deglaciation. Several readvances also occurred within the Hudsonian ice sheet prior to its demise.

Regime of Hudsonian and Keewatin ice masses during late phases of glaciation

Although both Keewatin and Hudsonian glaciers were active during the early part of the last glaciation, by late glacial time and during deglaciation the Keewatin and Hudsonian ice masses had markedly different glaciologic regimes (cf. Table 3). These differences affected the patterns and timing of deglaciation (described in the next section), and allowed the proglacial lake, which abutted the retreating ice fronts, to expand well into what was once the heart of the Keewatin glacier.

Keewatin ice, with its centre well beyond the influence of sea and lakes, remained stable and grounded until its final disappearance. There were a number of ice streams within the glacier as shown by swarms of drumlins. The presence of substratified till, long esker systems, radial moraines, and belts of conjugate ridges indicates an abundance of meltwater, both in subglacial channels (or diffuse drainageways) and as crevasse systems. Belts of transverse bedforms (ribbed moraine) juxtaposed with longitudinal bedforms (drumlin fields) indicate that there were zones of relatively high and low shear stresses at the base of the ice, and the superposition of drumlins on ribs suggests that the mobility of the basal part of the ice varied over time. The difference in ice sheet mobility could relate to basal pore water pressures. Moraine plateaus and conjugate ridges mark the area where ice actually stagnated. Ice recession occurred by downwasting, melting of the ice front, sapping of the southern ice margin by a proglacial lake, and in northeastern Manitoba, by sapping of the eastern margin by a postglacial sea. There are very few recessional end moraines.

Hudsonian ice flowed actively and vigorously both during main glacial time and during deglaciation. The ice was thick enough to remain grounded despite the buoying forces of a deep proglacial lake against its southern front and the rising postglacial sea somewhere behind (in Hudson Strait or the northern part of Hudson Bay). This situation, however, produced a quasi-stable condition, one of potential instability, resulting in a catastrophic end to the ice sheet (discussed below). Ice flow within the glacier was plastic enough to produce broad grounding line moraines (as opposed to shear moraines) and to form fluted bedforms even during the last stages. The relatively close spacing of the moraines, as well as evidence of a readvance, indicates that forward flow was vigorous enough to prevent rapid backwasting of the ice front despite the calving that occurred where the ice front lay against a deep glacial lake. An ice ramp or ice shelf extended into the proglacial lake, from which icebergs calved and later grounded on underwater ridges. The substratified diamicton associated with the retreat shows the intimate relationship between this ice mass and Lake Agassiz.

Table 3. Contrasting deposits and landforms associated with Keewatin and Hudsonian ice retreat against Lake Agassiz

	Keewatin Ice	Hudsonian Ice
ice conditions	zones of mobile and less mobile ice some downwasting and back-wasting	active, vigorous forward flow
	gently sloping ice front	steep calving ice front
	ice front against shallow water	ice front in deep water
Till types	sandy till, bouldery till	silty till
	terrestrial basal till (basal melt out)	terrestrial and waterlaid till
Subglacial features	till blanket, ribbed moraine, flutes, crevasse fillings	till blanket rare fluting
Ice marginal features	eskers, radial moraines, delta pads, De Geer moraines	grounding line moraines
Associated lake deposits	thin sand blanket	massive or varved pelite, crossbedded turbidite sands waterlaid till and flow till,

At the time of deglaciation, the suture between the Keewatin and Hudsonian ice domains lay along the lowlands now occupied by South Knife Lake. The suture, marking the edges of the two adjacent ice masses, was a zone of relatively thin ice and hence a line of weakness. Meltwater was drawn down from within the ice towards and along this zone, whose location is marked by a string of interlobate kames mostly deposited at the ice front as the two ice masses separated and retreated.

Deglaciation

The section begins with a summary statement about the extent and deposits of the northern part of the Lake Agassiz basin, and then outlines the main events during deglaciation.

Overview: Extent and deposits of Lake Agassiz

During deglaciation, Lake Agassiz formed by the ponding of meltwater in front of the receding ice margin. This glacial lake began to form 12 000 years ago when the Laurentide ice margin lay in Minnesota; it was ponded between the ice sheet and high land to the south and west. It followed the receding ice sheets northwards into the northernmost part of Manitoba. The configuration of Lake Agassiz varied as the ice margin retreated and water levels fluctuated. Its northern and eastern margins were the Keewatin and Hudsonian ice fronts. Because of the regional topography, the lake in northern Manitoba was shallowest to the west and north and deepest in the east. Lacustrine deposits and beaches indicate that the lake extended as far north as Kasmere Lake in the west but barely reached Seal River in the east-central part of the area shown in Figure 30. The eastern boundary of the lake is presently unknown, but lacustrine deposits underlie till and marine sediments almost as far east as Churchill (Dredge, 1983c). Fine textured sediment also covers the Kaskattama upland in extreme northeastern Manitoba (Fig. 1), and it is thus possible that Lake Agassiz extended into part of the area presently occupied by Hudson Bay.

The main sediment supply to the northern Lake Agassiz basin came from the Keewatin and Hudsonian ice sheets. The type and areal distribution of sediments associated with these two ice masses are markedly different due to differences in ice dynamics, character of source sediment, and water depths along the ice fronts. Figure 30 shows the major types of sediments on the floor of the lake. In areas of Keewatin ice the chief deposits are bulky radial moraine and esker deposits, including lateral kames and delta pads, stratified blanket sands, beach ridges, and De Geer moraines. In addition, where the lake was short lived, the principal surface deposit is washed till. A few river deltas were constructed where streams, flowing over exposed land, emptied into the lake. The sediments associated with Hudsonian ice in the deeper part of the lake basin are a silty waterlaid diamicton (waterlaid till) and massive or varved silty clays. The clayey lake bed is scarred by iceberg furrows. Beach ridges and wave-cut notches are rare in the Hudsonian ice area.

Overview: Style and pattern of ice retreat

Although deglaciation was due primarily to climatic factors, the rate and pattern of ice retreat was affected by the development of Lake Agassiz. During deglaciation, natural drainage towards the east was blocked by Hudsonian ice. A deep proglacial lake therefore developed, expanded

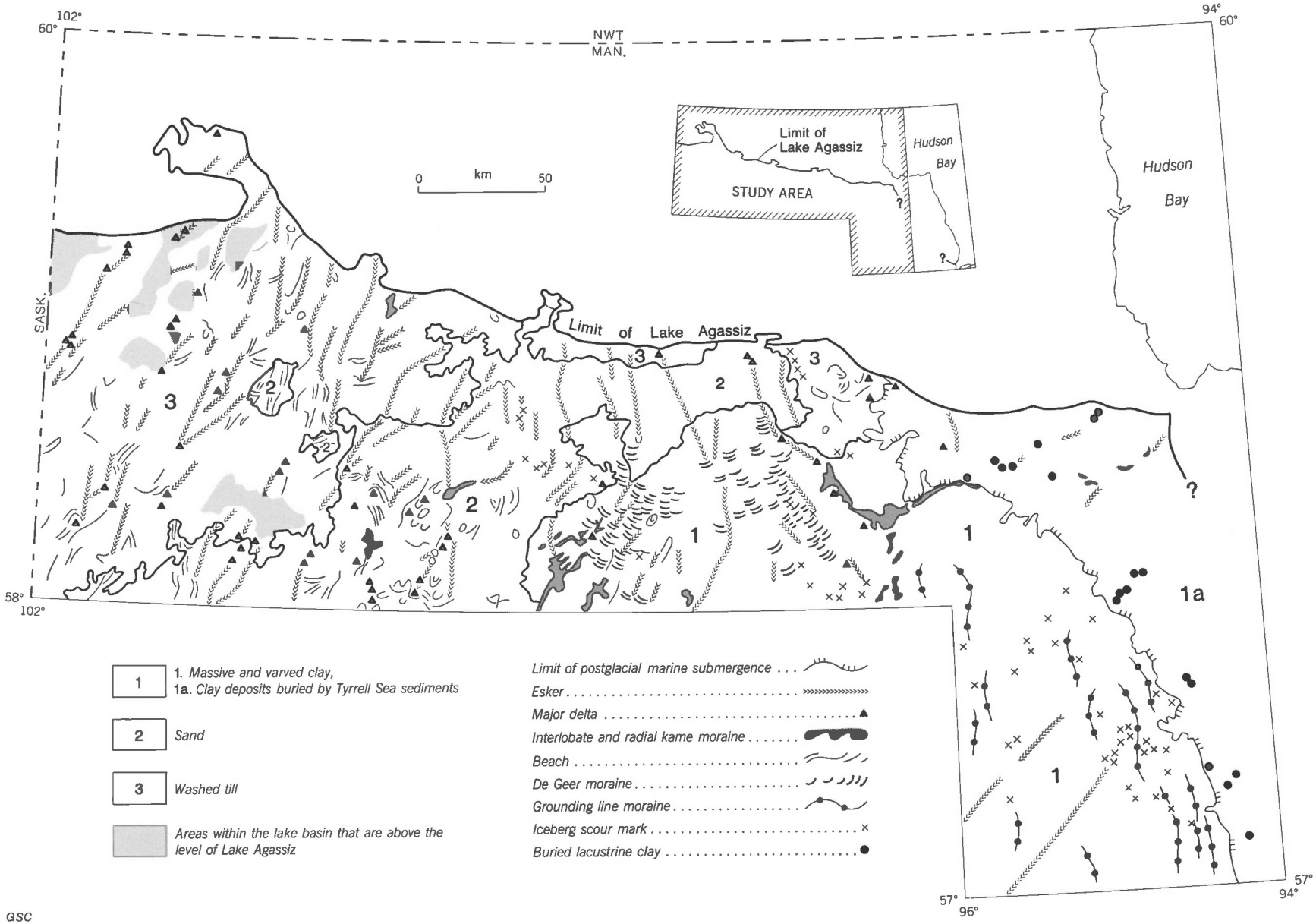

Figure 30. Sedimentation pattern in the Lake Agassiz Basin. Markedly different sediments were derived from the Keewatin and Hudsonian ice masses.

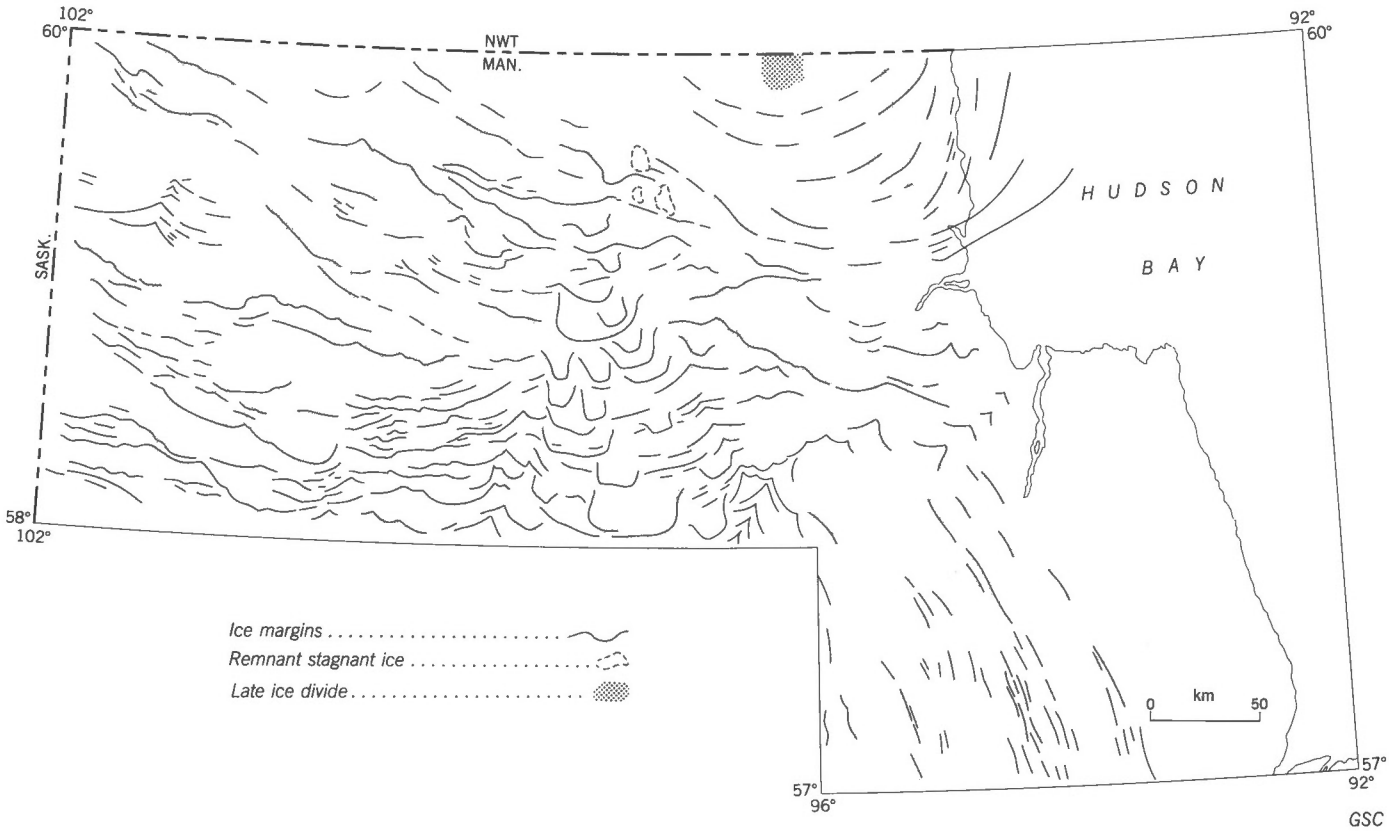

Figure 31. Pattern of ice retreat in northern Manitoba.

rapidly as the ice sheets retreated, and lasted until the disappearance of Hudsonian ice. The presence of this lake accelerated the retreat of the ice fronts by acting as a heat source, and by mechanically sapping the ice margins through buoyancy and wave erosion. Preferential sapping occurred along radial and interlobate lines of weakness within the ice and between ice masses.

The pattern of recession is shown in Figure 31, along with the generalized relative position of the two main ice masses. This figure is an interpretation which is based on ice marginal forms, esker trends, streamlined landforms, crosscutting striae, and topography.

In northern Manitoba, ice recessional positions are rarely marked by end moraines. Successive approximate positions can be determined, however, by following and linking lateral (ice frontal) kames, esker beads, delta pads, grounding line moraines, and small morainal forms. Margins determined in this way also represent successive northern and eastern lake limits until the elevation of the land being deglaciated exceeds the level of the lake. Lake elevations were linked to ice margins by examining the distribution and limits of beaches and lake sediment, and by interpreting sediment facies relationships. Key stages were drawn according to the elevation of meltwater channel base levels and subaerial deltas. Rising stages were recognized by fining-upward depositional sequences, where these were found over a considerable area and were overlain by coarser sediment. Figure 32 shows a reconstruction of the main stages in the evolution of northern Lake Agassiz. Those stages depicted are part of a continuum and do not necessarily signify long-lived water planes. The general pattern is one in which ice recession is generally accompanied by falling levels; this pattern is interrupted by a single rising phase.

The main elements in the pattern are (1) the progressive opening of the suture between the two ice margins; (2) the contemporaneous expansion of Lake Agassiz into the areas vacated by the melting ice sheets; (3) after Lake Agassiz had drained, continued recession of Keewatin ice to southeast Keewatin, and development of isolated glacial lakes, contemporaneous with (4) the beginning of the Tyrrell Sea episode. These main events were, to a large degree, interactive. Contemporaneous events are shown sequentially on Figure 32. The time-transgressive aspect of some elements is clarified in Table 4.

Rupture of the suture between Keewatin and Hudsonian ice (Fig. 32A)

Figure 32A shows the positions of the Keewatin and Hudsonian ice masses at the beginning of deglaciation. Keewatin ice flow was predominantly southwards; Hudsonian flow was westwards. Deglaciation began in this area along the outermost part of the zone of confluence between the two ice masses, in the weakest and thinnest part of the ice. Initially Lake Agassiz formed as a triangular wedge in the suture zone, which it gradually expanded. Where sediment-laden meltwater flowing along the suture, an area of drawdown, debouched from tunnels and channels into the proglacial lake, mounds of deltaic sediment were deposited; the train of mounds marks the (time-transgressive) locus of separation of the two ice masses.

During the initial phases of opening, the path of separation was from south to north along the lowlands now occupied by South Knife Lake, and the resulting deposits which form a discontinuous ridge, in plan convex towards the west, are called the Knife River Interlobate Moraine. This moraine consists partly of till, deposited subglacially as interlobate moraine, and partly of the fluviolacustrine kame

Table 4. Sea, ice, and lake relationships

EPISODE AND TIME SPAN	ISOLATED GLACIAL LAKES	LAKE AGASSIZ	KEEWATIN ICE	SUTURE	HUDSONIAN ICE	TYRRELL SEA	AGE
13. Tyrrell Sea			Disappearance of ice			Present Hudson Bay	Present
12. Final Keewatin centre	↑		Margin inundated by Tyrrell Sea Stagnation Radial recession			Emergence	6750 BP
11. Ice flow shifts and isolated glacial lakes	Baralzon Nejanilini		Ice divide southeast Keewatin, with limb in northern Manitoba			Great Beach forms, emergence Marine limit 180 m	7200 BP
10. Demise of Hudsonian ice	unnamed		↑	Holcroft kame	Catastrophic break-up		8000 BP-8200 BP
9. ? Lake Netterville ?	Nueltin	Outlet to Tyrrell Sea via Keewatin/ Hudsonian suture 110m	↑		↑	Rising phase in ?northeast Hudson Basin ?	
8. Lake Agassiz abrupt drops	Booth Munroe	155 m 210 m 245 m 275 m Contracting	Northeastward recession		Readvances into Lake Agassiz; ice quasi stable		
7. Gradually falling levels	Lakes begin	380-355 m Contracting Flights of beaches	Reorientation of eskers Ice divide migrates south		Centre of outflow shifts north; flow west and west-southwest		
6a. Quinn readvance		395 m Maximum northerly extent	Quinn Lake readvance		Margin recedes east of Owl River watershed		
6. Maximum extent		Kaskattama outlet to Lake Ojibway begins	Ribs and eskers		Concave calving margin Active ice		? 8300 BP ≤ Minago
5. Sandy Lake phase		414 m Lake expands and deepens	Ice divide shifts to central Keewatin; flow south and southwest	Rupture migrates east	↑		
4. 377 m level		377 m Expanding	Southwest flow component begins Nares pulse	Massive kame deposits	Calving bay develops		
3. Money Lake phase		425 m Expanding	Northward recession		Margin straight		
2. Early high level Lake Agassiz		442 m Expansion phase Hudwin outlet to Nipigon	Re-entrants at radial moraines	Rupture migrates north	Active ice Margin convey		
1. Rupture		Enters northern Manitoba as a small wedge in suture zone		South Knife Interlobate Moraine			? 8800 BP
Glaciation			Active ice; flow south from M'Clintock divide	Retreat to Burntwood-Etawney Moraine Convergence at North Knife Lake	Active ice; flow west from centre in southwest Hudson Bay		

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deposits mentioned above. The moraine is an continuation of the Burntwood-Etawney moraine in central Manitoba (Klassen, 1983). A massive mound of sand at about 58°20'N, 96°25'W marks a turning point in the orientation of moraine as deglaciation progressed; from there the separation was northeastwards, and the fluviolacustrine deposits associated with retreat form a continuous, arcing hummocky ridge of stratified sand which extends beyond the limits of the map area and terminates at Holcroft Lake near Churchill, the final joining point between the Keewatin and Hudsonian ice masses.

Early high-level lake (Fig. 32B)

Following initial rupture along the interlobate moraines in the southeastern part of the region, deglaciation proceded by widening of the suture and by frontal recession. The proglacial lake began as a wedge occupying the suture and then expanded along the margins of the retreating ice front.

In the early stages of Lake Agassiz, Keewatin ice retreated northwards and the lake advanced across the entire southern part of the map area between Reindeer Lake basin and South Knife Lake. The lake margin abutting Keewatin

ice was oriented approximately east-west, but was slightly lobate in upland regions; these lobes were separated by re-entrants either in local topographic lows or along collection lines for englacial meltwater, marked by eskers and the Seal River radial moraines. The Hudsonian margin was oriented north-south, and ice marginal features indicate that the ice sheet lobed outwards towards the west.

The earliest and highest shoreline features in northermost Manitoba lie in the southern part of the map area. This early lake phase reached 442 m in elevation, and water depths along the glacial margin were as much as 200 m. Its level is recorded as scattered beaches, developed on till, in the area northeast of Reindeer Lake. Because few ice marginal features mark the early stages of the lake, the configuration shown is only approximate.

Money Lake phase (Fig. 32C)

The lake encroached preferentially over the area formerly occupied by the relatively inactive Keewatin ice mass during this and later stages. Hudsonian ice, in contrast, backwasted more slowly because vigorous forward flow was maintained even during the last stages of glaciation. The evidence supporting this conclusion is the contrasting suites of glacial bedforms, ice disintegration features, and glacio-lacustrine landforms associated with the two ice masses, and the ability of Hudsonian ice to prevent the incursion of the Tyrrell Sea. During this lake phase, the Hudsonian ice margin gradually lost its convexity, as shown by the shape of grounding line moraines.

As Keewatin ice retreated northward, the lake level dropped as a result of either downcutting of a southern outlet or a change in outlet. There was an initial lowering to about 425 m, exposing the Money Lake Highland. This level is marked by beaches and by deltas where meltwater channels emptied into the lake.

When the lake was at this level it may have emptied into Lake Nipigon and thence to Lake Superior through an outlet south of the Hudwin moraine in Manitoba and the Agutua moraine in northwestern Ontario (locations on Fig. 1).

The 377 m Lake level and eastward extension of the interlobate moraine (Fig. 32D)

Retreat of the Keewatin ice margin resulted in crustal rebound and a further drop to the 377 m level. Meltwater flowed across the newly exposed land southwest of Morand Lake through two deeply incised channels, which emptied into the lake, forming a major delta. A massive mound of interlobate kame was deposited south of Nares Lake and moraine continued to accumulate eastward along the suture between the Keewatin and Hudsonian ice masses. A large esker or kame delta developed along a secondary rupture in the Keewatin ice and a local pulse caused crumpling of the proximal side of the kame moraine south of Nares Lake.

Sandy Lake phase: Deepening of Lake Agassiz (Fig. 32E)

After ice retreated to the Sandy Lake area, the level of Lake Agassiz rose. Beaches were formed initially at an elevation of 414 m near the receding ice margin, but levels rapidly fell to 410 m and then to 405 m in the newly deglaciated area. Stratigraphic evidence, consisting of clay sharply overlying sand, suggests that the beaches near Sandy Lake formed during a deeping of the lake and are not simple northward extensions of the waterplane associated with the 377 m beaches farther south. Previously exposed areas west of the lake were resubmerged at this time.

Maximum expansion of Lake Agassiz (Fig. 32F)

Additional backwasting of Keewatin ice coincided with a drop in lake level related to a lowering or change of outlet. The drop is recorded stratigraphically as a coarsening-upward sequence of sediments west of Tadoule Lake. The lake stood at about 395 m along its northern limit at this time and formed beaches at elevations between 390 m and 380 m farther south. The slope of this waterplane is thus about 0.2 m/km. This stage marks the most northerly extent of Lake Agassiz. The lake was shallow in the north along the Keewatin ice front. Many parts of western Manitoba stood out above the level of the lake, but eastern areas adjacent to the Hudsonian ice front were covered by about 140 m of water. The ice front extended southeastward from Snyder Lake, possibly around the north end of Kasmere Lake, down to Tadoule Lake, and thence eastwards. The position of the eastern (Hudsonian) boundary of Lake Agassiz is unknown because marine deposits (area 1a on Fig. 30) overlie lacustrine clays; here it is likely that the eastern margin of the lake lay east of the highland forming the headwaters of Owl River and Deer River.

During this phase Lake Agassiz may have drained eastwards into Lake Ojibway through the lowland directly south of the Kaskattama upland in northeastern Manitoba (Fig. 1).

Shifting ice divide and the Quinn Lake readvance (Fig. 32F,G)

As ice recession continued in northern Manitoba the Keewatin ice divide shifted eastwards to a north-south line roughly along the meridian of Yathkyed Lake (98°W). The western part of the ice sheet in northern Manitoba which came to be farther and farther from the ice divide therefore became relatively inactive. Ribbed moraine and bifurcating eskers in the western part of the map area probably developed behind the ice margin at this time; the centre of ice flow shifted, and the ice margin was gradually re-oriented northwest-southeast.

Farther east, the central part of the Keewatin ice mass in Manitoba, now in direct line with the new ice divide (K_3 on Fig. 28), remained active (Fig. 32F). Local readvances are marked by small end moraines. More significantly, increased activation of ice in this central area created either (1) a single major ice stream, marked by drumlin swarms, which originated south of Nejanilini Lake and advanced into Lake Agassiz, extended at least 140 km into the lake, and reached a maximum frontal width of about 120 km at its terminus or (2) a series of smaller ice streams, which successively advanced for shorter distances into the lake as the ice retreated. This advance or series of advances is called the Quinn Lake readvance. The recessional pattern of the ice tongue is marked by numerous De Geer moraines. The number and spacing of the moraines suggest recession over a period of 132 years, with a retreat rate of about 2 km per year. Quinn Lake marks the northerly limit of the floating recessional ice ramp.

By this phase, the shape of the Hudsonian ice margin had gradually changed from convex, when the ice front lay along South Knife River (Fig. 32B), to straight, when it lay at the eastern margin of the map area, and finally to increasingly concave as a major calving bay developed (Fig. 32E to G). Hudsonian ice flowed westwards. The shape of the ice margin is marked by grounding line moraines. An ice ramp or ice shelf protruded beyond the grounding line, from which icebergs calved. The keels of these bergs dragged across submerged moraines and scarred their surfaces. Retreat of the Hudsonian ice was eastwards, parallel to the slope of the land. Thus, as the ice front receded it abutted against increasingly deeper water. Towards the end of its existence, the Hudsonian ice margin had receded over the local drainage divide into an area later inundated by the Tyrrell Sea.

Gradually falling lake levels (Fig. 32G)

After Lake Agassiz had reached its northerly limit, there was a gradual lowering of the lake, marked by numerous beaches between 380 and 335 m. Increasingly more land was exposed to the west.

Abrupt drops in lake level (Fig. 32H)

Beaches in the central part of the Agassiz basin and wave cut notches at equivalent levels around small rises in the northeastern zone are found at 275 m, (Fig. 32H), 245 m, 210 m, and possibly 155 m (possibly marine?).

A possible late, low-level phase: Lake Netterville (Fig. 32I)

A low-level shoreline at 110 m and varved silts near Port Nelson (northeastern Manitoba) may mark a very low lake stage after Lake Agassiz per se had drained, leaving a low-level remnant lake in the Hudson Bay Lowland. The inlet for the lake, named glacial Lake Netterville, is marked by the channels draining Lake Antevs (Prest, 1970) at Sturgeon River near the Manitoba/Ontario border. The outlet for the lake may have been northwards along the zone of Keewatin/Hudsonian confluence to a sea level in Hudson Strait that was lower than the Tyrrell Sea maximum. The existence of this lake is still in question because it demands a low sea level at the time of the marine incursion.

Readvance and catastrophic demise of Hudsonian ice: the end of Lake Agassiz (Fig. 32J)

Stratigraphic evidence on North Knife River, consisting of undisturbed varves overlain by contorted varves and, in turn, by calcareous till, indicates that Hudsonian ice readvanced into Lake Agassiz. The till is overlain by marine sediment dated at 7750 ± 140 BP (GSC-3070). The timing, together with the limited areal extent of the readvance and delicacy of fluting, suggests that the till may have been deposited by a surge similar to the Cochrane readvances in northwestern Ontario that produced streamlines of fluted terrain visible on airphotos. Possibly surging of the ice margin was the critical contributing factor that caused the catastrophic break-up and sudden disappearance of ice in Hudson Bay.

Break-up would have occurred once the buoyant forces acting on Hudsonian ice had exceeded the static ice load. The buoying forces acting on the ice margin were: 1) the proglacial lakes, Agassiz and Ojibway, which deepened as the ice receded down the grain of the land, affecting the entire southern sector of the ice front; 2) the rising Tyrrell Sea, which may have been flooding into the northern part of the Hudsonian ice domain; combined with 3) the considerable quantities of meltwater, which may have been present within the ice, particularly at its base.

The static load was decreased during deglaciation by: 1) general ablation and downwasting of the upper surface of the ice and 2) readvances along the perimeter, which flattened the profile, and thinned the ice.

It is possible that calving of the Hudsonian ice front all along its southern perimeter caused oversteepening of long sections of the ice mass, perhaps already destabilized by rising sea levels. The ice mass responded by surging in various places along its southern perimeter. This action thinned and flattened the profile of Hudsonian ice and may eventually have caused lifting and uncoupling of the glacier from its bed and total break-up of the ice sheet in Hudson Bay. Hudsonian ice would thus have rapidly evolved into a large ice pan. This catastrophic event removed the ice barrier, which had upheld the proglacial lakes, marked the end of Lake Agassiz and the beginning of the Tyrrell Sea episode.

Shift in the Keewatin ice divide and development of isolated glacial lakes

During late stages of Lake Agassiz (after maximum expansion) and after the lake had drained, Keewatin ice recession continued by terrestrial subaerial frontal meltback and downwasting, interrupted by a few minor readvances, such as the one that created the moraine forming the southern margin of Munroe Lake (Map 1608A). Crosscutting striae, the orientation of streamlined forms, and changing trends of esker systems suggest a continued shift and contraction of the centre of glacier outflow from the Yathkyed Lake area to South Henik Lake, due north of the central part of the area, and thence eastwards. The result of this shift is (1) the development of a more radial ice flow pattern in northwestern Manitoba, (2) more active flow in the east-central part of the map area, and (3) loss of vigour in the western part. Ribbed moraine, abundant bifurcated eskers, and radial moraines suggest a sluggish, water-laden ice sheet with abundant meltwater in organized glacial drainage systems. The more active central part of the Keewatin glacier continued to produce ice moulded forms; several striae with a northward sense suggest that a limb of the ice divide may have extended across the Manitoba border.

Glacial lakes developed against the receding Keewatin ice front in areas where southward drainage was blocked by moraines or where natural drainage was to the north. The largest were expansions of present lakes Munroe, Blevins, Nejanilini, Nueltin, and Baralzon (Fig. 33). The glacial lakes were very shallow. Their existence is marked by scattered raised beaches, isolated esker deltas, mud boil covered tills which reflect the incorporation of fines, and pockets of blanket sands.

Radial recession of Keewatin ice to a final centre near Hudson Bay (Fig. 32K)

The final remnants of Keewatin ice retreated towards an ice centre near Hudson Bay, just north of the Manitoba border. A limb of the last ice divide extended into Manitoba as far as Caribou Lake. Final ice flow was generally southwest and southeast over the northeast part of this field area and adjacent northeastern Manitoba. Ribbed moraines and conjugate ridges (crevasse fillings) are the predominant landforms in this area; they suggest that ice was thin and brittle in its last stages and flow was not plastic. Similar features mapped by Aylsworth et al. (1981) in southern District of Keewatin and more extensive areas of transverse moraines shown by Prest et al. (1968) also confirm widespread decay of the final Keewatin ice mass. In addition, moraine plateaus between Nejanilini Lake and Caribou Lake suggest that an isolated remnant may have stagnated in northern Manitoba.

Tyrrell Sea episode

The Tyrrell Sea, a name proposed by Lee (1960), is the inland sea in Hudson Bay Lowlands which once reached levels higher than present owing to glacioisostatic deformation. In this area it began as a high sea and regressed to the present position of Hudson Bay. The Tyrrell Sea episode began after the demise of Hudsonian ice, while Keewatin ice remnants still lay in the area, but persisted long after the ice had disappeared. Because the Tyrrell Sea inundated only a small part of the map area, its history is only mentioned briefly.

The limit of marine submergence is indicated on Figure 33. The elevations of highest wave cut notches, beaches, and marine sediments rise from 160 m near South Knife River to nearly 180 m at North Knife River. North of Seal River the marine limit drops slightly, probably because the sea flooded the last remnant of the Keewatin ice sheet. The uppermost marine levels are thus unrecorded.

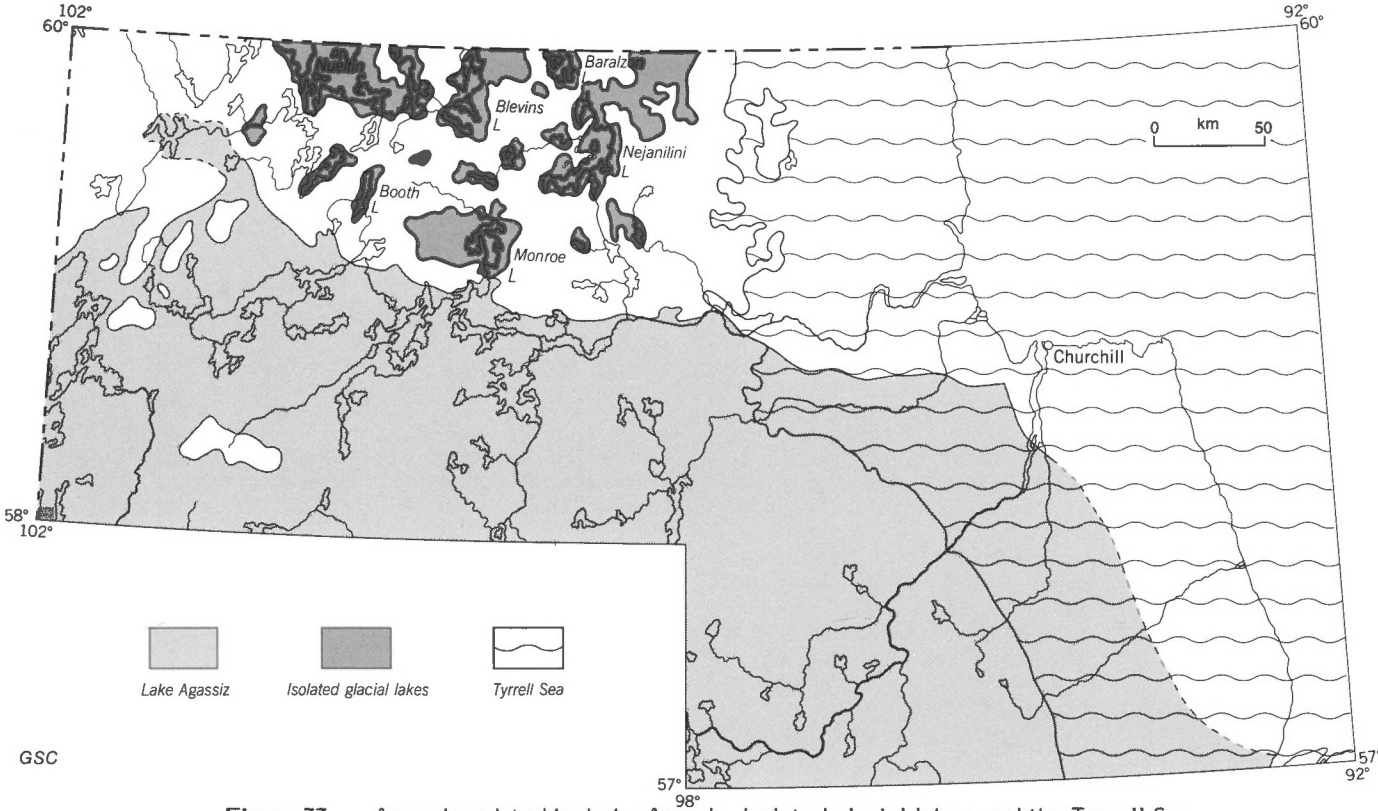


Figure 33. Areas inundated by Lake Agassiz, isolated glacial lakes, and the Tyrrell Sea.

Emergence began at least 7750 ± 140 BP (GSC-3070), a date derived from marine shells found along North Knife River several kilometres east of the map area, and possibly as early as 8000 ± 200 BP (BGS-817; Nelson River). Emergence is continuing at present at a rate of about 60 cm per 100 years. The principal effect of the marine episode in this area was to slightly rework the till surface and to deposit, particularly in low lying areas, a thin layer of marine sediment.

Postglacial climate changes

From their studies of pollen profiles and the location of relict stands of aspen and white spruce, Nichols (1967) and Ritchie (1962) concluded that the climate of northern Manitoba has varied over the course of postglacial time. Nichols' climatic reconstructions show that the forest/tundra margin, which now runs through the study area, was once 300 km farther north, and that summer temperatures between 6000 and 3500 years ago were about 3°C warmer than those at present. Coker and DiLabio (1979) further suggested that there was no permafrost in northwestern Manitoba during that period. Nichols proposed a cooling period between 3500 and 1500 BP, followed by a warming trend which lasted until 600 years ago. Cooler conditions, similar to present, have persisted since that time.

Correlation of northern and southern Lake Agassiz levels

Correlations linking the lake levels and outlets for the northermost part of Lake Agassiz with the lake levels of the southern part are difficult to make because of the paucity of radiocarbon dates in areas north of Lake Winnipeg, and because the elevation of strandlines is too variable to be of value in the reconstruction of waterplanes that could be projected over long distances. It is known, however, that (1) the northern part of the lake must postdate the Grand Rapids phase (8880 to 8500 BP) when the ice front lay just south of Southern Indian Lake (Klassen, 1983) and (2) that on a shoreline diagram (cf. Elson, 1967, p. 46), the waterplanes related to successive regressional lake stages must lie below those of earlier lake phases in the same general area because of isostatic recovery.

Although it was not possible to construct definitive shoreline diagrams for most lake stages because of difficulties in correlating beaches within the area, the beaches that relate to lake level at the time Lake Agassiz had reached its most northerly extent are traceable over long distances; consequently, the slope of waterplane can be calculated. This waterplane slopes downwards to the south-southwest at a rate of 0.2 m/km. Subsequent regressive stages would consist of a family of curves, or lines, of lesser slope lying below the measured waterplane on a shoreline diagram. The waterplanes reltaing to lake levels in northwestern Manitoba would fit onto Elson's (1967, Fig. 5) shoreline diagram as lines below The Pas level, and onto Klassen's (1983) diagram below his Grand Rapids level. Because of the imprecision of the data and large distances involved with this extrapolation we have not attempted to correlate levels more precisely.

Figures 34 and 35 show possible province-wide configurations of Lake Agassiz during its late stages. The highest lake level shown is somewhat younger than 8800 BP (using the chronology of Klassen, 1983) and drained eastward (outlet A, Fig. 34) into the Lake Nipigon basin south of the Hudwin moraine in Manitoba and the Agutua moraine in northwestern Ontario. Levels between 395 and 335 m, with the same outlet, correspond with the Minago level of Ringrose (1975), and thus should date at about 8310 ± 180 BP (GSC-1679; Ringrose, 1975). Levels between 275 and 210 m probably drained into Lake Ojibway through a more northerly eastern outlet (outlet B, Fig. 34) in the lowland between Gods Lake and the Kaskattama upland. The lake may also have

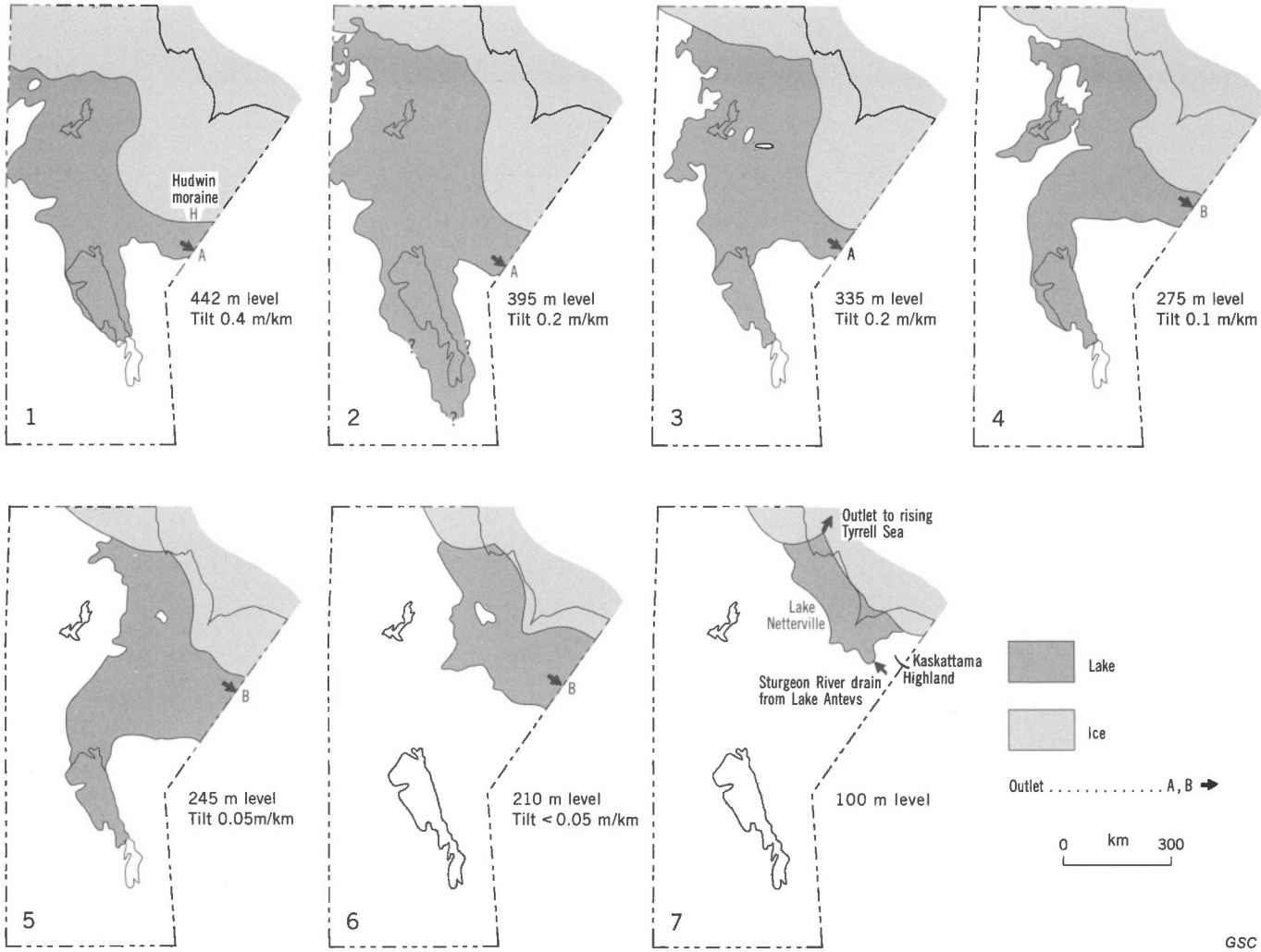


Figure 34. Late phases of Lake Agassiz in Manitoba. Numbers refer to elevation of waterplane in northern Manitoba; these levels tilt downwards towards the southwest and south-southwest.

lowered by draining to a marine base level in the northern part of Hudson Bay through the subglacial, partly ice-walled channels along Limestone and Nelson rivers, and across the Kaskattama Highland of northeastern Manitoba during these intermediate stages, although the subglacial channels originally carried meltwater towards the lake margin. Lower stages are probably older than 7750 BP, the oldest date on marine shells in this area, and may have drained northwards along the zone of Keewatin/Hudsonian confluence to a sea level in Hudson Strait which was lower than the Tyrrell Sea maximum.

ECONOMIC AND ENGINEERING GEOLOGY

Introduction

Map 1608A and earlier descriptions in this report show the distribution and main physical properties of materials, and provide a general basis for regional planning and a focus for site specific studies.

Some aspects which relate directly to potential regional economic development are addressed in this section. Those affecting land use are described first. The second part of the section deals with till geochemistry.

Land use concerns

Sand and gravel

Many of the unconsolidated deposits in the region have a sandy to gravelly texture. the best sources of sorted sand are eskers and radial moraines. Gravel, as well as sand, can be obtained from marine deposits, the Keewatin tills, crevasse fillings, and some eskers, although the gravel is commonly muddy. Sand and gravel is more limited in areas covered with Hudsonian till and lake deposits. The major sources in the southeast are the eskers, which cut across the lake bed, and the Knife River Interlobate Moraine, but blanket lacustrine sands and scattered beach ridges beneath the peat could also be used. The eskers, because of their linear continuity, provide good access ways across the swampy terrain.

Foundering of equipment in loose till

Till that is moderately dense to dense is stable and has a relatively high bearing strength. Much of the sandy till in northwestern Manitoba, however, is fairly loose and has a high volume of voids. Despite the coarse texture of sandy till, it is commonly only moderately drained because the terrain is so flat. Bearing problems may thus develop if the materials are disturbed (especially vibrated) by construction machinery when the soils are saturated and pore pressures build up, such as during snowmelt and after heavy rainfall, or when temperatures are sufficiently warm to melt out deep ground ice.

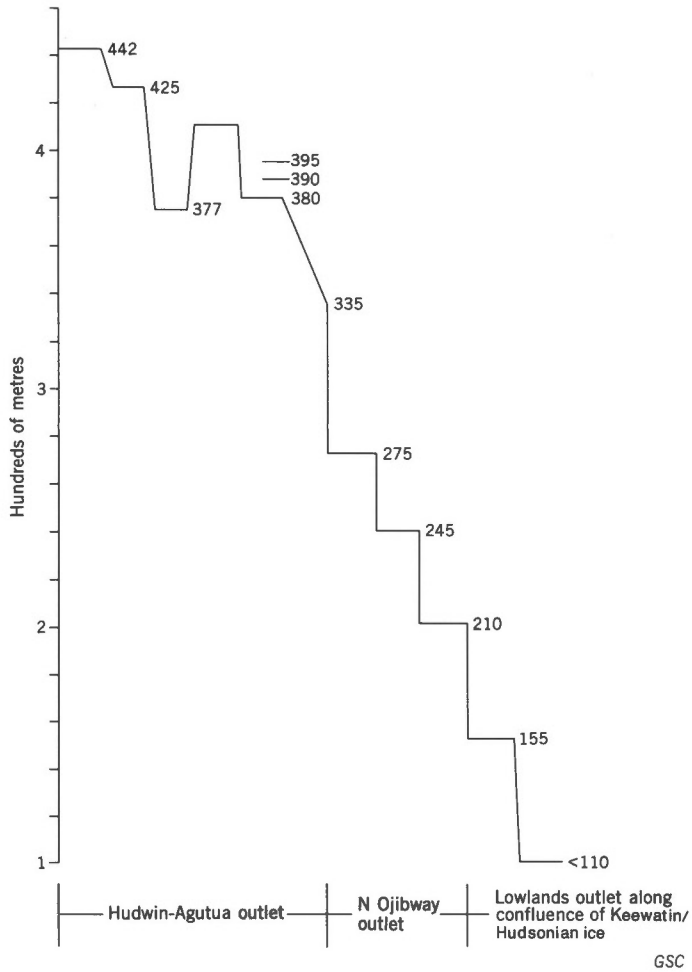


Figure 35. Lake level summary for the northern part of Lake Agassiz.

Permafrost and ground ice

This region lies along the border between continuous and discontinuous permafrost. Although the exact limit is difficult to place because some materials contain small amounts of ground ice the northeastern part of the region – the area beyond treeline – is probably continuous permafrost. In the remainder of the area, permafrost is widespread in areas of lacustrine sediments, silty till, and peat; is absent in kames; and may or may not be present in till. Permafrost is apparently absent in eskers, although discordant lake levels on opposite sides of some ridges could indicate that some esker segments have icy, relatively impermeable cores. There may be taliks below the upper frozen zone in discontinuous permafrost areas.

In permafrost areas the active layer depth ranges from about 30 cm in the north, to 60 or 70 cm in the south; it is deeper in wet peat than in dry peat (see description of materials; Dredge, 1979). Where the peat mantle is more than 1 m thick, thawing commonly does not extend into the mineral substrate.

Ground ice is common in variable amounts, both in peat and mineral soils, although no ground ice was encountered in eskers, radial or interlobate kames, or ribbed moraine. In bog peat, ground ice was observed in cores as coatings around fibres, as random crystals, and as laminae or lenses; commonly an ice layer separates the base of the peat from the mineral soil. Larger bodies of massive ice are also common, as manifested in the ice-wedge polygons around Quinn Lake and in the numerous thermokarst depressions, particularly in the area east of 98°W and south of 58°30'N. Palsas are present in fenland throughout the area and indicate that segregated ground ice occurs in that environment. Ice contents in mineral soils are highly variable. Silty to clayey soils have relatively high amounts of ground ice, as random crystals, stringy laminae, and segregated layers. At many sites the extracted core flowed as a slurry upon melting, and thaw flowslides were observed where the insulating peat cover had been disturbed. The ice content of sandy and bouldery till, eskers, and beach ridges appears to be low or nil.

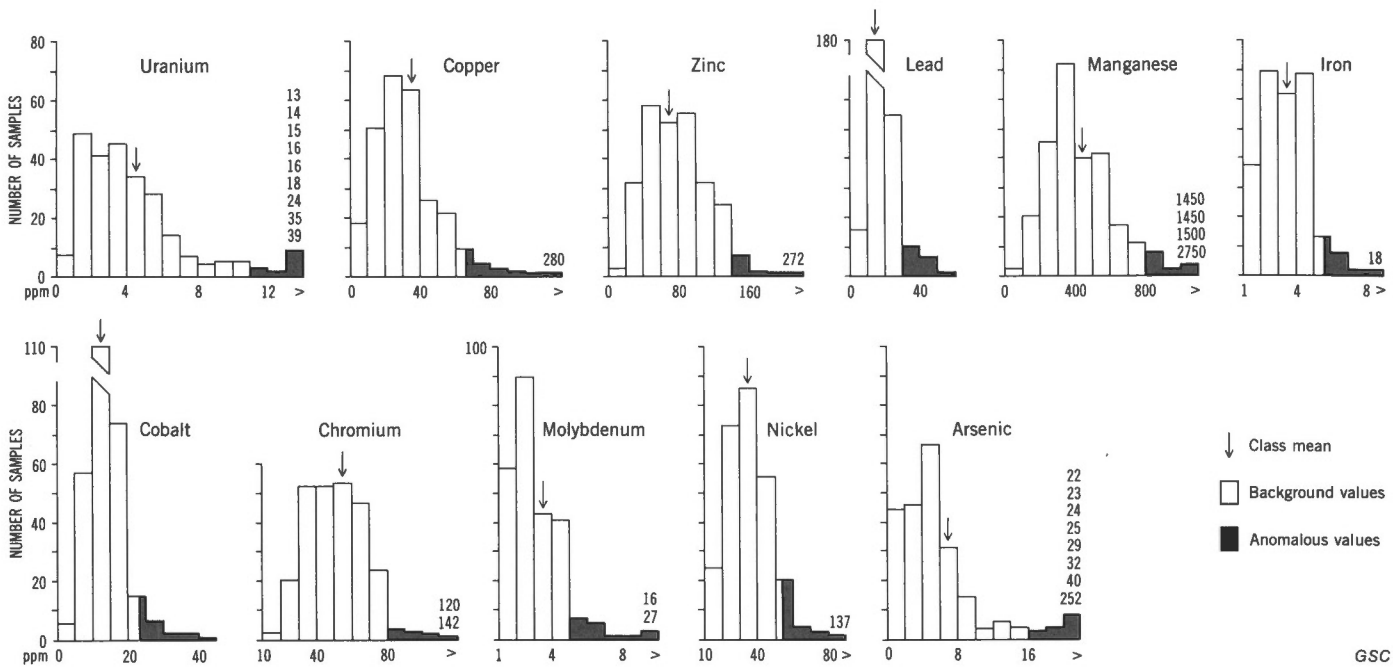
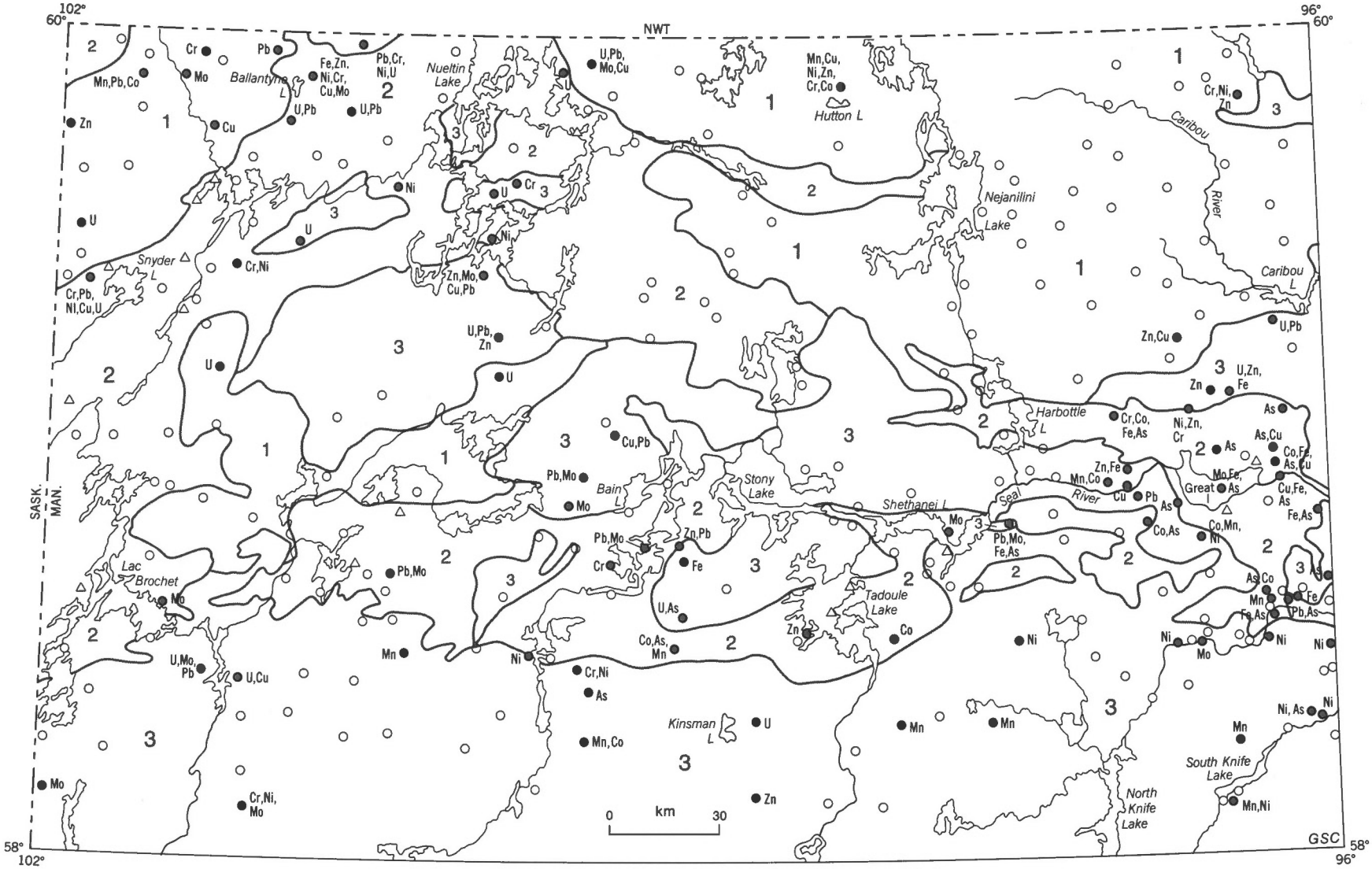


Figure 36. Uranium and base metal concentrations in till in northwestern Manitoba. Arrow denotes class mean value. Shaded area represents anomalous values.



1	*Archean granitoid complexes: granulite, quartz monozonite, diorite, and related gneisses.*
2	*Aphebian metasedimentary and metavolcanic rocks: volcanic rocks, greywacke, arkose-derived gneisses and schist, and migmatite.*
3	*Hudsonian granite and granodiorite, porphyritic granite, granite gneiss and pegmatite*

Sites with anomalous values . . . . . ●
Other sample sites . . . . . ○
Outcrop with mineralization . . . . . △

Figure 37. Bedrock types and location of uranium and base metal anomalies in northwestern Manitoba. (1) Archaean granitoid complexes: granulite, quartz monzonite, diorite, and related gneisses. (2) Aphebian metasedimentary and metavolcanic rocks: volcanic rocks, greywacke, arkose-derived gneisses and schist, and migmatite. (3) Hudsonian granite and granodiorite, porphyritic granite, granite gneiss, and pegmatite.

Peatlands

More than 40% of northwestern Manitoba is mantled by peat, which attains a thickness of up to 4 m. The peat creates large tracts of continuous muskeg, which has a low density, little tractive strength when thawed, and high moisture content. The upper part of the peat is commonly excessively wet; the lower part is frozen and may contain high quantities of ground ice. The thermal and physical properties of the peat are described in detail in Dredge (1979) and Dredge and Nixon (1979). Transportation over peatlands should be confined to the winter months; summer transport across the peatlands should be along eskers.

Construction problems related to permafrost conditions

This region is particularly sensitive to changes in the thermal regime because summer ground temperatures are usually only slightly above or below zero. Changing the soil temperature by a few degrees may create a change of state. The principal construction problems relating to thermal changes are:

1. Heave and subsidence due to ground ice: Many of the difficulties associated with construction in permafrost are related to the aggradation or degradation of bodies of ground ice. Small disturbances leading to the removal of the surface cover of insulating peat or to fresh exposure of frozen, icy subsoils in cuts may cause subsidence. Conversely, draining of ponds may promote deep freezing and the growth of ground ice.
2. Liquefaction of soils: Most of the silty and clayey soils are of low plasticity. Liquid limits range from 20 to 24 and plastic limits are between 8 and 9. Moisture contents in thawed soils are generally between the liquid and plastic limits, but moisture contents are excessively high in some places where the soils are frozen. Newly excavated slopes are therefore potentially unstable.
3. Seasonal soil churning and frost heave of bedrock: All mineral soils except those of eskers, kames, beach ridges, and blanket sands have enough fines to render them susceptible to seasonal frost churning. The activeness of this process is manifested by the prevalence of unvegetated mudboils throughout the region, both in the boreal forest and on the barrens; stony earth circles around the margins of lakes; solifluction lobes north of treeline; palsas covered with dead swamp grasses and not yet revegetated by terrestrial plants; and by rock blisters and the presence of blockfields where moisture accumulates at the bottom of slopes.

Till geochemistry

Introduction

A total of 270 surface till samples, collected over 77 000 km^2 of the map area have been analyzed for base metals and uranium. Because this project was not directly oriented towards drift prospecting, the sampling density is much too low for detailed geochemical interpretations of the data. The results do, however, provide good estimates of background values characteristic of the region, show major differences due to ice flow direction and source rocks, and indicate a few areas where more detailed geochemical sampling may be warranted. Drift sampling for mineral exploration is important in this region because less than 2% of the area is rock outcrop.

Dredge (1982b, 1983a, b) discussed the till geochemistry of northern Manitoba as a whole, and also described (1981a) results from the Jackfish Lake area within the northwestern region. Field and laboratory methods used to obtain and analyze the samples are described in those reports.

Base metal concentrations

Figure 36 shows frequency distributions for uranium and base metal concentrations. Anomalies, or elevated values, are here defined as those lying at or beyond the 95th percentile of the frequency distribution. For northwestern Manitoba, the boundary between background and anomalous concentrations is 11 ppm for uranium, 130 ppm for zinc, 5 ppm for molybdenum, 22 ppm for cobalt, 65 ppm for copper, 800 ppm for manganese, 52 ppm for nickel, 80 ppm for chromium, 32 ppm for lead, 16 ppm for arsenic, and 6% for iron. Arrows show the class mean value on each histogram.

Location of Anomalies

The precise locations of all samples, the base metal concentrations for each sample site, and contoured distribution patterns for each element are presented in Dredge (1983b). Figure 37 shows the distribution of sampling sites and location of anomalies for northwestern Manitoba. Uranium anomalies most commonly occur over the semi-pelitic gneisses between Snyder Lake and Ballantyne Lake, or slightly down-ice from this rock type. Arsenic and iron-zinc-chromium combinations are grouped in the Great Island area underlain by volcanic and related metasedimentary rocks. Elevated gold concentrations are associated with the arsenic anomalies. Manganese is more common in silty tills emplaced by ice from the east, than in the rest of the area. Multiple base metal associations are common between Hutton Lake and Baralzon Lake. Other elements, either singly or in combination, are associated with each major rock type, and are scattered over areas underlain by granitoid rocks.

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